Evidence for a large fraction of Compton-thick quasars at high redshift

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Accepted 2007 April 11. Received 2007 March 27; in original form 2006 July 31

ABSTRACT
Using mid-infrared and radio selection criteria, we pre-select a sample of candidate high-redshift type 2 quasars in the Subaru XMM–Newton Deep Field (SXDF). To filter out starburst contaminants, we use a Bayesian method to fit the spectral energy distributions (SEDs) between 24-μm and the B-band, obtain photometric redshifts, and identify the best candidates for high-z type 2 quasars. This leaves us with 12 zpho ≥ 1.7 type 2 quasar candidates in an area ≈0.8 deg², of which only two have secure X-ray detections. The two detected sources have estimated column densities N_H ∼ 2 & 3 × 10²⁷ m⁻², i.e. heavily obscured but Compton-thin quasars. Given the large bolometric luminosities and redshifts of the undetected objects, the lack of X-ray detections suggests extreme absorbing columns (NH ∼ 10²⁸ m⁻²) are typical. We have found evidence for a population of ‘Compton-thick’ high-redshift type 2 quasars, at least comparable to, and probably larger than, the type 1 quasar population, although spectroscopic confirmation of their active galactic nuclei nature is important.

Key words: galaxies: active – galaxies: nuclei – quasars: general – X-rays: galaxies.

1 INTRODUCTION
High-redshift quasars with column densities NH ≥ 10²⁸ m⁻² are so heavily absorbed that they are barely detectable in even the most sensitive hard X-ray surveys (see, e.g. Brandt & Hasinger 2005), and are known as ‘Compton-thick’. While in the local Universe 40 per cent of active galactic nuclei (AGN) are found to be Compton-thick (Risaliti, Maiolino & Salvati 1999), the fraction of high-redshift quasars with such absorbing columns is currently unknown.

An alternative to (hard) X-ray selection is in the mid-infrared (mid-IR), where the obscuration due to dust becomes small. AGN are powerful mid-IR emitters due to dust surrounding the accretion disc (the torus) reprocessing the ultraviolet (UV) and X-ray photons from the central engine. AGN invisible in X-rays were indeed found by Donley et al. (2005), who used a mid-IR and radio excess criterion to select a sample of AGN. The majority of these AGN are at z ≲ 1 and are better described as Seyfert 2s by virtue of their low luminosities. The authors found that while the sources detected in the X-ray were unlikely to be Compton-thick, the AGN not detected in the X-ray (∼20 per cent of their sample) could be Compton-thick (NH ≥ 10²⁸ m⁻²). The obscured and gravitationally lensed quasar IRAS FSC 10214+4724, at z ∼ 2.3, also appears to be Compton-thick (Alexander et al. 2005).

Polletta et al. (2006) use two different selection criteria, X-ray and IR, to look for Compton-thick AGN in an area of 0.6 deg². Their X-ray selection, with a flux limit ∼10⁻¹⁸ W m⁻² in the 2.5–8 keV band, finds five Compton-thick AGN. Of these, two are spectroscopically confirmed high-redshift quasars. Of the IR-selected sources, the strict spectral energy distribution (SED) criteria imposed on the sources guarantee AGN, but are likely to exclude heavily obscured (A_V ≥ 20) high-redshift (z ≥ 1) sources which do not show power-law mid-IR spectral energy distributions (SEDs), but have significant contributions from stellar light at 3.6 and 4.5 μm. It is not surprising, therefore, that they find a smaller Compton-thick fraction (∼10 per cent) than expected in their IR-selected sample, as it is probably biased against heavily obscured AGN. At high luminosities and redshift, Alonso-Herrero et al. (2006, AH06) find ∼50 per cent of their sources are undetected in X-rays (although not necessarily Compton-thick). This sample is based on a power-law criterion, and could plausibly also be missing the most heavily obscured sources.

