A young, dusty, compact radio source within a Lyα halo

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ABSTRACT

We report here on the discovery of a red quasar, J004929.4+351025.7 at a redshift of z = 2.48, situated within a large Lyα emission-line halo. The radio spectral energy distribution implies that the radio jets were triggered less than 10^4 years prior to the time at which the object is observed, suggesting that the jet triggering of the active galactic nucleus is recent. The loosely biconical structure of the emission-line halo suggests that it is ionised by photons emitted by the central quasar nucleus and that the central nucleus is obscured by a dusty torus with A_v ∼ 3.0. The large spatial extent of the Lyα halo relative to the radio emission means this could only have occurred if the radio jets emerged from an already established highly-accreting black hole. This suggests that the radio-jet triggering is delayed with respect to the onset of accretion activity on to the central supermassive black hole.

Key words: galaxies: active – galaxies: halos – galaxies: high-redshift – quasars: individual: J004929+351025

1 INTRODUCTION

Most quasars exhibit a blue optical and ultraviolet continuum, broad emission lines, and narrow forbidden emission lines of highly ionised elements (e.g. Schneider et al. 2003). However, there is also a population of reddened quasars predicted by the unification schemes (Urry & Padovani 1995), and which have been known for a number of years (e.g. Webster et al. 1995). The origin of red quasars and their fraction relative to normal quasars is still subject of debate: we still do not know the fraction that are intrinsically red, e.g. in radio-loud quasars the synchrotron tail can extend into the near-infrared and optical wavebands (Whiting et al. 2001), or the fraction that are reddened by dust (e.g. Richards et al. 2003). For the dusty quasars, it is not clear if the dust is typically situated in a dusty torus around the central quasar nucleus (e.g. Antonucci 1993), or whether it is distributed more widely throughout the host galaxy (e.g. Martínez-Sansigre et al. 2006).

Determining the fraction of very red quasars (red, reddened or both) in the total population is essential for a precise determination of the quasar Luminosity Function (LF) and also for understanding the evolution of quasars and the nature of the quasar-galaxy connection. If a large fraction is eliminated from optical surveys by simple dust reddening then the relative comoving space density of such objects may be much higher and would have a much more profound effect on the evolution of massive galaxies.

Historically optical surveys, relying on the ultraviolet-excess and power-law shape of the typical (i.e. blue) quasar spectrum, have failed to discover this red population, principally due to the fact that the blue excess is not present in reddened quasars (Richards et al. 2004). Unsurprisingly, recent radio and infrared surveys have shown a better promise in finding red quasars over all redshifts (Glikman et al.
Although previous large area attempts have suffered from incompleteness, this is still the most promising approach.

Many powerful, high-redshift radio-loud active galactic nuclei (AGN), are now known to be surrounded by large-scale, highly-luminous, Lyα emission-line haloes (Chambers et al. 1998; Villar-Martín et al. 2002; Reuland et al. 2003). Similar Lyα emission haloes have also been found around a radio-quiet quasar (Weidinger et al. 2004), and submillimetre galaxies (Steidel et al. 2000; Chapman et al. 2004; Bower et al. 2004; Geach et al. 2005). This suggests that giant Lyα halos may be associated with the onset of quasar and/or starburst activity (see also Haiman & Rees 2001; Ohvama et al. 2003; Wilman et al. 2003). However, the recent discovery of a number of large diffuse Lyα haloes around seemingly quiescent galaxies (Nilsson et al. 2006; Smith & Jarvis 2007; Saito et al. 2007) suggests a model in which the origin of some Lyα haloes is cold gas accreting on to the dark-matter halo of a massive galaxy (Fardal et al. 2001; Dijkstra et al. 2003). There may therefore be several mechanisms responsible for giant Lyα halos. However, most of the large > 50 kpc haloes discovered so far seem to surround massive galaxies, thus the large haloes may be a product or a requisite ingredient in the formation of massive galaxies at high redshift, regardless of the mechanism behind their ionisation.

In this paper we report the discovery of a reddened quasar that conforms to the idea that red, young, radio quasars at z ∼ 2.5 might pick out dust, possibly star-forming, massive galaxies within giant Lyα haloes. In section 2 we present the photometric and spectroscopic data and in section 3 we discuss the properties of this object. In section 4 we make some concluding remarks concerning the implications of this object for jet-triggering in AGN. We assume throughout that H₀ = 70 km s⁻¹ Mpc⁻¹, Ω₀ = 0.3 and Λ₀ = 0.7. All quoted magnitudes are in the Vega system.

