The mysterious absence of neutral hydrogen within 1 Mpc of a luminous quasar at redshift 2.168

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ABSTRACT

The intense ultraviolet (UV) radiation from a highly luminous quasi-stellar object (QSO) should excite fluorescent Lyman α (Lyα) emission from any nearby neutral hydrogen clouds. We present a very deep narrow-band search for such emission near the $z = 2.168$ quasar PKS 0424-131, obtained with the Taurus Tunable Filter on the Anglo-Australian Telescope. By working in the UV, at high spectral resolution and by using charge shuffling, we have been able to reach surface brightness limits as faint as 4.7×10^{-19} erg cm^{-2} s^{-1} arcsec^{-2}. No fluorescent Lyα emission is seen, whereas QSO absorption-line statistics suggest that we should have seen $\gtrsim 6$ clouds, unless the clouds are larger than $\sim$100 kpc in size. Furthermore, we do not even see the normal population of Lyα-emitting galaxies found by other surveys at this redshift. This is very different from observations of high-redshift radio galaxies, which seem to be surrounded by clusters of Lyα emitters. We tentatively conclude that there is a deficit of neutral hydrogen close to this quasar, perhaps owing to the photoevaporation of nearby dwarf galaxies.

Key words: galaxies: high-redshift – intergalactic medium – quasars: absorption lines – quasars: individual: PKS 0424-131 – diffuse radiation.

1 INTRODUCTION

Quasi-stellar object (QSO) absorption-line statistics tell us that the high-redshift ($z > 2$) Universe contains many clouds of neutral hydrogen: clouds containing as many baryons as all the stars today (e.g. Pei, Fall & Hauser 1999; Péroux et al. 2003). The absorption-line statistics do not, however, tell us the sizes, shapes and physical nature of these clouds.

There are two broad schools of thought on the nature of these gas clouds. They could be large (>10 kpc) disc-like structures, associated with young disc galaxies (e.g. Prochaska & Wolfe 1998). Alternatively, they could lie in tiny irregular protogalactic fragments (e.g. Haehnelt, Steinmetz & Rauch 1998). At intermediate redshifts, Mg II absorbers (which are probably the same thing as Lyman-limit systems) seem to lie in large circular structures surrounding disc galaxies (e.g. Bergeron & Boissé 1991; Chen et al. 2001; Steidel et al. 2002), and extending out many tens of kpc. However, at higher redshift, associations between galaxies and neutral hydrogen remain obscure (e.g. Møller et al. 2002; Adelberger et al. 2003; Francis & Williger 2004).

Perhaps the most direct way to constrain the nature of these clouds would be to measure their typical sizes. One way to do this is to use close pairs of QSOs and look for the fraction of absorption lines seen in both spectra (e.g. Foltz et al. 1984; Francis & Hewett 1993; Smette et al. 1995; Crotts & Fang 1998; Rauch, Sargent & Barlow 1999; Impey et al. 2002). These observations show that the lower column density Lyman α (Lyα) forest lines, and perhaps high ionization metal-line systems have sizes of at least tens of kpc. There are, however, too few such QSO pairs to put useful constraints on damped Lyα and Lyman-limit absorbers, though there is some evidence that the probably related low-ionization metal-line systems are not so large.

Is it possible to directly image these clouds? Their 21-cm emission is too faint for current telescopes. Fluorescent Lyα emission is a more promising technique. Originally suggested by Hogan & Weymann (1987), the idea is that the ultraviolet (UV) background at high redshifts will ionize any neutral gas clouds, and cause them to emit the Lyα line. Gould & Weinberg (1996) showed that the number of Lyα photons emitted will be $\sim$60 per cent of the number of incident ionizing photons.

One could thus use either narrow-band imaging or spectroscopy to search for this fluorescent emission. Unfortunately, the predicted surface brightnesses ($\sim$3 × 10^{-20} erg cm^{-2} s^{-1} arcsec^{-2} at

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redshift 4) are very faint, and have not yet been reached (e.g. Bunker, Marleau & Graham 1998; Francis, Wilson & Woodgate 2001a).

In this paper, we use three tricks to bring this faint emission within reach.

(i) Work in the UV. Most of the deepest narrow-band Lyα searches made to date have been performed at redshifts 3–7, where the Lyα line lies at visible or red optical wavelengths (e.g. Bunker et al. 1998; Steidel et al. 2000; Ouchi et al. 2003; Hu et al. 2004). The observed surface brightness of a given object is, however, a very strong function of redshift. Move a given Lyα-emitting cloud from redshift two out to redshift five and the observed flux per arcsec^2 recorded at the Earth drops by more than an order of magnitude. This effect more than compensates for the increased sensitivity of most charge-coupled devices (CCDs) at red wavelengths. So if the aim is to detect low luminosity sources, you are better off working at the lowest redshift possible. The very faint and stable sky background also helps. In addition, working in the UV minimizes the number of strong emission lines in foreground sources that could imitate Lyα. Luckily, the Anglo-Australian Telescope (AAT) has recently commissioned an EEV CCD which achieves close to the theoretical maximum in blue quantum efficiency ($\approx$90 per cent at B; see http://www.aao.gov.au/cgi-bin/ttf).

(ii) High spectral resolution. Most narrow-band Lyα imaging to date has used custom monolithic interference filters, operated in converging beams (e.g. Campos et al. 1999; Steidel et al. 2000; Palunas et al. 2004). This set-up has many advantages, allowing use of a wider range of telescopes and large fields of view at prime focus. Unfortunately, it forces the use of a relatively wide spectral bandpass, typically 50–150 Å. We use a much narrower (7 Å) bandpass, reducing the sky background substantially, albeit at substantial cost to the comoving volume surveyed.