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Martínez-Sansigre et al. (2005), hereafter MS05, found a population of high-redshift type 2 quasars at least as numerous as the unobscured (type 1) population and which possibly outnumber the type 1s by $\sim 2 - 3 : 1$. The most recent X-ray studies agree with a large obscured fraction but disagree on the relative numbers of Compton-thick sources: Dwelly & Page (2006, DP06) find a $\sim 3 : 1$ ratio amongst Compton-thin type 2 and type 1 quasars, while Gilli, Comastri & Hasinger (2007) infer a $\sim 1 : 1$ ratio of Compton-thin type 2 to type 1 quasars, although the total type 2 to type 1 ratio can increase to $\sim 2 : 1$ when Compton-thick sources are included.

In this Letter, we present the X-ray properties of a sample of obscured (type 2) high-redshift quasars, selected from mid-IR and radio data in the Subaru XMM–Newton Deep Field (SXDF).

2 SAMPLE SELECTION AND DATA SET

We proceed to select a similar sample to that of MS05, in the SXDF, where deep X-ray data are available. In this work we decrease the lower radio flux density criterion, to increase the number of candidates. This is important as here we have a smaller area ($\sim 0.8$ deg$^2$ as opposed to 3.8 deg$^2$ in the MS05 sample). The selection criteria used here are $S_{24 \mu m} > 300$ $\mu$Jy, $S_{1.4 \mathrm{GHz}} \leq 45$ $\mu$Jy and 100 $\mu$Jy $\leq S_{1.4 \mathrm{GHz}} \leq 2$ mJy, which yields 38 candidates. For a detailed discussion of these criteria see Martínez-Sansigre et al. (2006a, hereafter MS06).

As a brief summary, the two mid-IR criteria are able to target $z \sim 2$ type 2 quasars with $A_V \gtrsim 5$, but will also allow $z \lesssim 1$ ultraluminous IR galaxies (ULIRGs) in the sample. These ULIRGs will have radio luminosities following the far-IR–radio correlation (Condon 1992), and so by choosing a high enough radio flux, one can cut out all but the most extreme starburst contaminants. The MS05 criteria were carefully chosen to avoid starburst galaxies, and lowering the radio criterion has the disadvantage that less extreme starbursts are allowed in the sample.

The mid-IR data were obtained by using the SWIRE DR2 (Surace et al. 2005), which covers the SXDF, and has flux density limits of $\sim 250$ $\mu$Jy at 24 $\mu$m (5$r$) and 10 $\mu$Jy for both 3.6 and 4.5 $\mu$m (10$r$ and 5$r$, respectively). The 1.4-GHz catalogue used is described in Simpson et al. (2006) and comes from a B-array ($\sim 5 \times 4$ arcsec$^2$ beam) Very Large Array (VLA) survey with a peak flux density limit of 100 $\mu$Jy ($\sim 5 - 8$r).

The spectroscopic completeness of the SXDF is poor at this stage, so we decided to undertake this preliminary study using photometric redshifts (see Section 3). The optical data were obtained from the Subaru $B$, $V$, $R$, $i'$ and $z'$ imaging (Furusawa et al., in preparation). The near-IR data ($J$ and $K$) were taken from the UKIDSS ultra-deep survey (UDS) DR1 (Warren et al. 2007). The X-ray data were obtained with the XMM–Newton observatory, which covered the SXDF field in seven pointings, with exposures of 50 ks each, except for the central pointing which was observed for 100 ks (Ueda et al., in preparation).

3 PHOTOMETRIC REDSHIFTS AND FILTERING OUT ULIRG CONTAMINANTS

In order to disentangle type 2 quasars from ULIRGs and obtain photometric redshifts, the SEDs of the candidates were fitted using a model consisting of three components (warm dust, galaxy light and blue light). The normalizations of the components were allowed to vary together with the redshift, $z$, although for a given $A_V$ and $z$, the normalization of the warm dust component was fixed to fit the 24-$\mu$m data. Two different models were investigated, and the Bayesian odds ratio (e.g. Sivia 1996) was used to select between the models. These models differed only in their warm dust properties and consisted of a quasar (with dust) and a ULIRG. The redshift was given a flat prior between $0 \leq z \leq 7$. No real quasars have been detected at $z \gtrsim 7$, justifying this cut-off.