### Table 1. Summary of radio properties of J0049+3510. The quoted limits are 5σ.

| Survey   | Frequency / GHz | Flux Density / mJy |
|----------|-----------------|--------------------|
| VLA      | 8.4             | 33.4 ± 1.4         |
| GB6      | 4.85            | 67 ± 9             |
| NVSS     | 1.4             | 122.0 ± 3.7        |
| WENSS    | 0.325           | 101 ± 18           |
| 6C       | 0.151           | < 400              |
| VLSS     | 0.074           | < 500              |

Figure 1. Observed-frame radio spectral energy distribution for J0049+3510. The peak of the SED is shown to be around 1.2 GHz (4.2 GHz in the rest frame for z ∼ 2.5), corresponding to a source age of ∼ 10⁷ years (see O'Dea 1998).

122.0 ± 3.7 mJy, giving an inverted radio spectrum between 325 MHz and 1.4 GHz, α_{325MHz,14GHz} = −0.134. As inspection of the Digitized Sky Survey showed no optical counterpart at the radio position, it was marked for follow up in the optical and near-infrared wavebands as a candidate z > 6 quasar.

### 2.2 Radio data

A search in the literature showed counterparts for J0049+3510 in the GB6 4.85 GHz survey (Gregory et al. 1996) but no counterparts in the 6C 151 MHz survey (Hales et al. 1993), nor the VLSS 74 MHz survey (Cohen et al. 2007). The source position is not covered by the FIRST survey (Becker et al. 1995).

Archive observations from the VLA, in A-array, X-band (8.0 – 8.8 GHz), were recovered and a map made from the data available. This revealed a compact radio source (unresolved at 0.3 arcsec resolution) with a flux density S_{8GHz} = 33.4 ± 1.4 mJy (see Table 1). The radio-spectrum of J0049+3510 is shown in Figure 1 and it is apparent that the SED is peaked around 1.2 GHz. Given the compact nature and the peak of the SED at 1.2 GHz we classify this quasar as a Giga-Hertz-Peaked-Spectrum (GPS; O'Dea 1998) source.

### 2.3 Optical and near-infrared imaging

The quasar was subsequently observed at Harlan J. Smith Telescope (HJST) at McDonald Observatory for 150 s in the R-band. The data were bias-subtracted, flat-fielded, and combined with standard IRAF packages. For flux calibration we used standard stars observed on the same night. Aperture photometry was performed using the IRAF APPHOT package with a 2 arcsec diameter aperture. No identification was found at the position of the radio source, implying that our source was fainter than R ∼ 23.9 mag at the 3σ level.

Following our search method, we targeted it with near-infrared K-band imaging on the UK Infrared Telescope
We identified a broad emission line at 2μm which we later confirmed to be the [O III] doublet at a redshift of z ~ 2.48, thus suggesting that the bright emission line may be Hα. If the redshift were indeed z = 2.48 or z = 7.2, then we should be able to detect the Lyα line with optical spectroscopy.

Optical spectroscopy was carried out with the Gemini Multi-Object Spectrograph (GMOS) on Gemini North. We used a 0.75 arcsec long slit with PA of 78° with a nodding of 10 arcsec. We selected the G150 grating centred at 750 nm for a total exposure time of 1200 s. The data was reduced with IRAF and a spectrum was wavelength-, flux-calibrated and extracted over 1.5 arcsec (the spatial scale was 0.145 arcsec pixel$^{-1}$) with our own IDL routines. The spectrum showed no lines but a very faint continuum roughly between 4800 and 8000 Å. The seeing, measured as the Full Width Half Maximum (FWHM) of a gaussian fit to the spatial profile of an unresolved object on the slit, was 1.3 arcsec.

### 2.4 Optical and near-infrared spectroscopy

Near-Infrared spectroscopy observations were performed with the UKIRT Imaging Spectrometer (UIST) using the standard ‘ABBA’ nodding sequence (with a nod of 12 arcsec) on the night of 2004-09-16. The total exposure time was 160 minutes and the data were reduced with ORACDR. The spectrum was extracted over 1.2 arcsec (the pixel scale is 0.12 arcsec pixel$^{-1}$) with the IRAF APF01/1T packages. We identified a broad emission line at 2.292 μm, first identified, in view of the optical and near-infrared SED, as the MgII$\lambda$2799 line redshifted to z = 7.2. No other obvious lines were identified in the HK Spectrum, but continuum was present throughout the wavelength range. Figure 3 shows the extracted one-dimensional near-infrared spectrum of the quasar. The spectrum also shows tentative evidence for a second emission line at 1.74 μm which we later confirmed to be the [O III] doublet at a redshift of z ~ 2.48, thus suggesting that the bright emission line may be Hα. If the redshift were indeed z = 2.48 or z = 7.2, then we should be able to detect the Lyα line with optical spectroscopy.

