Spectral Energy Distributions of type 2 QSOs: obscured star formation at high redshifts

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ABSTRACT

We present new mid-infrared and submillimetre observations for a sample of eight high redshift type-2 QSOs located in the Chandra Deep Field South. The sources are X-ray absorbed with luminosities in excess of $10^{44}$ erg s$^{-1}$. Two of the targets have robust detections, $S/N > 4$, while a further three targets are marginally detected with $S/N \geq 2.5$. All sources are detected in multiple mid-infrared bands with the Spitzer Space Telescope. The multiwavelength spectral energy distributions (SEDs) of the type-2 QSOs are compared to those of two local ultraluminous galaxies (Arp220 and IR22491) in order to assess contributions from a star-forming component in various parts of the SED. We suggest that their submillimetre emission is possibly due to a starburst while a large fraction of the mid-infrared energy is likely to originate in the obscured central quasar. Using the mid-infrared and submm observations we derive infrared luminosities which are found to be in excess of $L > 10^{12} L_{\odot}$. The submillimetre (850 $\mu m$) to X-ray (2 keV) spectral indices ($\alpha_{SX}$) span a wide range. About half of the type-2 QSOs have values typical for a Compton-thick AGN with only 1 per cent of the nuclear emission seen through scattering and, the remaining with values typical of submm-bright galaxies. Combining the available observational evidence we outline a possible scenario for the early stages of evolution of these sources.

Key words: galaxies: active - galaxies: nuclei - quasars: general - submillimetre - infrared

1 INTRODUCTION

The discovery that most local spheroids contain massive black holes (MBH) in their centres has renewed the interest in the physical properties of active galactic nuclei. A number of correlations, such as the one between the masses of MBH and the properties of the host galaxies (e.g. Gebhardt et al. 2001, Merritt & Ferrarese 2001) and the proportionality between the mass and the velocity dispersion of the stars, suggest a direct link between the formation/growth of the black hole and the stellar mass of the galaxy spheroid.

The availability of major facilities in the submm (e.g. SCUBA on the James Clerk Maxwell Telescope and MAMBO on IRAM) led to the discovery of a large population of luminous infrared galaxies at high redshifts (e.g. Hughes et al. 1998, Bertoldi et al. 2000, Borys et al. 2003). Followup observations in CO molecular gas-line emission suggest that such galaxies are in fact massive (e.g. Greve et al. 2005, Chapman et al. 2008). The launch of the Spitzer Space Telescope (SST, Werner et al. 2004) has shed new light into luminous dusty high redshift galaxies. Sensitive mid-infrared observations have unveiled the presence of obscured AGN whose properties would have otherwise remained unnoticed (e.g. Lacy et al. 2004, Stern et al. 2005, Alonso-Herrero et al. 2006 hereafter AH06, Donley et al. 2007).

There are two obvious ways one can investigate the coeval formation of black holes and galactic bulges. One approach is to follow up on known mm/submm sources with X-rays. Somewhat surprisingly, however, only a small fraction of SMGs contain a visible luminous QSO (e.g. Fabian et al. 1999, Almaini et al. 2003). Such a result implies that the epoch of black hole formation does...
not coincide with the epoch of major star-forming activity. Using deep X-ray data Alexander et al. (2005) found that ~75% of the Chapman et al. (2005) SCUBA sources do contain an AGN however, the bolometric output is dominated by intense star formation. This claim has more recently been confirmed by mid-infrared studies of submm-luminous sources by Pope et al. (2008). The second approach is to select “obscured AGN” and follow them up in the submillimetre wavelengths. Such an approach has already been adopted by Page et al. (2001), Archibald et al. (2001) and, in the submm wavelengths. Such an approach has already been adopted by Page et al. (2001), Archibald et al. (2001) and, in the submillimetre wavelengths. Such an approach has already been adopted by Page et al. (2001), Archibald et al. (2001) and, Stevens et al. (2005) with encouraging results. These authors selected targets from the ROSAT surveys (e.g. Page et al. 2001), XMM-Newton and Chandra (e.g. Page et al. 2003) that span the redshift range \(1<z<3\), luminosity range \(44.1<\log L_X<44.4\) and absorbing column densities \(21<\log N_H<23\).

The advantage of the present work is that we are using a sample of “heavily” X-ray absorbed (\(\log N_H>23 \text{ cm}^{-2}\)) and very luminous (\(\log L_X>44 \text{ erg s}^{-1}\)) AGN, the so-called type-2 QSOs, located in the Chandra Deep Field South (CDF-S) and selected from Szokoly et al. (2004). The first submm detection of such a heavily absorbed QSO has been reported in Mainieri et al. (2005).