The stellar population was modelled by taking the SED of a $z = 0$ elliptical galaxy from Coleman, Wu & Weedman (1980). SEDs showing smaller 4000-A breaks were well fitted by the elliptical galaxy together with the blue component (see below). The elliptical was normalized to match the $K$-band luminosity of an $L^*$ galaxy in the local $K$-band luminosity function of Cole et al. (2001). The luminosity of the galaxy relative to the local $L^*_K$ was then allowed to vary with a prior flat in log-space, between $-1.3 \leq \log_{10}(L_{bol}/L^*_K) \leq 1.3$. This choice brackets the reasonable range of host galaxies for a powerful quasar accounting for passive evolution: from a very faint 0.05$L^*_K$ to a very bright 20$L^*_K$ galaxy. The choice of a prior flat in log-space means that the host galaxy is believed, a priori, to be as likely to lie between 0.1$L^*_K$ and $L^*_K$ as between $L^*_K$ and 10$L^*_K$. This is more realistic than a prior flat in real space, which would imply a quasar is as likely to be hosted by an $L^*_K$ galaxy as by a 10$L^*_K$ one.

The blue component, between 912 and 5000 Å, has a physical motivation as well as serving a practical purpose. It can represent the scattered light from the obscured quasar, blue light from young stars or a UV upturn that is brighter than that of the template elliptical galaxy used (and therefore a smaller 4000-A break). The slope was therefore set to $S_{\nu} \propto \nu^{-0.5}$, which is representative of both type 1 quasars and star-forming galaxies. The normalization of the blue component is given as a ratio of the luminosity to that of an $L^*_K$ galaxy at 5000 Å, and was allowed to vary independently of the galaxy, with a flat prior between $-2 \leq \log_{10}(L_{bol}/L^*_K/5000\AA) \leq 2$, spanning the range between a blue component fainter than an $L^*_K$ elliptical galaxy’s UV-upturn, and as bright as the most powerful type 1 quasar. To avoid overfitting and losing the ability to discriminate between models, neither the stellar or the blue component are reddened by dust.

The ULIRG dust component was modelled using the models of Siebenmorgen & Kruegel (2007), hereafter SK07, only allowing variation of one parameter, $A_V$. For a given $A_V$ and $z$, the bolometric luminosity of the ULIRG $L_{bol}$ was chosen to make the SED go as close as possible to the 24-$\mu$m data point. The values of $L_{bol}$ are only restricted by the range available in the SK07 library: $10.1 \leq \log_{10}(L_{bol}/L_\odot) \leq 12.7$ for our choice of parameters. Of the other parameters, the nuclear radius was fixed to 1 kpc, the ratio of luminosity of OB stars with hot spots to $L_{bol}$ was fixed to 0.6, and the hydrogen number density was fixed to $10^{10}$ m$^{-3}$. The models have a discrete set of values of the extinction ($A_V = 2.2, 4.5, 6.7, 9, 17.9, 35.9, 72$ and 119), so the prior for the $A_V$ consists of a set of $\delta$ functions (with equal probability) at these values.

The mid-IR SED for quasars was modelled using the Elvis et al. (1994, hereafter E94) type 1 SED, and obscuring it with dust from the models of Pei (1992). For consistency with SK07, only Milky Way (MW)-type dust is used. This SED and dust model would allow us, in principle, to vary the values of $A_V$ continuously, but to make the fitting procedure as fair as possible, we restricted the values of $A_V$ to those present in the models of SK07 and assigned the same prior to them. This flat prior reflects our ignorance about the range in $A_V$, particularly for quasars. For each object, the quasar bolometric luminosity $L_{bol}$ was not allowed to vary freely, but was fixed for a given $A_V$ and $z$ by the observed flux density at 24 $\mu$m. There is, however, no upper limit set on $L_{bol}$.

