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

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\begin{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 B-band, obtain photometric redshifts, and identify the best candidates for high-z type-2 quasars. This leaves us with 12 $z_{\text{phot}} \geq 1.7$ type-2 quasar candidates in an area $\sim 0.8$ deg$^2$, of which only two have secure X-ray detections. The two detected sources have estimated column densities $N_H \sim 2 \times 10^{22}$ 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 $N_H \sim 10^{28}$ 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 AGN nature is important.

\textbf{Key words:} quasars; general-galaxies; nuclei-galaxies; active-X-rays; galaxies
\end{abstract}

1 INTRODUCTION

High-redshift quasars with column densities $N_H \gtrsim 10^{28}$ m$^{-2}$ are so heavily absorbed that they are barely detectable in even the most sensitive hard X-ray surveys (see, e.g., \textsuperscript{13}Brandt & Hasinger 2005), and are known as “Compton-thick”. While in the local Universe, 40\% of active galactic nuclei (AGN) are found to be Compton-thick \textsuperscript{14}(Risaliti et al 1996), 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, where the obscuration due to dust becomes small. AGN are powerful mid-infrared emitters due to dust surrounding the accretion disk (the torus) reprocessing the UV and X-ray photons from the central engine. AGN invisible in X-rays were indeed found by \textsuperscript{15}Donley et al (2005), who used a mid-infrared and radio excess criterion to select a sample of AGN. The majority of these AGN are at $z \lesssim 1$ 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 (\sim20\% of their sample) could be Compton-thick ($N_H \gtrsim 10^{28}$ m$^{-2}$). The obscured and gravitationally-lensed quasar IRAS FSC 10214+4724, at $z \sim 2.3$ also appears to be Compton-thick \textsuperscript{16}(Alexander et al 2003).

\textsuperscript{13}Polletta et al (2006) use two different selection criteria, X-ray and infrared, to look for Compton-thick AGN in an area of 0.6 deg$^2$. Their X-ray selection, with a flux limit $\sim 10^{-17}$ W m$^{-2}$ in the 2.5-8 keV band, finds 5 Compton-thick AGN. Of these 2 are spectroscopically confirmed high-redshift quasars. Of the infrared-selected sources, the strict SED criteria imposed on the sources guarantee AGN, but are likely to exclude heavily obscured ($A_V \gtrsim 20$) high-redshift...
(z \geq 1) sources which do not show power-law mid-infrared 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%) than expected in their infrared-selected sample, as it is probably biased against heavily obscured AGN.

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 ~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 ~3:1 ratio amongst Compton-thin type-2 and type-1 quasars, while Gilli, Comastri & Hasinger (2006) infer a ~2:1 ratio of type-2 to type-1 quasars, with approximately half of the type-2 population being Compton-thick.

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

2 SAMPLE SELECTION AND DATASET

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 (~0.8 deg² as opposed to 3.8 deg² in the MS05 sample). The selection criteria used here are S_{24} \mu m > 300 \mu Jy, S_{3.6} \mu m \leq 45 \mu Jy, and 10 \mu Jy < S_{1.4GHz} \leq 2 \mu Jy, which yields 38 candidates. For a detailed discussion of these criteria see Martínez-Sansigre et al. (2006a, MS06).

As a brief summary, the two mid-infrared criteria are able to target z ~ 2 type-2 quasars with A_V \geq 5, but will also allow z \leq 1 ultra-luminous infrared galaxies (ULIRGs) in the sample. These ULIRGs will have radio luminosities following the FIR-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-infrared data were obtained by using the SWIRE DR2 (Surace et al., 2005), which covers the SXDF, and has a flux density limit of ~250 \mu Jy at 24 \mu m (5σ), and 10 \mu Jy for both 3.6 and 4.5 \mu m (10σ and 5σ respectively). The 1.4 GHz catalogue used is described in Simpson et al. (2006) and comes from a B-array (~5x4 arcsec² beam) VLA survey with a peak flux density limit of 100 \mu Jy (~5-8 σ).