In this paper we combine the submm observations of the entire sample of eight type-2 QSOs with observations obtained with SST. We discuss the spectral energy distribution of the sources and compare them with local templates. We investigate a possible link between type-2 QSOs and SMGs, especially those known to contain a black hole. We explore the origin of the mid-infrared and submillimeter emission and finally discuss a possible evolutionary scheme for type-2 QSOs. Throughout the paper we assume a cosmology \(\Omega_M = 0.3, \Omega_lambda = 0.7\) and \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\).

2 SAMPLE SELECTION AND OBSERVATIONS

2.1 The type-2 QSO Sample

The deep (~1 Msec) Chandra survey of the Chandra Deep Field South (CDF-S, Giacconi et al. 2002) resulted in the discovery of a unique sample of heavily X-ray absorbed (\(\log N_H>22 \text{ cm}^{-2}\)) and very luminous (\(\log L_X>44 \text{ erg s}^{-1}\)) AGN, the so-called type-2 QSOs. The type-2 QSOs for this program have been selected from the deep (~1 Msec) survey of the CDF-S (Szokoly et al. 2004). From the 10 objects contained in the original list, 7 objects were observed with the JCMT within the allocated time. To this sample, source XID 901, was added. Although the source does not meet the formal \(L_x\) criterion described above, it is a heavily absorbed object at \(z>2\). In Table 1 we list properties of the sample of type-2 QSOs studied here: names, coordinates, redshifts, X-ray luminosities and absorbing column densities. We note that X-ray luminosities are corrected for absorption (values taken from Tozzi et al. 2006).

2.2 Submillimeter data

Observations at 850 \(\mu\text{m}\) were carried out on the JCMT during 2004 August and November. We used the Submillimetre Common User Bolometer Array (SCUBA, Holland et al. 1999) in photometry mode, in which the source is placed on the central bolometer of the array and the secondary mirror is jiggled in a \(3 \times 3\) pattern with 2 arcsec intervals with a 1 sec integration at each position. The secondary mirror was chopped 45 arcsec in azimuth at a frequency of 7.8 Hz and nodded between the source and reference positions every 18s. We placed each source in the central bolometer (H7) and used the median of the remaining bolometers for additional sky removal. We used Uranus to calibrate the derived flux densities. Calibration uncertainties are about 10% at 850 \(\mu\text{m}\). The pointing of the telescope was checked frequently while the sky opacity was monitored via regular skydips using the JCMT Water Vapour Monitor and the CSO (Caltech Submillimetre Observatory) Tau Meter. Observations during August 2004 were made under very good weather conditions with the 225- GHz sky opacity as measured at the adjacent CSO, \(\tau_x<2.5\), in the range 0.05–0.13 (at the airmass of the target).

We reduced data using the standard STARLINK software collection SURF. After compensating for the nod the data were flat-fielded and corrected for atmospheric extinction. Each jiggle in turn was then corrected for residual sky noise which is correlated across the SCUBA field of view and often dominates the signal from faint sources. After sky-subtraction the data were clipped at the 3-sigma level. Since data for the same source were collected on different nights we tested them for consistency with one another using a Kolmogorov-Smirnov test, rejecting anything below the 5% mark. Submm fluxes are reported in Table 2. Two sources were detected at \(S/N\geq 4\), while a further 3 are observed at \(S/N\geq 2.5\) level. We note that CDFS-202 is the only type-2 QSO for which the SCUBA observations yielded no signal at all and therefore a formal upper limit (corresponding to the sensitivity limit achieved by the observations) is quoted.

2.3 Spitzer Observations

The CDF-S was observed at 24 and 70 \(\mu\text{m}\) with the Multiband Imaging Photometer for Spitzer (MIPS, Rieke et al. 2004) and the InfraRed Array Camera (IRAC, Fazio et al. 2004) covering a total area of \(1.5\times0.5\) as part of the MIPS Guaranteed Time Observations (GTO). Additional observations of the central region of CDF-S were taken as part of the Great Observatories Origins Deep Surveys (GOODS, for an overview see Dickinson et al. 2003). Finally, additional 70 \(\mu\text{m}\) data were taken as part of the FIDEL (P.I. M. Dickinson) program.

The 24\(\mu\text{m}\) source extraction and photometry is described in detail in e.g. Papovich et al. (2007). In summary, all sources were treated as point-like, given the \(\sim 5''\) FWHM angular resolution. PSF fitting and flux measurements were performed using DAOPHOT packages. The resulting 5 \(\sigma\) flux density limit was 80 \(\mu\text{Jy}\) reaching a completion of 75% at this level. IRAC observations were carried out at 3.6, 4.5, 5.8 and 8.0 \(\mu\text{m}\). Source detection, extraction and photometry was performed in a similar manner to the MIPS data i.e. using DAOPHOT routines. IRAC photometry was carried out using a PSF of \(1''\) 8–2''. The aperture fluxes in each band were subsequently corrected to total fluxes using known PSF growth curves from Fazio et al. 2004; Huang et al. 2004. The resulting 5\(\sigma\) flux density limits were 1.73, 3.02, 10.96 and 8.3 \(\mu\text{Jy}\) at 3.6, 4.5, 5.8 and 8.0 \(\mu\text{m}\), respectively.