(iii) Work near a QSO. If we image a region close to a luminous QSO, its UV emission will increase the ionization and hence the Lyα emission of any nearby neutral hydrogen clouds. A 17th magnitude QSO, for example, will increase the ionizing flux incident on a cloud by a factor of $\sim$5 at a distance of one proper Mpc. The price paid for this is that the regions close to luminous QSOs are not typical parts of the high-redshift Universe: clustering might enhance the number of gas clouds, but as discussed in Section 5.3, the QSO may destroy nearby gas clouds. This technique was suggested by Haiman & Rees (2001) for studying gas in the haloes of very high-redshift QSOs, and was successfully used by Møller & Warren (1993) to image a damped Lyα system.

In this paper, we present high spectral resolution narrow-band imaging in the near-UV of the volume around the very luminous quasar PKS 0424-131, at redshift 2.159. We reach sensitivity limits that should have allowed us to see the fluorescent Lyα emission from any neutral hydrogen clouds within $\sim$1 Mpc of the quasar. None were seen, and we discuss the reasons for this non-detection.

We assume $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\mathrm{matter}} = 0.3$ and $\Omega_{\Lambda} = 0.7$ throughout this paper. We quote proper (rather than comoving) distances throughout.

2 OBSERVATIONS AND REDUCTION

2.1 Target selection

We required a target QSO that was as bright as possible, and lay at a redshift that placed its Lyα emission within one of the intermediate band blocking filters of the Anglo-Australia Observatory. More

challengingly, the QSO systemic redshift needed to be known to an accuracy of better than 10^{-3}, so that we could confidently target Lyα emission from nearby gas clouds even with a very narrow-band filter.

The best way to measure a QSO systemic redshift with enough precision is to observe its narrow forbidden emission lines, which are shifted into the near-infrared (IR) at these redshifts. As these lines are thought to be emitted at distances of hundreds of parsecs or more from the QSO nucleus, they should reflect the redshift of the host galaxy with adequate precision, unlike the broad emission lines, with the possible exception of Mg II (2798 Å) (e.g. Espey et al. 1989).

Espey et al. (1989) and McIntosh et al. (1999) have measured accurate forbidden-line redshifts, in the near-IR, for small samples of luminous QSOs. The best placed of these QSOs for our scheduled observing dates was PKS 0424-131. PKS 0424-131 is an optically bright ($B = 17.6$) QSO with a strong narrow [O III] (5007 Å) emission line seen in the spectrum of McIntosh et al. (1999). Using this line, a redshift of 2.168 was measured. A consistent redshift was also measured from its Mg II (2798 Å) line.

PKS 0424-131 is a powerful radio source (1.0 Jy at 1.4 GHz, Condon et al. 1998), with a radio spectral index ($F_\nu \propto \nu^{-0.55}$) that places it close to the conventional boundary between flat- and steep-spectrum sources. It is a compact (<0.5 arcsec) radio source at 6-cm wavelength (Barthel et al. 1988). This QSO has been the subject of over 100 papers, though little of the data in these papers is relevant to this project. An archival *Hubble Space Telescope* (*HST*) faint object spectrograph spectrum shows that there is no Lyman-limit absorption along our line of sight within the region we probe. There are Lyα forest lines within this region, and curiously, an associated metal-line absorption system at redshift 2.172 88 (Petitjean, Rauch & Carswell 1994), i.e. infalling at over 400 km s^{-1}, compared with the [O III] or Mg II redshifts. There are a variety of faint near-IR sources seen close to the QSO, either published in Aragon-Salamanca et al. (1994) or seen in the deep archival *HST* NICMOS imaging, but no information is available on the redshifts of these sources.

The [O III] redshift would place Lyα emission at 3851 Å. Mg II would place it slightly bluer at 3848 Å, while Lyα emission at the redshift of the associated absorber would lie at 3857 Å. Our three bandpasses (Section 2.2) cover all these possibilities.

We can estimate the black hole mass in this quasar, using the measured width of the Hβ line (McIntosh et al. 1999) and the rest-frame 5100-Å (observed frame K-band) flux from the Two Micron All-sky Survey, using the relations in Kaspi et al. (2000). The inferred mass is 6.6×10^9 M$_\odot$. Extrapolating still further, using the results of Ferrarese (2002), we infer a dark halo mass of 5×10^{14} M$_\odot$. Note that both numbers are based on large extrapolations from the existing low-redshift data, and should therefore be regarded with caution.

The Galactic extinction along this sight-line, from Schlegel, Finkbeiner & Davis (1998), is $A_B = 0.3$ mag.

2.2 Technical details

Our observations were carried out on the nights of 2003 December 22–25, using the Taurus Tunable Filter (TTF, Bland-Hawthorn & Jones 1998) on the Anglo-Australian Telescope. The TTF is an etalon used in low order, with a greatly extended physical scan range, to give a relatively wide and tunable bandpass. Conditions were photometric throughout, and the median seeing was 1.8 arcsec.

A blue sensitive EEV CCD was used as the detector, the pixel size being 0.33 arcsec on the sky.

We observed a field 500 arcsec east–west by 235 arcsec north–south, centred on the QSO PKS 0424-131. The filter bandpass was a Lorentzian of full width at half maximum transmission 7 Å. A narrower bandpass would have improved the sensitivity, but would have required a narrower bandpass blocking filter than was available to block other orders. The field was observed with the TTF set to three different central wavelengths: 3851 Å (Lyα at the QSO redshift), and wavelengths 6 Å blueward and redward of this. This is the wavelength at the centre of the field; it shifts to the blue quadratically towards the edge of the field. The shift at a radius of 2.5 arcmin is 6 Å to the blue. Other interference orders were blocked by an 170-Å band blocking filter, centred at 3900 Å.

Wavelength calibration proved a challenge at these UV wavelengths. Extensive experimentation showed that the best calibration lamp was a low pressure Xe lamp, which gave three measurable lines within the blocking filter bandpass. Wavelength calibration scans were performed every three hours during the night. Wavelength shifts between scans were typically 1 Å or less.