The spectroscopic completeness of the SXDF are poor at this stage, so we decided to undertake this preliminary study using photometric redshifts. This was much helped by the fact that, for most of our target objects, the optical to near-infrared light originates from the host galaxy only, as the quasar is severely obscured at these wavelengths (except possibly the object ID135, see Table 1 and supplementary Figures 3). The dataset for this came from two sources. The optical data were obtained from the Subaru B,V,R,i’ and z’ imaging (Furusawa et al., in prep.). The near-infrared data (J and K) from the UKIDSS ultra-deep survey (UDS) DR1 (Warren et al. 2006). The X-ray data were obtained with the XMM-Newton observatory, which covered the SXDF field in 7 pointings, with exposures of 50 ks each, except for the central pointing, which was observed for 100 ks (Ueda et al., in prep.).

3 PHOTOMETRIC REDSHTS 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 normalisations of the components were allowed to vary together with the redshift, z, although for a given A_V and z, the normalisation 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 > 7, justifying this cutoff.

The stellar population was modelled by taking the SED of a z = 0 elliptical galaxy from Coleman, Wu & Weedman (1980). SEDs showing smaller 4000-Å breaks were well fitted by the elliptical galaxy together with the blue component (see below). The elliptical was normalised to match the K-band luminosity of an L^* galaxy as by a 10^9 L^* galaxy. The SEDs of the 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_{gal}/L_{K}^*) \leq 1.3. This choice brackets the reasonable range of host galaxies for a powerful quasar accounting for passive evolution: from a faint 0.05L_K^* to a very bright 20L_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 0.1L_K^* and 10L_K^* as between L_K^* and 10L_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 100L_K^* one.

The blue component, between 912 ˚A and 5000 ˚A, has a physical motivation as well as serving a practical purpose. It can represent the scattered light from the obscuring dust, galaxy light and blue light. The normalisations of the blue components were allowed to vary together with the redshift, z, and consisted of a quasar (with dust) and a ULIRG.

The spectroscopic completeness of the SXDF are poor at this stage, so we decided to undertake this preliminary study using photometric redshifts. This was much helped by the fact that, for most of our target objects, the optical to near-infrared light originates from the host galaxy only, as the quasar is severely obscured at these wavelengths (except possibly the object ID135, see Table 1 and supplementary Figures 3). The dataset for this came from two sources. The optical data were obtained from the Subaru B,V,R,i’ and z’ imaging (Furusawa et al., in prep.). The near-infrared data (J and K) from the UKIDSS ultra-deep survey (UDS) DR1 (Warren et al. 2006). The X-ray data were obtained with the XMM-Newton observatory, which covered the SXDF field in 7 pointings, with exposures of 50 ks each, except for the central pointing, which was observed for 100 ks (Ueda et al., in prep.).
Evidence for high-z Compton-thick quasars

Table 1. Best-fit 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 $S_{17} = 10^{-17}$ W m$^{-2}$ for convenience. The errors in $\sigma_{\text{phot}}$ are estimated from the full-width half-maximum values from the marginalised 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. For the objects with $\sigma_{\text{phot}} > 4$, the value is likely to be an overestimate due to the lack of H-band data (i.e. they are likely to be at $z \sim 3$). The median value of $\log_{10}[L_{\text{gal}}/L^*_{\text{gal}}]$, 0.75, corresponds to a 5.6$L^*_{\text{gal}}$ (where $L^*_{\text{gal}}$ 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 present-day $\sim L^*_{\text{gal}}$ galaxy. The limits quoted for X-ray non-detections are the flux returned by the task EMILDETECT at the position of the source, plus the error quoted for this flux. This is approximately the same as a 2$\sigma$ limit. The high value for $L_{\text{bol}}$ is probably due to an overestimation of the $A_V$. The reason for these high values for the fluxes is that the background noise is significantly higher in these two sources. The 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 $L_{\text{bol}}$ limit. The PDF has at least 12 separate distributions, but the prior for the $z_{\text{phot}}$ is the measurement error in that band and $\sigma_{\text{phot}}$ is the observed flux at $z_{\text{phot}}$. The models are 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 $\delta$-functions (with equal probability) at these values.