At this stage J0049+3510 was considered a good candidate for a z ≥ 6 quasar as the optical and near-infrared SED suggested the presence of a steep spectral break between the near-infrared and optical bands. This would correspond to the Gunn-Peterson trough, with the Lyα line redshifted between the I- and J-bands. We therefore sought spectroscopy in order to determine the redshift and nature of this source.

### 2.5 The Lyα Halo

The quasar was observed using the Sloan Gunn $g$ (≈ 420 – 550 nm) filter used with the Isaac Newton Telescope Wide-field camera (INT–WFC) for 1800 s during the night of 2003-12-13. The image showed extended diffuse structure to the south of the quasar position in addition to some emission co-spatial with the unresolved K-band identification which we take to be dominated by line emission; we refer to these as

### Table 2. Summary of optical and near-infrared imaging observations and photometry of J0049+3510. Quoted limits are 3σ. J0049+3510 is a point source in the J-, H-, and K-band images.

| Date       | Telescope & Instrument | Filter | Exposure (s) | Seeing (arcsec) | Aperture (arcsec) | Magnitude Vega |
|------------|------------------------|--------|--------------|-----------------|-------------------|----------------|
| 2004-12-13 | INT–WFC                | $g$    | 1800         | 1.1             | 10                | 19.56 ± 0.15    |
| 2003-08-28 | HJST-IGI               | $R$    | 150          | 1.2             | 2                 | > 23.9         |
| 2003-09-22 | WHT–PFIP               | $H$    | 1200         | 1.2             | 2                 | > 24.5         |
| 2004-11-04 | WHT–LIRIS              | $J$    | 3000         | 0.6             | 2                 | 21.06 ± 0.20   |
| 2003-09-26 | UKIRT–UFTI             | $H$    | 540          | 0.7             | 2                 | 18.69 ± 0.15   |
| 2003-09-15 | UKIRT–UFTI             | $K$    | 540          | 0.5             | 2                 | 17.62 ± 0.07   |

Figure 3. Near-infrared HK spectrum of quasar J0049+3510. The spectrum has been smoothed using a 0.003 μm FWHM gaussian, with the broad Hα line at 2.292 μm, and a very weak [O III] doublet confirming the redshift of this source as z = 2.48.
Figure 2. (left) K-band image (greyscale) overlayed with the radio 8GHz (contours) showing the compact radio source matching the unresolved near-infrared object within the astrometric uncertainty of the K-band image. The radio contours are $\sim 2\sigma$ and $2\sigma \times \sigma$, where \( n = 2, 3, 4, \ldots, 14 \) with $\sigma = 282 \mu$Jy. (right) The K-band image (grey-scale) is overlayed with the optical g-band (contours) showing diffuse blue emission near to our source and a detection of the quasar itself, which we called the south and central blobs respectively. There is also tentative evidence for further Ly$\alpha$ emission to the north-east of the central source. However, this is at a much lower level than the central and southern components. There are no co-spatial identifications for either the southern and northern components down to $K = 19$ (3\sigma). We have also added the position of the long slit used in the WHT–ISIS spectroscopy.

Subsequent WHT–ISIS spectroscopy on 2004-12-09 targeted the brightest two (central and south) blobs using a 2 arcsec slit with position angle of 170° east of north, with a total exposure time of 40 min. We used the R300B grating, giving a spectral resolution of $\sim 9\AA$. The ISIS spectra were reduced with IRAF, wavelength calibrated with a CuAr+CuNe arc and flux calibrated using observations of the SP1942+261 standard star. The one-dimensional spectrum was extracted with the IRAF APEXTRACT task for several different apertures.