We used the charge-shuffling technique linked to frequency switching (Bland-Hawthorn & Jones 1998; Maloney & Bland-Hawthorn 2001) to minimize systematic errors in sky subtraction. We only observed with a quarter of the CCD at a time. Every minute, the charge was shuffled up and down the chip, synchronized with shifts in the TTF plate spacing. The result is three images on the same chip, one at each of our three central wavelengths, observed at essentially the same time and through the same pixels. We ran for 45 min between reading out the CCD, giving a 15-min exposure at each of the three central wavelengths. The pointing of the telescope was shifted by ~10 arcsec after every readout, to further improve sky subtraction.

The total exposure time at each central wavelength was 24 420 s. Flux calibration was obtained using the same instrumental set-up, and observing three spectrophotometric standard stars. Twilight flat-field frames were obtained with the etalon removed from the beam, but with the blocking filter in place.

2.3 Data reduction

The reduction and analysis of tunable filter images is discussed in detail in Jones, Shopbell & Bland-Hawthorn (2002). The raw data showed many horizontal bars of elevated charge, probably due to charge trapping sites in the CCD. To remove these, a master night sky flat was produced by combining all the data frames unshifted, and using rejection of high pixels to remove stars. This worked very well and reduced the bars to undetectable levels.

The data frames were flat-fielded and bias subtracted, and then aligned, using all bright stars in the field to compute offsets. Integer pixel shifting was used, to avoid introducing spurious correlations between adjacent pixels. The shifted frames were then combined. Pixels discrepant at the 5σ level, together with their neighbours, were removed from the final co-added image: this did an excellent job of removing cosmic ray hits. Observing conditions were so uniform that no weighting of the co-added frames was required.

The three different images with their different wavelengths were then extracted from the co-added CCD frame. The average of two images was used as the 'off-band' for the other image, and subtracted from it to provide a difference image.

The noise properties of the data show that the sky subtraction technique had succeeded in minimizing systematic errors. The standard deviation of the sky pixel values in the co-added image was within

10 per cent of that predicted by dividing the standard deviation in an individual image by the square root of the number of frames combined. Noise properties were also highly uniform across the field. When the co-added image was binned up, once again the standard deviation went down as $\sqrt{n}$, where n refers to the number of detected photoelectrons, even up to very large binning factors (30 × 30 pixels).

3 RESULTS

The three narrow-band images are shown in Figs 1–3. The images were searched for narrow-band emission by blinking them, by visual inspection of the difference images, and using the source extractor (SEXTRACTOR) program (Bertin & Arnouts 1996). The excellent noise properties of the images allowed us to search for low surface brightness features both by binning up the data and by looking for large numbers of contiguous pixels as little as 0.2 standard deviations above the background level.

No sources were found with excess flux in any of the narrow-band filters significant at the 5 σ level, on any scale. Our 5 σ sensitivity limit for unresolved (<2 arcsec) sources corresponds to a line flux of 9.6×10^{-18} erg cm^{-2} s^{-1}. For sources larger than 3 × 3 arcsec^2, our 5σ surface brightness limit is 1.6×10^{-18} erg cm^{-2} s^{-1} arcsec^{-2}. This drops to 4.7×10^{-19} erg cm^{-2} s^{-1} arcsec^{-2} for sources larger than 10 × 10 arcsec^2. Galactic absorption at this wavelength is ~0.33 mag (Schlegel et al. 1998).

4 PREDICTED SOURCE PROPERTIES

The Lyα sources could be ionized by the quasar (externally ionized) or by UV sources within them (internally ionized). We consider these in turn.

4.1 Externally ionized hydrogen

4.1.1 Surface brightness

How bright should the fluorescent Lyα emission from a neutral hydrogen cloud lying close to a bright QSO be? Let us approximate the spectrum of a QSO as a power-law, of the form $L_\nu = L_0 (\nu/\nu_0)^\alpha$ where L_ν is the luminosity per unit frequency, and L_0 is this luminosity at a particular frequency ν_0. For PKS 0424-131, we measured a flux of 4.3×10^{-16} erg cm^{-2} s^{-1} Å^{-1} at a wavelength of 5000 Å, which corresponds at this redshift to a luminosity of 5.5×10^{23} W Hz^{-1} at rest-frame 6×10^{14} Hz (correcting for Galactic extinction). This is very consistent with the various brightness measurements of this quasar in the literature: we see no evidence for variability. In the rest-frame far-UV, QSOs have $\alpha \sim -0.7$ (Francis et al. 1991). The number of ionizing photons emitted per unit time is thus:

$$N = L_0 \int_{\nu_{LL}}^{\infty} \frac{1}{h\nu} \left(\frac{\nu}{\nu_0} \right)^\alpha d\nu = \frac{-L_0}{\alpha h} \left(\frac{\nu_{LL}}{\nu_0} \right)^\alpha, \tag{1}$$

where ν_{LL} is the frequency of the Lyman limit (3.29×10^{15} Hz).