The mid-infrared SED for quasars was modelled using the SEDs of Elvis et al. (1994), hereafter E94, type-1 SED, and obscuring it with dust from the models of Pei (1992). For consistency with SK06, 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 SK06 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 $L_{\text{bol}}$ 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 $L_{\text{bol}}$.

For a given model, the likelihood of a given combination of parameters is given by the n-dimensional probability density function

$$p(\text{data} | \text{model } A, z, A_V, L_{\text{gal}}, L_{\text{blue}}) = \frac{1}{(2\pi)^{n/2} \prod_i \sigma_i} e^{-\chi^2_\lambda/2},$$

(1)

where

$$\chi^2_\lambda = \sum_i (\text{model } A_i - \text{data}_i)^2/\sigma_i^2,$$

(2)

model $A_i$ is the flux predicted by model $A$, given the parameters, over a given waveband, data, 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% of the flux density of the object, it was set to 10%. 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 $\chi^2$. 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 1$\sigma_i$ 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 penalising nondetections in one band.

To select between models, we follow Sivia (1996) in calculating the odds ratio (OR),

<table>
<thead>
<tr>
<th>Name</th>
<th>RA (J2000)</th>
<th>Dec</th>
<th>$z_{\text{phot}}$</th>
<th>$\log_{10}[L_{\text{bol}}/W]$</th>
<th>$\log_{10}[L_{\text{gal}}/L^*_{\text{gal}}]$</th>
<th>$\log_{10}[L_{\text{blue}}/L^*_\text{gal}]$</th>
<th>ln[OR(q/u)]</th>
<th>$\log_{10}[p(d/q)/(S_{17})^{12}]$</th>
<th>$S_{2-12\text{keV}}$</th>
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<tr>
<td>ID052</td>
<td>02 16 17.92</td>
<td>-05 07 18.56</td>
<td>1.90±0.05</td>
<td>42.11±</td>
<td>119</td>
<td>0.85</td>
<td>0.55</td>
<td>13.0</td>
<td>-10.0</td>
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<tr>
<td>ID123</td>
<td>02 19 28.76</td>
<td>-05 09 08.81</td>
<td>1.75±0.05</td>
<td>41.12</td>
<td>72</td>
<td>0.65</td>
<td>0.20</td>
<td>5.2</td>
<td>-9.7</td>
</tr>
<tr>
<td>ID135</td>
<td>02 19 01.89</td>
<td>-05 11 14.22</td>
<td>4.15±0.05</td>
<td>41.14</td>
<td>2.2</td>
<td>1.20</td>
<td>0.15</td>
<td>26.0</td>
<td>-9.4</td>
</tr>
<tr>
<td>ID142</td>
<td>02 17 23.82</td>
<td>-04 35 13.72</td>
<td>4.05±0.05</td>
<td>41.29</td>
<td>6.7</td>
<td>1.25</td>
<td>0.45</td>
<td>10.0</td>
<td>-8.9</td>
</tr>
<tr>
<td>ID147</td>
<td>02 19 10.31</td>
<td>-05 16 03.00</td>
<td>1.80±0.05</td>
<td>41.01</td>
<td>35.9</td>
<td>0.75</td>
<td>-0.05</td>
<td>28.6</td>
<td>-13.4</td>
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<td>02 18 15.71</td>
<td>-05 10 10.34</td>
<td>1.75±0.05</td>
<td>40.95</td>
<td>72</td>
<td>0.75</td>
<td>0.50</td>
<td>8.4</td>
<td>-9.1</td>
</tr>
<tr>
<td>ID224</td>
<td>02 19 13.74</td>
<td>-04 56 04.27</td>
<td>1.75±0.05</td>
<td>40.89</td>
<td>35.9</td>
<td>0.50</td>
<td>0.00</td>
<td>25.2</td>
<td>-9.2</td>
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<tr>
<td>ID332</td>
<td>02 17 05.35</td>
<td>-05 09 24.61</td>
<td>3.85±0.05</td>
<td>40.90</td>
<td>9.0</td>
<td>1.20</td>
<td>0.30</td>
<td>4.6</td>
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<td>ID345</td>
<td>02 16 29.56</td>
<td>-05 10 16.65</td>
<td>2.00±0.08</td>
<td>40.68</td>
<td>35.9</td>
<td>1.00</td>
<td>0.10</td>
<td>10.4</td>
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<tr>
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<td>02 18 09.64</td>
<td>-05 18 42.42</td>
<td>1.75±0.05</td>
<td>41.06</td>
<td>72</td>
<td>0.55</td>
<td>-0.30</td>
<td>5.8</td>
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<tr>
<td>ID386</td>
<td>02 17 25.11</td>
<td>-05 16 17.27</td>
<td>1.90±0.05</td>
<td>40.26</td>
<td>17.9</td>
<td>0.50</td>
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<td>6.2</td>
<td>-11.5</td>
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<tr>
<td>ID401</td>
<td>02 16 23.02</td>
<td>-05 08 06.76</td>
<td>1.90±0.12</td>
<td>40.93</td>
<td>35.9</td>
<td>0.70</td>
<td>0.40</td>
<td>26.7</td>
<td>-8.9</td>
</tr>
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</table>
OR(A/B) = \frac{p(d|A)p(A)}{p(d|B)p(B)}, \quad (3)