The Spitzer photometric data are listed in Table 2. Only one (XID 901) of the sources was detected at 70\(\mu\text{m}\) (B. Weiner, prov. comm.).

3 SPECTRAL ENERGY DISTRIBUTIONS

In Figure 1 we show rest-frame (Spectral Energy Distributions (SEDs)) for the present sample of type-2 QSOs. To construct the rest-frame SEDs we used optical photometry from HST/ACS observations (as part of the GOODS survey, Giavalisco et al. 2004), near-IR ISAAC imaging data (Retzlaff et al. 2009), IRAC/MIPS...
SEDs of type 2 QSOs

Table 1. Optical coordinates, spectroscopic redshifts, X-ray luminosities and absorbing column densities

| ID  | RA(2000)   | Dec(2000)   | $L_X [0.5 – 2\,K\,eV]' [2,3]$ | $L_X [2 – 10\,K\,eV]' [2,3]$ | $N_H / 10^{22} [\text{cm}^{-2}]$ | $z$     |
|-----|-------------|-------------|---------------------------------|---------------------------------|---------------------------------|--------|
| 202 | 03 32 29.86 | -27 51 05.8 | 19.8                            | 5.69                            | 150.0                           | 3.700  |
| 54  | 03 32 14.61 | -27 54 20.7 | 3.03                            | 0.88                            | 10.67                           | 4.57   |
| 45  | 03 32 25.68 | -27 43 05.7 | 4.03                            | 1.10                            | 8.19                            | 4.57   |
| 263 | 03 32 18.83 | -27 51 35.6 | 8.67                            | 2.91                            | 150.0                           | 2.291  |
| 27  | 03 32 39.67 | -27 48 50.5 | 5.23                            | 2.13                            | 28.08                           | 7.97   |
| 112 | 03 31 52.07 | -27 53 28.2 | 7.52                            | 1.16                            | 28.99                           | 5.85   |
| 901 | 03 32 35.78 | -27 49 16.8 | 0.87                            | 0.13                            | 18.94                           | 17.86  |
| 51  | 03 32 17.16 | -27 52 20.7 | 5.88                            | 1.02                            | 22.42                           | 2.44   |

1: IDs are from Giacconi et al. (2002)
2: $N_H$ values from Tozzi et al. (2006)
3: X-ray luminosities corrected for absorption.

Table 2. Mid-Infrared and submm fluxes and 1σ uncertainties

| ID  | 3.6 (µJy) | 4.5 (µJy) | 5.8 (µJy) | 8.0 (µJy) | 24 (µJy) | 70 (µJy) | 850 (µJy) |
|-----|-----------|-----------|-----------|-----------|----------|----------|-----------|
| 202 | 3.82(0.5) | 1.63      | 4.69(0.5) | 10.47(0.5) | 76.10(0.5) | 0.0      | 2.0(2.6)  |
| 54  | 4.4(0.5)  | 0.0       | 10.1(1.4) | 5.41      | 60(9)    | 0.0      | 9.74(6.35) |
| 45  | 14.6(2.2) | 21.8(3.5) | 53.8(5.0) | 124.6(23) | 480(39)  | 0.0      | 2.22(1.09) |
| 263 | 7.68(0.6) | 6.82(1.1) | 11.3(1.9) | 45(3.5)   | 63(8)    | 0.0      | 4.82(1.11) |
| 27  | 13.6(1.2) | 15.5(2.2) | 18.9(3.4) | 24.6(3.0) | 154(22)  | 0.0      | 4.81(3.45) |
| 112 | 6.4(0.7)  | 9.6(1.0)  | 18.1(2.7) | 34.7(3.7) | 301(49)  | 0.0      | 9.87(1.76) |
| 901 | 14.9(1.5) | 16.7(1.9) | 30.3(3.5) | 41.0(3.9) | 520(45)  | 3320(1850)| 8.8(3.6)  |
| 51  | 66(5.7)   | 73(6.5)   | 0.0       | 99(22)    | 0.0      | 0.0      | 2.89(1.06) |

1: denotes a (3σ) upper limit
2: source completely undetected.

Spitzer observations, and X-ray data (Giacconi et al. 2002). The radio data come from the VLA survey of the CDF-S, Kellerman et al. (2008), Miller et al. (2008). Spectroscopic redshifts for all the type-2 QSOs presented here are reported in Szokoly et al. (2004). The overall shape of the SED of the type-2 QSOs is rather different from the standard (type-1) QSO SED (see discussion for CDFS-263 in Mainieri et al. 2005). From the shape of the SEDs presented in Figure 1 and the discussion in Mainieri et al. (2005) it is clear that type-2 QSOs and, in that instance CDFS-263, do not show the featureless steep continuum expected for a typical QSO. Instead, the shape of their SEDs implies the presence of an additional starburst component.