For a given model, the likelihood of a given combination of parameters is given by the $n$-dimensional probability density function
\[
p(d | \text{model } A, z, A_V, L_{\text{gal}}, L_{\text{blue}}) = \frac{1}{(2\pi)^{n/2}} \prod_i e^{-x_i^2/2},
\]
where
\[
x_i^2 = \sum_i (\text{model } A_i - \text{data}_i)^2/\sigma_i^2,
\]
model A$_i$ is the flux predicted by model A, given the parameters over a given waveband, data$_i$ is the observed flux at that band, \(\sigma_i\) is the measurement error in that band and \(n\) is the number of bands. In the cases where \(\sigma_i\) was smaller than 10 per cent of the flux density of the object, it was set to 10 per cent. To treat non-detections at a particular band, we followed the following method: when the observed galaxy flux density and the model fell below the flux density limit (5\(\sigma_{\text{band}}\), where \(\sigma_{\text{band}}\) is the rms noise in that band), the band made no contribution to \(x_i^2\). When the model lay above the limit, the object was assigned a flux density \(S_i\) and an error \(\sigma_i\), both equal to half of the flux density limit (so \(S_i = \sigma_i = 2.5\sigma_{\text{band}}\)). An undetected source would therefore only be \(\sigma_i\) away from zero flux density, and from the limit. This prescription was appropriate for our sources, selected to be faint and therefore close to the limits in most of the bands, to avoid excessively penalizing non-detections in one band.

To select between models, we follow Sivia (1996) in calculating the odds ratio (OR),
\[
\text{OR}(A/B) = \frac{p(d|A)p(A)}{p(d|B)p(B)}.
\]
where, for brevity, we refer to model A as A, model B as B, and data as d. We assume that models A and B are equally likely a priori, \(p(A)/p(B) = 1\), implying ignorance in the fraction of quasars (c.f. starbursting galaxies). Thus the evidence for model y (where y \(\in\{A,B\}\)) is proportional to \(p(d|y)\), which is simply the likelihood (from equation 1) integrated over the parameter space spanned by the priors, i.e.:
\[
p(d|y) = \int e^{-x_i^2/2} p(z)p(A_V)p(L_{\text{gal}})p(L_{\text{blue}}) dx dA_V dL_{\text{gal}} dL_{\text{blue}}.
\]

Table 1. Best-fitting parameters and X-ray fluxes for the high-redshift type 2 quasars. The names are from the radio catalogue of Simpson et al. (2006), and we define \(S_{17} = 10^{-17}\text{ W m}^{-2}\) for convenience. The errors in \(z_{\text{phot}}\) are estimated, given our model SEDs, from the full-width half-maximum values from the marginalized probability distribution functions (PDFs) for \(z_{\text{phot}}\). For most objects, the PDF has at least one secondary peak, always adjacent to the primary one, with peak value between 0.5 and 0.05 of the primary peak. The median value of \(\log_{10}[L_{\text{gal}}/L_\odot]\), 0.75, corresponds to a 5.6\(L_\odot\) (where \(L_\odot\) is the break in the local \(K\)-band luminosity function) galaxy at \(z \sim 2\), which, assuming passive evolution and using the models of Bruzual & Charlot (2003), would become a 10\(L_\odot\) galaxy. The limits quoted for X-ray non-detections are the flux returned by the task \textsc{emdetect} at the position of the source, plus the error quoted for this flux. This is approximately the same as a 2\(\sigma\) limit.