Let us assume that this photon flux impacts face-on upon a plane-parallel cloud of neutral hydrogen, lying at a distance r from the QSO. If the cloud is optically thick (typically $N_H > 10^{17.2}$ cm^{-2}), all ionizing photons will be absorbed. A fraction ε will then be re-radiated as Lyα photons. Gould & Weinberg (1996) showed that $\varepsilon \sim 0.6$. The Lyα luminosity emitted by a neutral hydrogen cloud
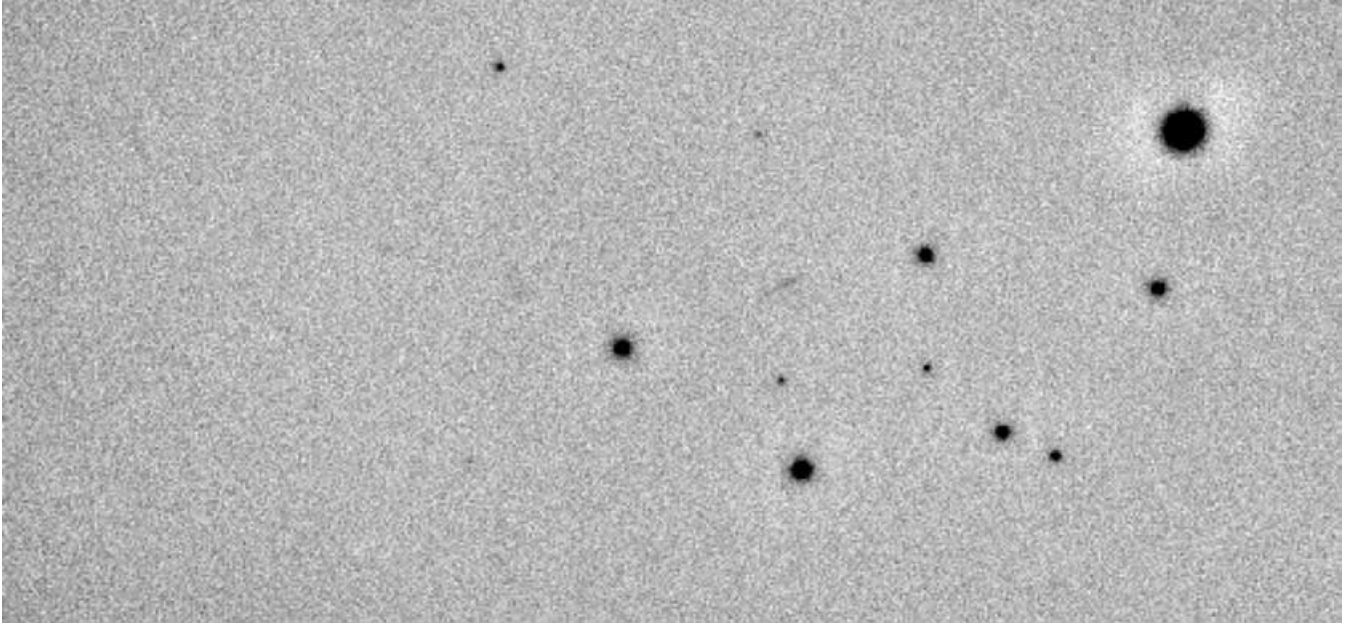
Figure 1. Image of our field centred at 3845 Å. North is upwards and east to the left. The field is 500 arcsec east–west and 235 arcsec north–south. PKS 0424-131 is the bright source slightly below the centre of the field.
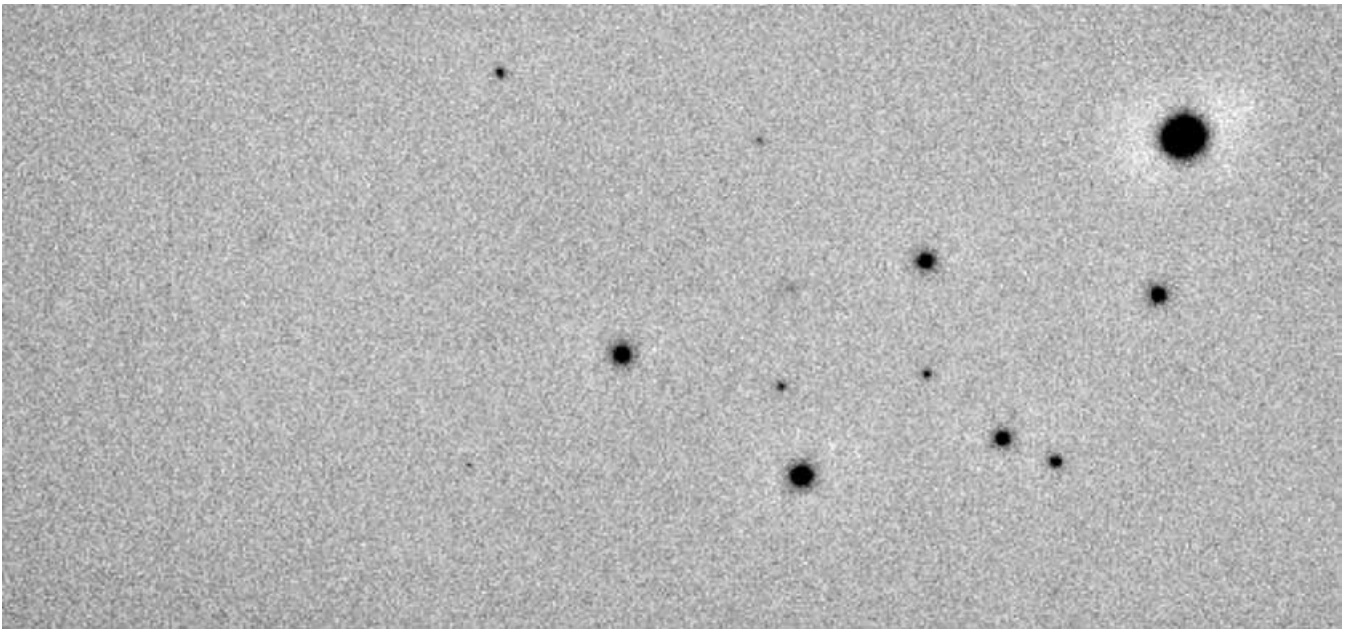

Figure 2. Image of our field centred at 3851 Å. Details as in Fig. 1.

of area A is thus:

$$L_{Ly\alpha} = \frac{\varepsilon}{4\pi r^2} \frac{L_0}{\alpha} \nu_{Ly\alpha} \left(\frac{\nu_{LL}}{\nu_0} \right)^\alpha. \tag{2}$$