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 ∈ {A, B}) is proportional to p(d|y), which is simply the likelihood (from eq 1) integrated over the parameter space spanned by the priors, i.e.:

\[ p(d|y) = \int e^{-\chi^2/2}p(z)p(A)p(L_{\text{gal}})p(L_{\text{blue}})\,dz\,dA\,dL_{\text{gal}}\,dL_{\text{blue}}, \quad (4) \]

\( \chi^2 \) is as defined in Equation 2, \( p(x) \) is the normalised prior probability distribution of parameter \( x \) and the integral is over the entire prior space. To make sure that our X-ray analysis did not include any ULIRGs, only objects with OR(quasar/ulirg) ≥ 100 were considered as quasars. This is equivalent to stating we are at least 99% confident of the quasar model over the ULIRG model. Note this criterion is very similar to the so-called Jeffreys’ criterion [Jeffreys 1961]. In addition, to make sure the fits were acceptable, only sources with evidence p(data|quasar)/(S17) ≥ 10⁻¹⁶ were accepted, where S17 = 10⁻¹⁷ W m⁻² (S17 is defined to avoid numbers of order 10⁻²⁰⁴ or smaller). Our range of evidences in Table 1, 1.3 × 10⁻⁹ ≤ p(data|quasar)/(S17) ≤ 5.5 × 10⁻¹⁶, corresponds approximately to values of reduced \( \chi^2 = 1.9 - 6.1 \). Finally, only sources with \( z_{\text{phot}} > 1.70 \) were kept, since Ly α is visible in optical spectroscopy, so the redshifts can be checked observationally, as long as this line is not obscured by dust on large scales (see MS06). Preliminary spectroscopy of the sample suggests our values of \( z_{\text{phot}} \) are in good agreement with spectroscopic redshifts (Martínez-Sansigre et al. in prep.), except for the objects with \( z_{\text{phot}} \sim 4 \), which are likely to lie at \( z \sim 3 \) with \( z_{\text{phot}} \) an overestimate due to the lack of H-band data.

Of the 38 candidates in the sample, 12 (32%) follow our above criteria and are considered our best candidates for high-redshift type-2 quasars. Their best-fit parameters are quoted in Table 3 and we proceed to analyse the X-ray properties of these sources. Visual inspection of the optical images showed several cases where the blue light was unresolved. This fits in well with scattered light from the quasar reaching us and justifies our choice of a “blue” component. Typically the best fitting normalisation for the blue component is ~5% of the normalisation of the quasar component, which agrees well with scattering fractions. The K-band images showed resolved sources in 11 cases, while ID345 is a point-source (suggesting a real \( \Delta V \lesssim 5 \); a reddened type-1, see MS06). The SED and \( \Delta V \) of ID335 (see supplementary Figures) also suggest a reddened quasar, rather than a genuine type-2, although since it is not point-like in K-band, the host galaxy probably contributes significantly to the near-infrared 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 prep.) with a flux limit of \( \sim 3 \times 10^{-18} \) W m⁻² in the 2-12 keV band, but only 2 out of 12 (17%) were detected: ID347 and ID401. These objects have likelihoods (EP DET ML) of 81 and 80 respectively, and so would have made it into the DP06 sample (see their work for an explanation of the likelihood).