| Name | RA (J2000) | Dec (J2000) | \(z_{\text{phot}}\) | \(\log_{10}[L_{\text{bol}}/L_\odot]\) | \(A_V\) | \(\log_{10}[L_{\text{gal}}/L_\odot]\) | \(\log_{10}[L_{\text{blue}}/L_\odot]\) | ln[OR(\text{quasar})] | \(\log_{10}[\text{d}z]\)/(\(S_{17}\)^2) | \(S_{2-12\text{keV}}/S_{17}\) |
|------|-----------|------------|-----------------|-----------------|--------|-----------------|-----------------|-----------------|-----------------|-----------------|
| ID052 | 02 16 17.92 | −05 07 18.56 | 1.90 ± 0.05 | 40.2 ± 0.05 | 119 | 0.85 | 0.56 | 13.0 | −10.0 | <0.7 |
| ID123 | 02 19 28.76 | −05 09 08.81 | 1.75 ± 0.05 | 40.2 ± 0.05 | 72 | 0.63 | 0.20 | 5.2 | −9.7 | <2.9 |
| ID135 | 02 11 14.22 | −05 11 14.22 | 4.15 ± 0.05 | 40.2 ± 0.05 | 2.2 | 1.20 | 0.15 | 26.0 | −9.0 | <0.4 |
| ID142 | 02 17 23.82 | −05 13 35.72 | 4.05 ± 0.05 | 40.4 ± 0.05 | 6.7 | 1.25 | 0.45 | 10.0 | −8.9 | <0.4 |
| ID147 | 02 19 10.31 | −05 16 03.00 | 1.80 ± 0.05 | 40.1 ± 0.05 | 35.9 | 0.75 | −0.05 | 28.6 | −13.4 | <0.3 |
| ID200 | 02 18 15.71 | −05 10 35.34 | 1.75 ± 0.05 | 40.1 ± 0.05 | 7.0 | 0.75 | 0.50 | 8.4 | −9.1 | <0.4 |
| ID249 | 02 19 13.74 | −05 46 04.27 | 1.75 ± 0.05 | 40.0 ± 0.05 | 35.9 | 0.50 | 0.00 | 25.2 | −9.2 | <0.6 |
| ID342 | 02 17 05.35 | −05 09 24.61 | 3.85 ± 0.05 | 40.0 ± 0.05 | 9.0 | 1.20 | 0.30 | 4.8 | −15.2 | <6.8 |
| ID345 | 02 16 29.56 | −05 10 36.65 | 2.00 ± 0.08 | 39.8 ± 0.08 | 35.9 | 1.00 | 0.10 | 10.4 | −11.1 | <0.6 |
| ID347 | 02 18 09.64 | −05 18 42.47 | 1.75 ± 0.05 | 40.2 ± 0.05 | 7.2 | 0.53 | −0.30 | 5.8 | −8.0 | 1.7 ± 0.9 |
| ID386 | 02 17 25.11 | −05 16 17.27 | 1.90 ± 0.05 | 39.4 ± 0.05 | 17.9 | 0.50 | −0.75 | 6.2 | −11.5 | <0.1 |
| ID401 | 02 16 23.02 | −05 08 06.76 | 1.90 ± 0.05 | 40.0 ± 0.05 | 35.9 | 0.70 | 0.40 | 26.7 | −8.9 | 3.4 ± 1.3 |

*This high value for \(L_{\text{bol}}\) is probably due to an overestimation of the \(A_V\). *This reason for these high values for the fluxes is that the background noise is significantly higher in these two sources. *This value of \(A_V\) suggests a reddened type 1 quasar rather than a genuine type 2. *ID345 is a point source at \(K\)-band, which suggests the value of \(A_V\) is an overestimate. *ID347 and ID401 have safe X-ray detections. The best-fitting SEDs for all 12 objects are available as Supplementary Material.

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it is not point-like in the K-band the host galaxy probably contributes significantly to the near-IR flux.

4 X-RAY PROPERTIES OF THE TYPE 2 QUASARS

The type 2 quasars were cross-matched with the X-ray catalogue of Ueda et al. (in preparation) with a flux limit of $\sim 3 \times 10^{-18}$ W m$^{-2}$ in the 2–12 keV band, but only two out of 12 (17 per cent) were detected: ID347 and ID401. These objects have likelihoods (EP_DET_ML) of 81 and 80, respectively, and are therefore clear detections (see DP06 for an explanation of the likelihood).

To obtain meaningful limits for the undetected sources, these objects had their counts measured directly from the X-ray image, using the XMM–Newton Science Analysis Software (SAS). The positions of the sources not detected in the XMM–Newton observations were added manually to the EBOXDETECT source lists of each observation. We then ran the SAS task EMDDetect keeping the positions of the sources fixed. EMDDetect performs a maximum likelihood fit on the distribution of observed counts of the sources previously extracted by the task EBOXDETECT. The fit uses the five different energy bands (in keV: 0.2–0.5, 0.5–1, 1–2, 2–4.5 and 4.5–12) and the three EPIC cameras (M1, M2, pn) simultaneously. This procedure allowed us to fit the sources as multiple components with separate point-spread functions (PSFs), and sources with no evidence of any X-ray detection were still fitted.