Given the observed brightness of PKS 0424-131, assuming $\alpha = -0.7$, $\varepsilon = 0.6$, and that the cloud surface is orthogonal both to the quasar light and to our sight-line, the predicted surface brightness is thus:

$$1.2 \times 10^{-18} \left(\frac{r}{1\,\text{Mpc}} \right)^{-2} \text{erg cm}^{-2}\,\text{s}^{-1}\,\text{arcsec}^{-2}. \tag{3}$$

Gas clouds where the surfaces are at an oblique angle to the incident photon flux will appear fainter, while those at an oblique angle to our line of sight will appear brighter: the two effects should cancel on average, but introduce a dispersion into the predicted surface brightnesses. We are ignoring radiative transfer within the cloud. The Lyα transition can have an enormous optical depth, but most of the clouds we will be seeing will be only marginally optically thick in the Lyman limit, so this effect may not be too severe. It will be severe for any damped Lyα systems lying near the QSO: we may only be able to see these if they lie on the far side of the QSO, so we are directly observing the illuminated face.
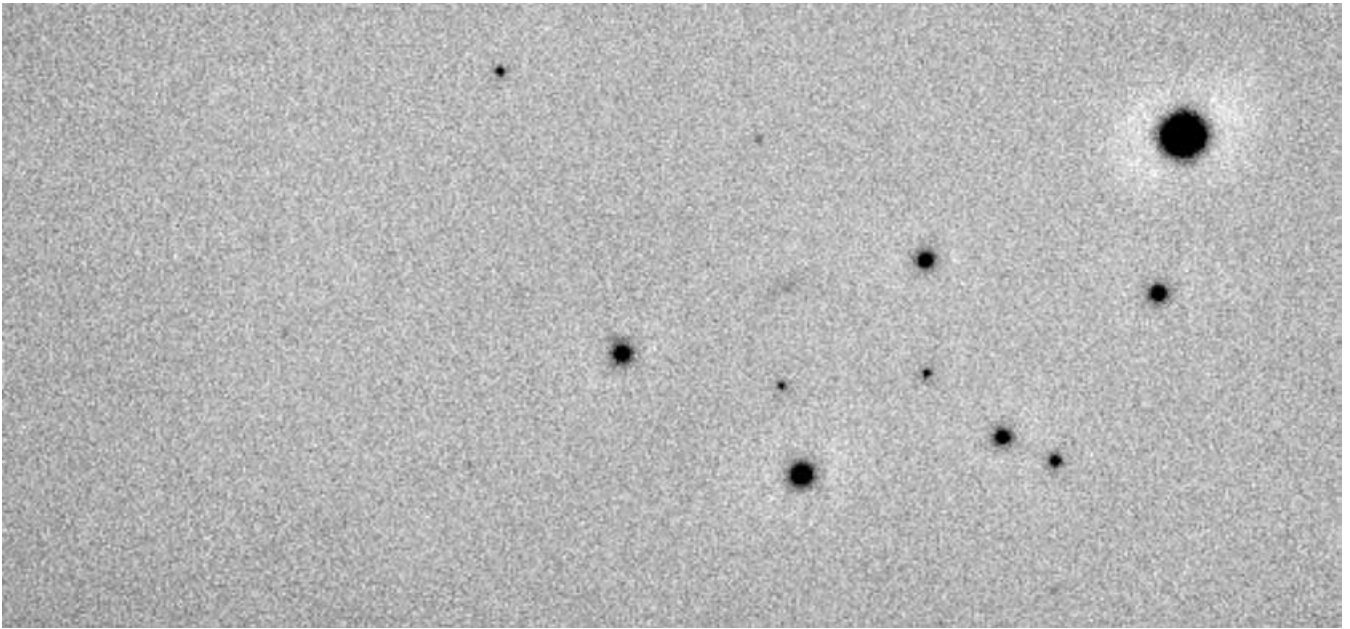
Figure 3. Image of our field centred at 3857 Å. Details as in Fig. 1.

Given these predicted surface brightnesses, and our measured sensitivity limits, we should be able to detect neutral hydrogen clouds that subtend 1×1 arcsec^2 (8.2 proper kpc) out to $r \sim 300$ kpc from the quasar. Larger clouds should be detectable at larger radii: clouds subtending 3×3 arcsec^2 should be detectable out to $r \sim 740$ kpc while clouds subtending 10×10 arcsec^2 should be detectable out to $r \sim 1350$ kpc.

4.1.2 Source density

We are sampling a much smaller comoving volume than most previous narrow-band Lyα surveys: is there a risk that we might not find anything in so small a volume?

QSO absorption-line statistics tell us the typical number of Lyman limit systems found per unit redshift along a QSO sight-line. Péroux et al. (2003) have compiled data from several surveys and give a number of Lyman-limit systems per unit redshift at $z = 2.16$ of $N(z) = 1.6$. In this section, we assume that the region close to the QSO is typical of the Universe at this redshift (however, see Section 5.3).

Let us now assume that Lyman-limit systems are all face-on squares of side-length r. Consider a square region of the sky, of size $D \times D$, observed with a narrow-band filter sensitive to Lyα emission over a redshift range Δz. The probability of any given sight-line through this volume intersecting a Lyman-limit system is $P = N(z) \Delta z$. This should be equal to the fraction of the cross-sectional area of this region covered by the Lyman-limit systems; i.e. nr^2/D^2, where n is the number of Lyman-limit systems in the region, and $P \ll 1$. Thus:

$$n = N(z)\Delta z \left(\frac{D}{r}\right)^2. \tag{4}$$

The three-dimensional (3D) geometry of the region we survey (ignoring peculiar motions) is shown in Fig. 4. Between our three central wavelength images, we fully sample a sphere around the QSO of radius 740 kpc (the radius to which we are sensitive to clouds subtending 3×3 arcsec^2 or larger), and sample most of a sphere of radius 1430 kpc (in which we are sensitive to clouds subtending 10×10 arcsec^2 or larger; Section 4.1.1).