Here we adopt a slightly different approach and using templates chosen from local Ultra-luminous Infrared Galaxies (ULIRGs) we try to assess the dominant contribution of starburst and/or AGN components in the various parts of the type-2 QSO SEDs. Our choice of templates (ULIRGs) was driven by the derived far-infrared luminosities of type-2 QSOs which are discussed in section 6. We stress that the aim of this exercise is not to find out whether there is an AGN in these type-2 QSOs (by definition they have a central massive accreting black hole), instead, we want to assess the relative contribution of the the two components (AGN or starburst) in various parts of the SED. In particular we focus on the near-infrared and submm wavelengths; it is clear that the mid-infrared is dominated by emission from the AGN. We chose two templates, the highly obscured ULIRG archetype Arp220 and the more typical (less obscured) starburst-dominated ULIRG IR22491 so that we can explore the effect of obscuration in the type-2 QSOs.

In Figure 2 we show the two templates and the SEDs of the type-2 QSOs presented in this study. The SEDs of the two templates as well as those of the type-2 QSOs have been normalised in the submm. It is clear that in all cases (all type 2 QSOs) an extra AGN component is immediately needed to explain the mid-infrared part of the SED. Two of the sources, CDFS-27, and CDFS-263 are consistent with the the lack of appropriate templates for typical QSOs. Rigby et al. (2008) discuss the the lack of appropriate templates for targets at redshifts 2–3. The remaining source CDFS-54 poses a real challenge when fitting the SED as it is undetected at 8 but detected at 24 microns. The SED of CDFS-54 falls below the SEDs of both templates considered here.

Although the current sample is small, the agreement between the templates and the SEDs of the type-2 QSOs suggests that type-2 QSOs might have a significant starburst component. Star-forming processes could account for both the visible/near-infrared light as
well as the submm. The mid-infrared, however, is in all cases powered by the central AGN. We note that the SEDs of the type-2 QSOs show a greater variety in shape than the SEDs of SCUBA galaxies (c.f. Pope et al. 2008). In the case of the type-2 QSO population this may reflect the various stages of evolution of the galaxies which may also affect the energetics (starburst vs central AGN).

Interestingly, two of the QSOs presented in our study are also part of the mid-IR selected powerlaw sample of AH06. CDFS-901 and CDFS-112 have been classified as Narrow-Line AGN (NLAGN) and ULIRG-like, respectively. Since, however, the division between the two categories is rather arbitrary we will, as in AH06, consider them as one class. According to AH06, galaxies in this category show a steep powerlaw continuum with a less prominent 1.6 micron bump. Both CDFS-901 and CDFS-112 follow the Arp 220 template SED (Figure 2), except for the mid-infrared where the additional need for a steep power-law (AGN) is evident. Overall, we find a dichotomy in the shape of the type-2 QSO SEDs which likely reflects the varying contribution of the starburst component to the overall energy output of the sources. While starburst-related activity is responsible for the energy released in the submillimetre, the mid-infrared is likely the place for the dominance of the central compact source which we discuss next.

4 MID-INFRARED CONTINUUM

At the redshift of our type-2 QSOs the IRAC bands probe the rest-frame near-infrared continuum while, the MIPS 24µm band probes the mid-infrared around 6µm which is significantly affected by the obscuring dust. The 24µm flux could originate either from emission related to star-forming processes (at this redshift the 6.2 µm Poly-Aromatic Hydrocarbon (PAH) feature enters the MIPS 24µm band) or it could contain indirect contributions from the AGN via heating of the surrounding dust which in turn emits in the mid-infrared. Due to the inherited complexity of the mid-infrared part of the spectrum, we will not attempt a decomposition of the mid-infrared part of the SED of type-2 QSOs but instead opt for simple colour-colour mid-infrared diagnostic diagrams.

A number of authors have published results on AGN selec-
SEDs of type 2 QSOs

Figure 2. Comparison of the Type 2 QSO SEDs with those of template galaxies Arp220 (long dashed line) and IR22491 (solid line). The template SEDs have been normalised at $850\,\mu m$. The photometry used to construct the SEDs of type 2 QSOs has been described in Figure 1.