This procedure allowed us to obtain fits to the counts for all sources in the five EPIC bands, and these were converted to fluxes in each band, assuming a photon index $\Gamma = 1.7$ and an obscuring column of $N_H = 3 \times 10^{24}$ m$^{-2}$ (the default SAS values). These are not the most likely values for obscured quasars, so we estimate the effects of using more representative values. Assuming instead $\Gamma = 1.9, N_H = 3 \times 10^{27}$ m$^{-2}$ at $z = 2$ we estimate the change in fluxes to be only $+9, +3$ and $-2$ per cent in the 1–2, 2–4.5 and 4.5–12 keV bands, and therefore negligible compared to the large uncertainties in the count rates. All the 10 sources undetected in the Ueda et al. catalogue were found to have fitted values consistent with background noise, even in the hard band (see Table 1). We therefore find that 83 per cent of our sources classified as high-redshift type 2 quasars are undetected in the X-ray image, even down to a flux limit of $\sim 3 \times 10^{-18}$ W m$^{-2}$ in the 2–12 keV band (the exact limit varies across the X-ray image).

5 DISCUSSION

We have found that 10 out of 12 of our sources classified as type 2 quasars are undetected in an X-ray image with an approximate flux limit $\sim 3 \times 10^{-18}$ W m$^{-2}$ (in the 2–12 keV band). For the two detections, we use the photometric redshifts and the Monte Carlo models of Wilman & Fabian (1999, WF99) to estimate the absorbing columns. The estimates for ID347 and ID401 are $log_{10}(N_H/m^2) = 27.50$ and 27.25 respectively (although ID347 requires a blackbody at $10^7$ K in addition to the WF99 spectrum, to fit an upturn in the soft X-rays). For both these objects, the intrinsic X-ray to mid-IR ratio seems to be slightly lower than the E94 expectation by a factor $\sim 2$–5.

For the undetected objects, it is not possible to estimate values of $N_H$. However, as Fig. 1 shows, the sensitivity of the XMM–Newton observations and the ‘negative K-correction’ in X-rays mean that our X-ray data are sensitive to heavily obscured Compton-thin quasars, even if, like ID347 and ID401, at X-ray energies they are intrinsically weaker than our first expectation from the medianSED of E94. Only when $log_{10}(N_H/m^2) \gtrsim 28.50$ do sources with $L_{bol} \sim 10^{40}$ W become too faint to be detected in the energy bands covering 2–12 keV (rest-frame $\sim$6–36 keV).

To get a handle on the possible values of $N_H$, in Fig. 2 we show fiducial tracks for a model quasar (see figure caption for details). From this figure, the two detected objects in X-rays and two of the non-detections have values consistent with being heavily absorbed but Compton-thin, while the other eight objects undetected in X-rays are likely to be Compton-thick. Spectroscopic confirmation of the AGN nature of our sources is now required.

Inspection of Fig. 2 shows most of our objects populate a region of the $S_{2–4.5}$ versus $S_{24}$ plane that is lacking in sources in previous work (e.g. AH06). The reason for this is that our selection criteria focus in on objects covering a fairly narrow range in redshift and bolometric luminosity over a fairly large sky area. Most previous studies (e.g. AH06) cover much larger ranges in $z$ and luminosity with few objects like ours expected because of small sky area coverage and mid-IR selection techniques (such as mid-IR-power-law selection) that bias against the most obscured objects.

Following MS05, we model the expected number of type 1 quasars following our 24-µm and radio flux density criteria, at $z \gtrsim 1.70$, and in 0.8 deg$^2$. We predict $2 \pm 0.8$ type 1 quasars following these criteria, while we have 12 type 2 quasars of which eight are likely Compton-thick. Assuming the error in the modelled number of type 1 quasars, and Poisson errors for the numbers of type 2 quasars, the type 2 to type 1 ratio (in the 68 per cent confidence interval) is in the range 3.0–12.9 while the Compton-thick type 2 to type 1 ratio is in the range 1.8–9.0.