Could we miss galaxies because of their peculiar motions in the potential well of a possible cluster surrounding PKS 0424-131? Between the three images we cover a velocity range of $\sim$1500 km s^{-1}, so this should not be a problem unless there is a very massive cluster indeed. The existence of a cluster this massive at this redshift would be interesting in itself (e.g. Rosati, Borgani & Norman 2002). The $z = 2.16$ cluster identified by Pentericci et al. (2000) had two subcomponents, with velocity dispersions of 300 and 500 km s^{-1}, so either would easily fit within our passband.

Given this geometry, and our field of view (ample for all except the largest sphere), and making the same assumptions concerning neutral hydrogen cloud size as in Section 4.1.1 we should have seen $\sim$20 1×1 arcsec^2 clouds, $\sim$25 3×3 arcsec^2 clouds, or around 6 10×10 arcsec^2 clouds. Only if the clouds were larger than 20 arcsec (160 kpc) would the expected number fall below one.

4.2 Internally ionized hydrogen

Many authors have shown that at sufficiently faint flux levels, a substantial population of Lyα-emitting sources is seen at high redshift (e.g. Cowie & Hu 1998; Pascarelle, Windhorst & Keel 1998; Kudritzki et al. 2000). As these sources are seen far from any QSOs, the ionization must be generated locally, probably by weak active galactic nuclei (AGN) or star formation within the galaxies.

We estimated how many of these sources we should see by comparing to the deepest existing Lyα surveys. The best match to our survey, both in redshift and depth, is that of Pascarelle et al. (1998). Their flux limit is very comparable to ours, and the comoving volume they survey more than twice ours. Allowing for this difference, their results predict that we should see $\sim$6 Lyα-emitting sources. Kudritzki et al. (2000) surveyed a much larger volume at $z = 3.1$, to a luminosity limit approximately four times brighter than ours. If we assume that the surface density of Lyα emitters increases by a factor of 5 for each magnitude we go deeper (Palunas et al. 2004), their
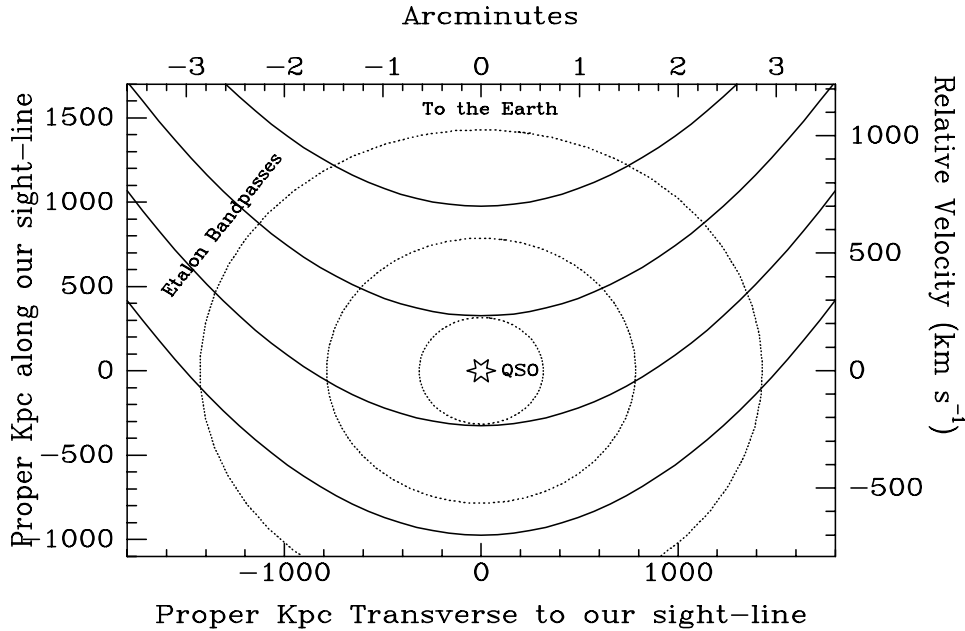
Figure 4. The 3D geometry of the volume in which we are sensitive to neutral hydrogen clouds. The solid lines show the volumes sampled by our three different central wavelength images. The dotted circles show the volumes out to which we should be able to find clouds subtending 1×1 (smallest circle), 3×3 and 10×10 arcsec^2 (largest circle). 1000 kpc equals two transverse arcmin at this redshift. A cloud subtending 1×1 arcsec^2 would be unresolved at our 1.8 arcsec seeing, which has been taken into account in computing the radius out to which it would be detectable.

results also predict that we should see ~5 sources. Similar numbers can be obtained by extrapolating from the results of Cowie & Hu (1998).

In practice, these numbers should be lower limits, as the region close to a luminous QSO is not a random part of the early Universe. Work on high-redshift radio galaxies has shown that they are surrounded by enhanced numbers of Lyα-emitting sources (e.g. Venemans et al. 2002 and references therein). Kurk et al. (2000) and Pentericci et al. (2000) searched for Lyα-emitting sources around a radio galaxy at an almost identical redshift to our source, and down to a flux limit very comparable to our own. They found at least 14 Lyα-emitting sources and a faint QSO, all within 1.5 projected Mpc of the radio galaxy. Comparable clusters of Lyα-emitting galaxies are seen around other high-redshift radio galaxies (e.g. Le Fevre et al. 1996; Pascarelle et al. 1996; Venemans et al. 2002).

Could the Lyα emitters seen near these radio galaxies simply be neutral hydrogen clouds photoionized by UV from the AGN, rather than galaxies? While we see no UV from these radio galaxies, it may be emerging along an ionization cone in some other direction. The Lyα sources are not, however, aligned in any particular area, or close to the radio jet axis, and the concealed nucleus would have to be far brighter in the UV than typical QSOs at this redshift. It therefore seems likely that these are indeed ionized internally.