To obtain meaningful limits for the undetected sources, these 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 EMLDETECT keeping the positions of the sources fixed. EMLDETECT 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, 4-5, 5-12) and the three EPIC cameras (M1,M2,pm) simultaneously. This procedure allowed 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 5 EPIC bands, and these were converted to fluxes in each band, assuming a photon index \( \Gamma = 1.7 \) and an obscuring column of \( N_H = 3 \times 10^{22} \) m⁻² (the default SAS values). These are not the most likely values for
obscured quasars, so we estimate the differences. 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% 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 harder bands (see Table 1). We therefore find that 83% 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 black body at $10^7$ K in addition to the WF99 spectrum, to fit an up-turn in the soft X-rays). For both these objects, the intrinsic X-ray luminosity seems to be slightly fainter than the E94 expectation by a factor $\sim 2.5$.

Our two X-ray detected objects are at the high-end of the Compton-thin $N_H$ range with mid-IR/X-ray flux ratios comparable to those of lower redshift objects (Rigby et al. 2004, Lutz et al. 2004) of lower intrinsic $N_H$ because for obscured objects redshifting boosts the observed X-ray to near-IR ratio.

For the undetected objects, it is not possible to estimate values of $N_H$. However, as Figure 1 shows, the sensitivity of the XMM-Newton observations and the “negative K-correction” in X-rays mean that we are sensitive to heavily obscured Compton-thin quasars, even if at X-ray energies they are intrinsically weaker than our first expectation from the median SED of E94. Only when $\log_10(N_H/m^2) \gtrsim 28.50$, do sources with $L_{bol} \sim 10^{49}$ 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 of the possible values of $N_H$, in Figure 2 we show fiducial tracks for a model quasar. The model quasar has $M_B = -25.7$, which from the E94 SED corresponds to $L_{bol} \sim 7 \times 10^{49}$ W and is therefore well matched to our candidates (see Figure caption for details). From this track, all our sources (including our X-ray detections) are expected to have $\log_10(N_H/m^2) \gtrsim 28.25$ and therefore would qualify as Compton-thick. This would be consistent with our lack of detections. ID347 and ID401 have lower values of $N_H$, but this is probably due to intrinsically weaker X-ray emission, compared to our fiducial model. If the other objects were heavily obscured but Compton-thin quasars, they too would be detected. However, if $N_H > 10^{28}$ m$^{-2}$, the quasars will be too faint for our observations, even at the higher energy bands. Spectroscopic confirmation of the AGN nature of our sources is now required.

Following MS05, we model the expected number of type-1 quasars following our 24-$\mu$m and radio flux density criteria, at $z \gtrsim 1.70$, and in 0.8 deg$^2$. We predict 24$\pm$8 type-1 quasars following these criteria. We have 2 Compton-thin type-2 quasars and possibly up to 10 Compton-thick type-2 quasars. Since Poisson errors dominate the number of type-2 quasars, we can easily estimate, at $z \gtrsim 1.70$, the ratio of Compton-thin type-2 to type-1 quasars as $1.1_{-0.8}^{+1.9}$, and the ratio of total type-2 (Compton thin and thick) to type-1 quasars as $6_{-3.0}^{+1.9}$.

Although we are clearly suffering from problems due to small-number-statistics, the implication of our study is that, at high redshift, Compton-thick quasars may be the dominant sub-population of quasars. Although such objects would be essentially absent from even moderately hard X-ray surveys (energy $\sim$2-10 keV), and their contribution to the hard X-ray background (energy $\gtrsim$10 keV) is diluted by their large distances, they could clearly represent a vital part of the accretion history of black holes.

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. (2006) 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.
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