Discussion based on mid-infrared colours (e.g Lacy et al. 2004, Stern et al. 2005, Hatziminaoglou et al. 2005 but see Barmby et al. 2006, Rigby et al. 2008 for a discussion of the various criteria in detail). The Lacy et al. (2004) plots involve IRAC and MIPS bands only and are, thus, more appropriate for our purposes. Here, we examine the mid-infrared colours of our sources and compare them to those of high-z submillimetre luminous galaxies (hereafter SMGs). For each of their SEDs, SMGs can be crudely divided into two main categories based on the shape of their SEDs, SMGs can be crudely divided into those that display a clear 1.6 $\mu m$ “stellar bump” and their overall SED shape is similar to that of Arp220 (referred to as "cold" SMGs) and, those with a steep powerlaw SED similar to the SED of Mrk231 (referred to as warm, see e.g. Egami et al. 2004). Figures 3a and 3b show the Lacy et al. (2004) mid-infrared colour-colour criteria for our type-2 QSOs and SMGs from Egami et al. (2004) and Ashby et al. (2006). In the IRAC plot (Fig. 3a) we find that CDFS-27, CDFS-45 and CDFS-263 display the reddest colours both in $S_{8.0}/S_{4.5}$ and $S_{5.8}/S_{3.6}$ and thus are similar to those of "warm" SMGs. These three type 2 QSOs were best fit by the less obscured IR22491 template (of course as discussed in Section 3 an AGN component is necessary to explain the mid-infrared part of the spectrum). Similarly, type 2 QSOs following the Arp220 SED show IRAC colours with values closer to those of "cold" SMGs. In the IRAC/MIPS plot (Fig. 3b) the colours of type 2 QSOs vary over a wider range (especially the 24/5.8 ratio). AGN display colours that would fall within the shaded area in Fig. 3b. As expected, “warm” SMGs fall within the shaded region. Among the type 2 QSOs, those that were fit with the less-obscured ULIRG template IR22491 (plus AGN) fall within the shaded region expected for AGN. The remaining type 2 QSOs fall outside the expected range for AGN.

Although the present type-2 QSO sample is small, the mid-infrared colour-colour plots allow us to draw some qualitative conclusions. First, in both plots the less obscured type-2 QSOs (those fit by IR22491) display colours akin to those of AGN-dominated or "warm" SMGs. In the IRAC plot, the 8.0/4.5 ratio provides a good measure of the AGN contribution (at $z\sim3$ the IRAC 8 $\mu m$ band corresponds to K rest-frame). Warm SMGs and less obscured type-2 QSOs both display the highest 8.0/4.5 values as expected from hot-dust contribution to the rest-frame K-band emission. In the IRAC/MIPS plot (Fig. 3b) type-2 QSOs fit by IR22491 (less obscured) and “warm” SMGs show very similar colours. Those type-2 QSOs that follow the SED of Arp220 (i.e. the starburst component is more obscured) show the most extreme values in 24/8
and 5.8/3.6 with some type-2 QSOs falling outside the shaded area expected for AGN type objects. We attribute the wide range variation in the $S_{3.6}/S_{8.0}$ ratio to the varying degree of obscuration, contribution from the central AGN and possibly differences in dust composition.

Sturm et al. (2006) presented mid-infrared IRS spectroscopy of a small sample of primarily lower-redshift type-2 QSOs (0.2<z<1.3) but also included CDFS-202. They tried to estimate the AGN contribution to the mid-infrared ($3.6-4.5$) part of the spectrum by performing a decomposition of their IRS spectra using a starburst (M82) and and AGN (linear continuum) template. Their results, together with the surprisingly absence of PAH features in the IRS spectra, indicate that the AGN contributes significantly (if not dominantly) in the mid-infrared. More recently, Martinez-Sansigre et al (2008) presented IRS spectra of a sample of $z<2$ type-2 QSOs (their selection was based on radio and mid-infrared criteria, see Martinez-Sansigre et al. 2006) and concluded that although they are predominantly continuum dominated a large fraction shows deep silicate absorption features and PAHs. The strength of the PAHs is similar to that found in submillimetre luminous galaxies (e.g. Valiante et al. 2007). The PAHs are thought to originate in the host galaxy and are indicative of vigorous star-forming activity. A similar conclusion has been reached by Zakamska et al. (2008) based on mid-infrared spectroscopy of optically selected type-2 QSOs. Combining our discussion here with the SED fits we also conclude that the mid-infrared part of the spectrum is dominated by emission from the AGN.

5 FAR-INFRARED LUMINOSITIES, STAR FORMATION RATES AND MASSES

In Table 3 we present far-infrared luminosities ($L_{\text{FIR}}$) for each source. We have used two different methods to estimate FIR luminosities based on: converting the Spitzer 24 $\mu$m flux to ($L_{\text{FIR}}$) and, interpolating from the measured 850 $\mu$m flux density. Although $L_{\text{FIR}}$ estimates of high-$z$ objects carry uncertainties, depending on the method chosen, it is reassuring that the methods presently considered, yield within errors, similar results. In what follows we discuss each method in detail.