We therefore conclude that we should have expected to see $\gtrsim$10 internally ionized Lyα-emitting sources near our quasar, whereas we actually saw none.

5 DISCUSSION: WHY DIDN'T WE SEE ANYTHING?

We showed in Section 4.1 that if the region surrounding PKS 0424-131 were typical, we should have expected to have seen the fluorescent Lyα emission from a considerable number of clouds. We

should also have seen internally ionized clouds. Instead, we saw nothing.

Could this just be a statistical fluke? Assuming Poisson statistics, the probability of seeing no sources given an expected number n is <1 per cent for $n > 4$ and <0.1 per cent for $n > 6$. Our non-detection is thus reasonably significant, though clearly observations of several other luminous QSOs would be needed to test this. There have, however, been very few comparable observations. Campos et al. (1999) imaged a pair of QSOs at $z = 2.58$, and found 37 candidate Lyα emitters, but they have no spectral confirmation, their QSOs are much fainter than ours, and they used a 130-Å bandpass filter so the candidates may well lie at a somewhat different redshift to the QSOs. Hu & McMahon (1996) and Hu, McMahon & Egami (1996) found three luminous Lyα sources near two bright QSOs, but both QSOs lie at very different redshifts from ours ($z >$ 4.5). The only observations comparable to ours were those of Bergeron et al. (1999), who observed the $z = 2.238$ QSO in the Hubble Deep Field South down to a flux limit approximately double ours. They found three candidate Lyα-emitting sources, though their large (86 Å) bandpass means that they too may lie at a different redshift, and they have not published spectral confirmation of these sources. None of these QSOs have radio luminosities approaching that of PKS 0424-131.

We thus conclude that there is no compelling evidence in the literature for or against a deficit of faint Lyα emitters close to luminous, high-redshift QSOs.

In this remainder of this section, we will assume that this deficit of Lyα emitters is a generic feature of extremely luminous QSOs at $z \sim 2$, and we will ask how such a deficit could be explained.

5.1 Lack of external ionization

How could we avoid the quasar PKS 0424-131 from ionizing any neutral hydrogen clouds in its vicinity?

If it had only recently switched on its UV emission (at the time when the continuum radiation we see from it was being emitted), there may not have been time for this radiation to reach nearby gas clouds, ionize them and for the Lyα emission to reach the Earth. This would require the current active phase of PKS 0424-131 to be younger than $\sim 10^6$ yr. This is shorter than most estimates of the total lifespan of luminous QSOs (e.g. Martini & Schneider 2003 and references therein). This total lifespan could, however, be divided up into several short active phases, or we could have been unlucky enough to have chosen a quasar very early in its active phase.

As noted in Section 2.1 it is possible that PKS 0424-131 is a compact steep spectrum quasar. If this is the case, the upper limit on the size of the radio source (0.5 arcsec), combined with the typical expansion speed of jets (Bicknell, Saxton & Sutherland 2003) allows us to place an upper limit on the age of the jet: $\sim 10^5$ yr. If this radio source is beamed towards us, however, the size places no limit on the age. We plan very long baseline interferometry (VLBI) observations to discriminate between these two possibilities.

The calculations in Section 4.1.2 assumed that the UV emission from PKS 0424-131 is isotropic. This is known not to be the case for many nearby Seyfert nuclei, where a 'torus' intercepts ~ 50 per cent of the ionizing flux. If this were the case here, the expected numbers of externally ionized hydrogen clouds would be fewer than we predict. Note, however, that recent X-ray observations suggest that a smaller fraction of luminous QSO UV emission is blocked by tori at high redshifts (e.g. Steffen et al. 2003). Observations of the transverse proximity effect in two QSOs (Liske & Williger 2001; Jakobsen et al. 2003) provide further evidence that the UV radiation from high redshift escapes into substantial solid angles. Furthermore, we know from nearby Seyferts that up to 5 per cent of the ionizing radiation field can be scattered almost isotropically by a warm nuclear wind (Bland-Hawthorn, Sokolowski & Cecil 1991; Miller, Goodrich & Mathews 1991). This would render H I clouds visible over a 100 kpc sphere. Note, however, that, especially if the clouds are large, even a small reduction in the radius out to which we can see clouds, or even a narrow obscuring torus can drop the predicted number of clouds below 4, and hence drop the statistical significance of our null detection below 99 per cent.

5.2 Absorption of the Lyα emission

The Lyα line is the optically thickest transition in astrophysics, and hence is easily destroyed. If the ionized neutral hydrogen clouds are optically thick in Lyα, their Lyα emission would only escape back towards the QSO. This would mean that we could only detect Lyα emission from clouds of the far side of the QSO. While this is likely to be true for any systems with $N_H \gg 10^{18}$ cm^{-2} lying close to PKS 0424-131, we would expect many of the neutral hydrogen clouds to have lower optical depths, and hence be visible from all directions.

The high optical depth means that Lyα photons generated within a cloud will have to random-walk their way out. If any dust is present, this gives it multiple chances to absorb the Lyα photons. We know, however, that the Lyman-limit systems seen in absorption against bright QSOs contain very little dust: if they were dusty, the background QSO would have been too faint to observe. There may be a population of dusty absorbers, but they would be in addition to the population known from QSO absorption-line statistics (e.g. Fall & Pei 1993).

We also know that many high-redshift galaxies emit Lyα, despite being ionized from the inside. Any Lyman-limit systems near the QSO would be ionized from the outside, enhancing the probability of any Lyα photons escaping.

We therefore tentatively conclude that the high optical depth of Lyα is unlikely to make all the hydrogen clouds in our field invisible. Even if it does render any externally ionized clouds undetectable, we should see at least the space density of internally ionized clouds found elsewhere in the high-redshift Universe.