Figure 4 shows the two-dimensional spectrum, where three separate emissions lines can be identified, associated with the three blobs present in the g-band image; together with one-dimensional spectra extracted from each blob. We find an emission line at 4222 $\AA$ in the central and southern blobs, which we identify as Ly$\alpha$, corresponding to a redshift of $z = 2.47$. No other lines (e.g. C iv, He ii, C iii, etc.) could be found associated with either blob. The combined flux from all of the Ly$\alpha$ blobs, after correcting for the aperture and the edge of the filter, can account for $\sim 90\%$ of the flux seen in the g-band image. Furthermore, the spectrum taken with GMOS-N, where only the central blob is positioned on the slit, shows some faint continuum of the order $\sim 22$; which corresponds to $\sim 30\%$ of the contribution of the central blob.

This result is consistent with the K-band emission line being H$\alpha$ at $z = 2.49$; and not MgI as it was first thought. With this established, the tentative line in the HK spectrum is now confirmed as the [O iii]4959/5007 doublet at $\sim 1.74\ \mu$m (Fig. 3). We, therefore, use the redshift determined form the [O iii]4959 line (i.e. $z = 2.48$), as the best estimate for the redshift of our source. We chose not to trust the redshift from the Ly$\alpha$ line as this could be affected by absorption and thus its position is more uncertain, while the H$\alpha$ line is likely to be contaminated with other emission lines, e.g. [Nii]. The emission line properties are summarised in Table 3.

The southern blob extends to $\sim 4$ arcsec ($\sim 33$ kpc) from the central K-band identification, with the overall ex-
tent of the Lyα emission, including the northern component, spanning ~10 arcsec (~83 kpc), suggesting this object is embedded in a very extended Lyα halo. The de-convolved velocity widths of the Lyα-embedded in a very extended Lyα1290 central and southern blob are very similar, with FWHM of wing redward of the main Lyα it is clear from Fig. 4 that there is evidence for a broader component in Hα the fact that we see very little sign of a broadened red com-

3 DISCUSSION

3.1 Origin of the Lyα halo

The radio SED of J0049+3510 (Fig. 1) shows that it is a powerful (L1.4 = 7.5 × 10^{25} W Hz^{-1} sr^{-1}) GPS radio source with a rest-frame peak at ν ~ 4.2 GHz. Using equation 1 in O'Dea (1998) to estimate the electron lifetime of typical GPS source we find that J0049+3510 is probably a very young radio source, viewed < 10^3 yr after the jet-triggering event. We can also use the strong anti-correlation between the turnover frequency and the projected linear size of the source (e.g. Fanti et al. 1999) to estimate the linear size of the radio emission in J0049+3510. Using equation 4 in O'Dea (1998), for a rest-frame turnover frequency of 4.2 GHz, we find that the projected linear size would be ~ 100 pc, which is consistent with jet hotspots advancing at ~ 0.25 c (as it has been measured in compact symetric radio sources; Owsiannik & Conway 1998)) for ~ 10^3 yr. The inferred limit on the size is also consistent (at z = 2.48) with the < 0.3 arcsec limiting spatial resolution of the 8.4 GHz radio observations.

If we were to consider a model in which accretion ac-

To summarise, J004929.4+351025.7 is a radio-loud GPS source at z = 2.48, reasonably bright in J, H and K but invisible in both I and R down to 3σ limiting magnitudes of R = 23.9 mag and I = 24.5 mag. It has a broad Hα emission line with a very weak [O III], and it lies within 83 kpc Lyα emitting halo.

Figure 4. The left panel is the two dimensional optical spectrum centred one the position of the host galaxy and smoothed over 3 pixels showing two clear and a third tentative spatially-distinct Lyα blobs at the same wavelength. The right panel shows spectra of the three blobs of emission: the central spectrum is from the central region co-spatial with the K-band identification; the top and bottom spectra are from the northern and southern blob shown in Fig. 2. An emission line is detected at 4222 Å and identified with Lyα at z = 2.47 in all three blobs.
furthermost parts of the Lyα halo. This is shorter than the expected duty cycle of a typical AGN lifetime (e.g. Martini & Schneider 2003), thus the Lyα halo could easily be photoionised by an obscured quasar, in place before the current jet activity was triggered.