At the redshifts of our type-2 QSOs the Spitzer 24$\mu$m band corresponds to rest-frame mid-IR (6–8 $\mu$m depending on redshift) which is, in general, used to infer the total thermal (8–1000 $\mu$m) $L_{\text{FIR}}$ (e.g. Chary & Elbaz 2002). A number of authors (e.g. Spinoglio et al. 1995, Rush et al. 1993) have shown that, especially for AGN, the MIR (12$\mu$m) luminosity is a good proxy for the FIR luminosity. Following AH06 we estimate the 12$\mu$m-to-FIR luminosity conversion factor according to the two templates (Arp220 and IR22491) we used to fit the SEDs of our type-2 QSOs. We derive the 12$\mu$m rest-frame luminosity by extrapolating from the observed 24 $\mu$m flux. The resulting $L_{\text{FIR}}$ values are listed in Table 3. All our type-2 QSOs are highly luminous, with luminosities formally in the “ultra-luminous” class ($L_{\text{FIR}}>10^{12}$ $L_{\odot}$).

In section 3 we showed that the far-infrared/submm part of the SED of type-2 QSOs can be well represented by the two ULIRG templates Arp220 and IR22491. In both of these template galaxies submm emission is emitted by dusty young stars (rather than the AGN continuum). Under the assumption that the submm emission in type-2 QSOs is also due to star-forming activity we can use the 850 $\mu$m fluxes to estimate $L_{\text{FIR}}$ (by scaling them with those of the templates used to fit each of the type-2 QSOs). For IR22491 we use log $L_{\text{FIR}}$=12.11 and for Arp220 log $L_{\text{FIR}}$=12.48 (e.g. Rigopoulou et al. 1999). $L_{\text{FIR}}$ values estimated in this way are of course subjected to uncertainties depending on the template of choice. We note however, that the choice of template only affects the normalization of the derived luminosities; its variation as a function of redshift over the range covered by our sources (1.0<$z<3.5$) is small for both templates considered, because the strong negative K-correction at 850 $\mu$m cancels out the effect of cosmological dimming (e.g. Blain & Longair 1993).

Additionally, for those sources with radio detections we have used the well-established radio-far-infrared correlation to estimate $L_{\text{FIR}}$ with values in good agreement with the previously discussed methods. We list the computed $L_{\text{FIR}}$ values in Table 3.

Using the $L_{\text{FIR}}$ values in Table 3 and following the prescription by Kennicutt (1998) we estimate SFR rates by $SFR=L_{\text{FIR}}/(5.8 \times 10^{3} L_{\odot}) (M_{\odot}/yr)$.

Using the observed 850 $\mu$m fluxes the dust mass is then given by:

$$M_{\text{dust}}=(1+z)^{-1}S_{850}D_{L}^{2}/k_{\text{rest}}B(u_{\text{rest}}, T_{d})$$

where $z$ is the redshift, $D_{L}$ is the luminosity distance, $k_{\text{rest}}$ is the rest frequency absorption coefficient and $B(u_{\text{rest}}, T_{d})$ is the rest frequency value of the Planck function from dust grains radiating at temperature $T_{d}$. Using $k_{\text{rest}}=0.15$ (e.g. Scott et al. 2002) and assuming optically thin thermal emission the derived $M_{\text{dust}}$ are listed in Table 3.

Finally, following Marconi et al. (2004) we estimate bolometric luminosities based on rest-frame absorption corrected $L_{\gamma}$. Assuming that $L_{\text{bol}}=L_{\text{Edd}}$, where $L_{\text{Edd}}$ is the Eddington luminosity we report (Table 3) lower limits on the black hole masses.

6 ORIGIN OF THE SUBMILLIMETRE EMISSION

A different approach to the relative importance of AGN and star formation activity is provided by comparing the submillimetre (850 $\mu$m) to X-ray (2 keV) spectral slope ($\alpha_{SX}$) of our type-2 QSOs to those of nearby template galaxies. We have, therefore, calculated the $\alpha_{SX}$ values for our sample galaxies using:

$$\alpha_{SX}=-\log_{10}\left[\frac{I_{2keV}}{I_{850}}\right] - 0.18 \times 0.163$$