5.3 Destruction of hydrogen clouds near the quasar

This leaves us with the third possibility; that we see no Lyα emitters because there are no neutral hydrogen clouds close to the quasar.

If this very luminous QSO lies in a rich cluster environment, the surrounding gas might be heated to X-ray-emitting temperatures, and the surrounding galaxies might be deficient in neutral hydrogen, by analogy with the traditional view of modern galaxy clusters (Giovanelli & Haynes 1985; Cayatte et al. 1990). However, recent studies show that stripping in clusters today is much less effective than originally suggested. The most comprehensive survey to date, incorporating 1900 galaxies in 18 clusters (Solanes et al. 2001), finds that more than one-half of spiral galaxies retain at least half their H I within 900 h_{70}^{-1} kpc. This is the scale, roughly 40 per cent of an Abell radius, over which we expect to see discs with bright H I discs or haloes. A third of the clusters in the Solanes et al. sample show no H I deficiency.

Furthermore, dense galaxy clusters are not thought to be common at such high redshifts (Rosati et al. 2002). One would also expect high-redshift radio galaxies to inhabit similar environments to our quasar, and as noted in Section 4.2, overdensities of Lyα-emitting sources are found around them. Other candidate high-redshift clusters also seem to have overdensities of Lyα emitters (e.g. Steidel et al. 2000; Francis & Williger 2004; Palunas et al. 2004).

Could a wind from the quasar have cleared its environment of neutral hydrogen, as suggested by Scannapieco & Oh (2004)? Adelberger et al. (2003) showed evidence for a similar effect around Lyman-break galaxies, though the reason for this effect is unclear (e.g. Croft et al. 2002; Bruscoli et al. 2003; Kollmeier et al. 2003). We note, however, that the existing evidence points to an overdensity of neutral hydrogen near AGNs, not a deficit. Furthermore, such a wind could easily increase the brightness of any neutral hydrogen clouds by driving shocks into them (Francis et al. 2001b).

The major difference between our quasar and the various high-redshift radio galaxies is its enormous UV luminosity (at least along our line of sight). One possibility is that the quasar environment contains the normal quantity of hydrogen, but that this UV radiation has almost completely ionized it, so it is no longer optically thick in the Lyman-limit and is hence far less efficient at reprocessing the quasar flux into Lyα emission (the same effect that produces the proximity effect for Lyα forest clouds). We can compare the incident quasar flux at 912 Å to the UV background flux at this wavelength ($\sim 7 \times 10^{-22}$ erg cm^{-2} Hz^{-1} Sr^{-1}, Scott et al. 2002). Given the observed brightness of the QSO, assuming a typical QSO spectrum (Francis et al. 1991), and allowing for the fact that the UV background will impact both sides of a gas cloud while the quasar illuminates only one side, we find that at 1 Mpc from the quasar, its flux exceeds the UV background by a factor of ~ 3. At closer distances, where we would be seeing small clouds, the factor is much larger. Note that the ratio of fluxes at 912 Å underestimates the ratio of ionizing flux as the UV background is more filtered by intervening material.

Given this enormous increase in ionizing flux, how much might the number of optically thick externally ionized clouds decrease? We can crudely estimate this by assuming that if the incident ionizing flux increased by a factor x, the cloud would need a hydrogen column

density greater by the same factor x to remaining optically thick. Péroux et al. (2003) showed that the cumulative number of QSO absorbers with hydrogen column densities greater than N_H goes as $N_H^{-0.3}$. Using these figures, the number of externally ionized clouds should decrease by a factor of ~ 2: not enough to explain our non-detection. There is no easy way to estimate the size of this effect on internally ionized clouds.

The extremely strong UV emission from PKS 0424-131 could physically destroy dwarf galaxies in its vicinity, as described by Barkana & Loeb (1999), Benson et al. (2002) and references therein. This photoevaporation mechanism heats the gas in small dark matter haloes so much that it becomes unbound. This destruction may have taken place at a much higher redshift, during the assembly of the very massive black hole we infer in this quasar. This mechanism has the advantage of explaining the absence of Lyα emitters around our UV bright source but not around radio galaxies, and could well destroy internally ionized Lyα sources, if they are dwarf galaxies residing in small dark matter haloes.

6 CONCLUSIONS

Why then did we see nothing? There are several possible reasons that might explain the lack of externally ionized clouds, but the lack of internally ionized clouds is harder to explain. The difference between this UV-bright quasar and radio galaxies at comparable wavelengths points to the UV emission as a possible explanation. We therefore tentatively conclude that the UV photoevaporation model seems the best explanation for our non-detection. With observations of only one QSO, however, this must be regarded as tentative at best.

How could we test this conclusion? Observations of more QSOs, and a better understanding of the background density of internally ionized Lyα sources at this redshift will clearly be vital to establishing whether this deficit of gas near luminous QSOs is real. With the recent decommissioning of TTF, this will have to be performed at a different telescope.

If the sensitivity can be increased by a factor of ~ 3, we should be able to detect neutral hydrogen clouds ionized only by the UV background, i.e. we can dispense with a nearby QSO. This should be quite feasible with long exposure times on an 8–10 m class telescope. Alas most such telescopes do not have imagers capable of achieving the necessary spectral resolution, and most detectors have poor quantum efficiency in the UV. One exception will be the Osiris instrument, which incorporates many of the features of TTF, currently under construction for the Gran Telescopio Canarias (Cepa et al. 2003). Not only should this allow us to image neutral hydrogen clouds far from QSOs and hence measure their sizes and shapes, the anticipated sensitivity of this machine should allow many tens of QSO fields to be surveyed out to $z \sim 5$ over a range of intrinsic ionizing luminosities. This may be a relatively direct way to establish the critical ionizing flux at which star formation is effectively suppressed in the local Universe.

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