3.2 Estimating the extinction

In order to investigate the reddening of the optical and near-infrared SED, we have used a simple χ²-fitting technique to estimate the amount of extinction. We used the SDSS composite quasar template (Vanden Berk et al. 2001) combined with the AGN spectral energy distribution from Elvis et al. (1994). To this, we applied extinction corrections for three different types of dust (Milky Way MW, Large Magellanic Cloud LMC, and Small Magellanic Cloud SMC) as in Pei (1992). We have neglected any contribution from a host galaxy principally because any such component would peak in the observed-frame SED around J band, where the emission is spatially unresolved, and secondly the host would have to be unreasonably massive (≥10¹²M☉, corresponding to a ≥26 L☉, elliptical after accounting for passive evolution) to contribute even at the ∼ 10% level. Furthermore, the K–z relation for a typical radio galaxy at z = 2.48 predicts a K magnitude of K = 19.1 ± 0.5 (Jarvis et al. 2003; Willett et al. 2003). We used extinction corrections as described in Section 3.2 for MW and LMC and Av = 20.8 ± 1.6 for SMC.

The Lyα/Hα line ratio might give extra information on extinction on this object. However, as discussed in Eales & Rawlings (1993), it is not easy to obtain a reliable intrinsic extinction value because of the effects of resonant scattering of Lyα. Therefore, we will only use this line ratio as an independent verification of our fitting results. The line ratio measured from the central blob is 1.8; similar to those found in high-redshift radio galaxies (HzRG) by Eales & Rawlings (1993). Moreover, if we assume an intrinsic Lyα/Hα=8 line ratio and apply an extinction of Av=3 with a MW type dust, the Lyα/Hα line ratio we should observe is 1.9, indicating that our fitting suggests a similar extinction to the optical continuum of the quasar and the narrow emission lines. We note that this level of reddening could be due to the edge of an obscuring torus, or could be due to dust in the host galaxy, although the latter is preferred as the narrow lines too appear to be reddened.

It is also plausible that the large diffuse line emission could be caused by gas cooling on to the dark matter halo of the galaxy (e.g. Fardal et al. 2001; Dijkstra et al. 2004; Nilsson et al. 2006; Smith & Jarvis 2007; Smith et al. 2008). However, the distribution of the ionised gas suggests a loosely biconical ionisation front, as would be expected from a central AGN, with an obscuring torus where the ionising photons can only escape through the opening angle of the dusty torus. This biconical structure is seen in other radio galaxies, and most convincingly in Cygnus A (Fradella et al. 2003). This spatial distribution could also, in principle, be caused by a large halo of absorbing gas around the galaxy as seen in many radio galaxies with small angular sizes (e.g. van Olst et al. 1997; Jarvis et al. 2003; Wilman et al. 2004; Jarvis et al. 2004). However, evidence suggests that such haloes may be roughly spherical in nature (Jarvis et al. 2003), and thus do not have a preferred orientation, although such gas may account for the observed broader redward component in the Lyα emission-line profile. Furthermore, there is no evidence of any other extended emission around the central source apart from in the biconical direction shown in Fig. 22.

4 CONCLUSIONS

During our search for z > 6 radio-loud quasars we have discovered an obscured quasar at z = 2.48 embedded in a large Lyα halo. The ionising source of the large-scale Lyα halo is most likely to be the central AGN, with a dusty torus or a dusty galaxy obscuring the AGN along our line-of-sight. The dusty torus would also explain the structure of the Lyα emission-line halo, with the ionising photons essentially being forced into a biconical structure according to the opening angle of the torus.

Using the peak of the radio spectral energy distribution to estimate the age of the radio jet, we find that the radio source has been active for ∼ 10⁵ years, assuming a jet speed of ∼ 0.25c. This implies that the accretion activity must have started prior to the radio-jet triggering event, suggesting that the triggering mechanism for the optical quasar is different, or at least not coincident in time with, the triggering of the radio jet.

Further work on J0049+3510, including integral field spectroscopy, will allow us to map the emission line profiles across the halo and examine the nature of the ionised gas. Higher-resolution radio observations would also allow us to test whether the ionising photons are being emitted in the same direction as the young radio-jet.

Completion of the follow-up for the rest of the ‘red’ candidates quasars will quantify how common these type of sources are, and hopefully find some genuine z≥6.5 radio-loud quasars.

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Figure 5. Near-infrared and optical SED of J0049+3510. The \( K_{\text{HJRI}} \) photometric data points, and \( g \)-band extended emission detection (filled orange squares) suggest a reddened quasar (\( I \) and \( R \)-band data points are 1.5\( \sigma \) limits). We also show the \( \text{Ly}\alpha \) line observed on the edge of the \( g \)-band in spectroscopy (filled red triangle). We also plot the best-fit composite quasar spectra for different dust types (as different line styles and colours as labelled) yielding best-fit extinctions of \( A_V \approx 3 \) in all cases.

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