where $I_{2keV}$ is the observed flux density at 2 keV (keV cm$^{-2}$ s$^{-1}$ keV$^{-1}$), calculated from the full-band flux using the estimated photo-index, and $I_{850}$ is the observed flux density at 850 $\mu$m (mJy). Figure 4 shows the estimated $\alpha_{SX}$ values as a function of redshift for our sample type-2 QSOs. In the same plot we also show template SEDs for: an unabsorbed quasar, quasars with varying degrees of absorption ($N_{H}=10^{23}, 10^{24}$ cm$^{-2}$ and Compton-thick with 1% of the nuclear emission scattered), a mean starburst and an Arp220-like. The templates used here are discussed in more details in Almaini et al. (2003). The type-2 QSOs yield values ranging between 1.41 (for CDFS-901) to 1.17 (for CDFS-45). Larger values of $\alpha_{SX}$ indicate stronger submillimetre emission relative to the X-ray emission. The $\alpha_{SX}$ indices are clearly incompatible with unabsorbed AGN. The $\alpha_{SX}$ index for CDFS901, CDFS54, CDFS51 and CDFS112 are compatible with the mean starburst and Arp220 templates. It is of interest to note that of these four sources three are best fit by the Arp220 template (see discussion in section 3). The remaining sources CDFS263, CDFS 27 and CDFS45, have indices that are close to the spectral index of a Compton-thick AGN in which only 1% of the nuclear emission is seen through scattering (the properties of CDFS263 have already been discussed in Mainieri et al. 2005). For comparison we report in Figure 4 the spectral indices calculated for the submillimetre sources studied by
SEDs of type 2 QSOs

Figure 3. Colour-colour plots involving IRAC (left) and IRAC and MIPS bands (right, adapted from Lacy et al. 2004). Symbols are as follow: filled circles: type-2 QSOs, filled squares: warm SCUBA sources, open squares: cold SCUBA sources (mid-infrared Spitzer data for SCUBA sources from Egami et al. 2004 and Ashby et al. 2006). Those type 2 QSOs that follow the Arp220 template SED (see discussion in section 3) are marked with a squared circle. The wedged-shaped (plot 3a) and the hatched areas (plot 3b) denote the regions occupied by AGN.

Table 3. FIR Luminosities, SFR, Dust and Black Hole Masses

| ID | log$L_{FIR}(12\mu m)$ | log$L_{FIR}(850\mu m)$ | SFR$^2$ | $M_{dust}$ | $M_{BH}$ |
|----|-------------------|-------------------|--------|------------|--------|
| 54 | 12.58             | 12.78             | 670–1165 | 4.9        | 0.5    |
| 45 | 12.49             | 12.72$^3$         | 540–905 | 4.1        | 1.4    |
| 263| 12.55             | 12.64             | 620–1190| 4.2        | 1.9    |
| 27 | 12.34             | 12.62$^3$         | 380–720 | 5.1        | 0.7    |
| 112| 12.67             | 12.88             | 710–1370| 5.5        | 0.8    |
| 901| 12.60             | 12.87             | 690–1460| 4.8        | 0.6    |
| 51 | 12.40$^4$         | 12.79$^4$         | 440–920 | 3.9        | 1.6    |

1: luminosities based on 24 $\mu m$ fluxes, see text
2: range of SFR based on different $L_{FIR}$
3: (:) denotes upper limit
4: black hole masses are lower limits

Alexander et al. (2005). These sources show a wide range in indices similar to what we reported for our type 2 QSOs. In terms of absolute $\alpha_{SX}$ value, the four type-2 QSOs we discussed before are indistinguishable from the submillimetre sources.

Another approach to assess the relative importance of the two components (AGN and starburst) is to examine the x-ray-to-far-infrared luminosity ratio. While this ratio is in principle quite similar to the $\alpha_{SX}$ spectral index, it is independent of the X-ray spectral slope (which one has to assume when converting broad band to monochromatic flux densities). In Figure 5 we plot the $L_x/L_{FIR}$ ratio for the present sample of type-2 QSOs (with values taken from Tables 2 and 3) and literature galaxies which also host obscured AGN. Such a comparison is instructive with the caveat that the $L_{FIR}$ estimates may originate from a variety of measurements (e.g mid-infrared, submm, etc). In the same plot we show a mean "starburst" $L_x/L_{FIR}$ ratio (adapted from the work of David, Jones and Forman 1992) and the same ratio for quasars (from Elvis et al. 1994). This finding implies that type-2 QSOs are likely to experience some level of star-formation activity which could be responsible for the $FIR$ and submillimetre emission. In turn, such star-forming processes could well contribute to the total bolometric output although, at this stage we cannot accurately attribute a specific fraction. Within our very small sample we do, however, see a range in the strength of the starburst which may reflect the evolutionary stage of each object. In the next section we investigate in more detail a possible evolutionary scheme for these sources.

7 THE EVOLUTION OF TYPE-2 QSOs

It has been suggested that the early phases of QSO evolution are characterised by substantial absorption (e.g. Fabian 1999). In such models the main obscured growth phase of the QSO coincides with the formation of the galaxy spheroid. Once this phase is completed
Figure 4. Submillimetre to X-ray spectral index ($\alpha_{SX}$) as a function of redshift. The curves show the expected $\alpha_{SX}$ values for a set of SEDs (QSOs with various degrees of obscuration, mean Starburst, Arp220). The values for the present type 2 QSOs are denoted by solid squares. Filled circles correspond to SCUBA galaxies from Alexander et al. (2005).