Although we are clearly suffering from problems due to small-number statistics, the implication of our study is that, at high
This corresponds to a range in gas-to-dust ratios horizontally only. The 12 type 2 quasars in our sample are overplotted on the X-ray image, and for our sample, the horizontal dotted line is the approximate flux limit of these objects having developed large-scale FRI-like jets. In principle, only mid-IR selection criteria are needed to find high-redshift quasars. Although such objects would be essentially absent from even moderately hard X-ray surveys (energy ~2–10 keV), and their contribution to the hard X-ray background (energy ~10 keV) is diluted by their large distances, they could clearly represent a vital component of quasars. Although such objects would be essentially absent from even moderately hard X-ray surveys (energy ~2–10 keV), and their contribution to the hard X-ray background (energy ~10 keV) is diluted by their large distances, they could clearly represent a vital component of the hard X-ray background. Our work to date (MS05, MS06) has included radio as well as mid-IR selection criteria. There is therefore a residual worry that the properties of the objects we have studied are influenced in some way by the presence of weak radio jets, and Martínez-Sansigre et al. (2006b) have shown that their radio properties are consistent with these objects having developed large-scale FRI-like jets. In principle, only mid-IR selection criteria are needed to find high-redshift quasars, although the difficulty lies in filtering out the starbursts from the quasars.

**ACKNOWLEDGMENTS**

We gladly thank Richard Wilman for access to his X-ray spectra, Filipe Abdalla for discussions about statistics, Ralf Siebenmorgen for useful comments on the ULIRG templates and the referee for comments. SR, DGB and CS thank the UK PPARC for a Senior Research Fellowship, a Studentship and an Advanced Fellowship respectively. OA acknowledges the support of the Royal Society.

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**SUPPLEMENTARY MATERIAL**

The following Supplementary Material is available for this article.

**Figure 2.** Hard X-ray flux ($S_{2–12keV}$) versus 24-μm flux density ($S_{24μm}$) as a function of redshift for a model obscured quasar. This quasar has been chosen to have log$_{10}(Lbol/W)=40.1$ and $A_V=35.9$, which are both the median values from Table 1. The quasar has the intrinsic SED of E94, with obscuring dust from the models of Pei (1992). We use the absorbed X-ray spectra of WF99, with four different absorbing columns, log$_{10}(N_H/m^2)=26.75,27.50,28.25$ and 29.25. This corresponds to a range in gas-to-dust ratio of $N_H/A_V=1.9 	imes 10^{25}$ to $5 	imes 10^{27} m^{-2}$ (the lower value being that of the Milky Way, the upper value being much larger but reasonable, see MS06 and Watanabe et al. 2004). The green and blue tracks are obscured but Compton-thin, the red track is mildly Compton-thick, and the yellow line is heavily Compton-thick. The black dots mark the values at particular redshifts. Changing the $A_V$ to any other value of Table 1 would move the tracks horizontally only. The 12 type 2 quasars in our sample are overplotted in blue. The vertical dotted line is the 300-μJy flux density limit imposed on our sample, the horizontal dotted line is the approximate flux limit of the X-ray image, $\sim 3 \times 10^{-18}$ W m$^{-2}$. For our two X-ray detections, the independent estimates of log$_{10}(N_H/m^2)$ are $\sim 27.50$, so at first one expects them to follow the blue track. That these two objects lie significantly below the blue track is not a cause for serious worry as it assumes a fiducial un-obscured quasi-stellar object SED that is subject to population variance. To make the objects ID347 and ID401 consistent with the track would mean a spreading of the population used in E94. While the two non-detections with high limits are approximately consistent with ID347 and ID401 and the Compton-thin tracks, the remaining eight sources are well below the expectations, suggesting they are Compton-thick.

**Figure 3.** Best-fitting quasar templates for the 12 candidate type-2 quasars that meet the strict criteria.

**Figure 4.** Best-fitting starburst (ULIRG) templates for the 12 candidate type-2 quasars.