Figure 5. Rest-frame far-infrared vs. absorption-corrected [2-10] keV luminosity for our type-2 QSOs (filled squares) and other obscured AGN from the literature. SDSS optically selected type-2 QSOs (open squares) from Zakamska et al. (2008), Submillimetre galaxies (filled circles) from Alexander et al. (2005), local Universe “template” objects, Arp 220, Mrk 231 and NGC 6240 (filled triangles). The diagonal lines show ratios of X-ray to far-infrared luminosity for Starbursts (adapted from the work of David, Jones and Forman 1992, the X-ray data have been converted to the [2–10] band used here assuming $\Gamma = 2.0$) and quasars (adapted from Elvis et al. 1994).

then the QSO blows away the obscuring material and starts its luminous unobscured phase (e.g. Silk & Rees 1998). Such models deviate from the traditional view of the “unified scheme” for local AGN (e.g. Antonucci et al. 1993) whereby the absorbing material is present in all objects in the form of a toroidal structure. Based on simulations of galaxy mergers that include black holes (e.g. di Matteo et al. 2005; Springel et al. 2005), Hopkins et al. (2005) determine the intrinsic lifetime of the strong accretion phase and, taking into account obscuration, infer a lifetime for the QSO. They find that the optical QSO phase is rather short compared to the intrinsic lifetime of the quasar. Additionally, their model suggests the presence of an obscured phase (type 2 QSOs) that occurs immediately before the dust is completely blown away.

By contrasting the X-ray/submillimetre properties of an X-ray absorbed, Compton-thin QSO sample with that of a matched unabsorbed sample of QSOs, Page et al. (2004) and Stevens et al. (2005) provided observational evidence for the last two stages of the evolutionary scenario described above. The X-ray absorbed
QSOs are observed during the transition phase, where the QSO is still actively forming stars (formation of the galactic bulge) while at the same time accretes material that assists the formation of the central black hole. Once the black hole has reached a mass of \( \geq 10^8 M_\odot \), the QSO enters its unobscured luminous phase, slowly switching off the star-forming process and eventually evolving into relaxed elliptical galaxies (e.g. Kukula et al. 2001, Dunlop et al. 2003).

With bolometric luminosities in excess of \( L_{bol} \geq 10^{46} \text{ergs}^{-1} \), obscuring column densities \( N_H > 10^{23} \text{cm}^{-2} \), the present type-2 QSO sample can be used to further investigate the QSO evolutionary scheme. In section 3 we compared the SEDs of type-2 QSOs with those of local ULIRG templates IR22491 and Arp220. Local ULIRGs are characterised by extremely high bolometric luminosities and similarly large column densities. If we convert the estimated \( \alpha_V \) of ULIRGs (e.g. from Genzel et al. 1998) to expected \( N_H \) that results in \( N_H \) values in excess of \( 10^{23} \text{cm}^{-2} \). Given the high obscuration, the present (albeit limited at the moment) detections in the submillimetre, large dust masses (and consequently gas) and high redshifts, the present sample of type-2 QSOs could be candidates for the initial highly obscured phase of QSO evolution. A pre-requisite for any QSO to be “caught” in this phase is of course submillimetre emission. During this phase the black hole must be accreting rapidly in order to achieve a mass of \( \sim 10^8 M_\odot \) and thus should also reach X-ray luminosities in excess of \( 10^{44} \text{ergs}^{-1} \). And likewise the local ULIRGs, the properties of QSOs in this initial phase of evolution are not homogeneous in terms of luminosity, submillimetre brightness, even the starburst/AGN contribution.

Is there a link between type-2 QSOs and submm-bright galaxies? In section 4 we compared the mid-infrared properties of the two samples and found that they show certain similarities. Additional evidence was provided in Figures 4 and 5 through the comparison of the \( \alpha_{SX} \) indices and the x-ray-to-far-infrared luminosity. For more than half of the type-2 QSOs their \( \alpha_{SX} \) index is identical to that measured for submillimetre-bright objects from the Alexander et al. (2005) sample. It is thus quite possible that a fraction of the submm-luminous sources are in fact caught during this initial highly absorbed and actively star-forming phase in the QSO evolution. The evidence provided by Alexander et al. (2005) on the existence of black holes in a fraction of the submillimetre-bright population gives further support to this claim. Likewise, we have found that the \( L_{\nu}/L_{FIR} \) ratio of the present type-2 QSOs is smaller than that found for the well studied quasars of Elvis et al. (or objects that are purely AGN dominated).

We have presented some evidence for the initial stages of QSO evolution by reporting measurements of submillimetre emission from a sample of highly absorbed type-2 QSOs discovered through deep X-ray surveys. Two out of the eight targets have firm detections (\( S/N > 4 \)) and a further three objects are marginally detected. These submillimetre detections coupled with their overall similarities to local ULIRGs suggest that these type-2 QSOs may be experiencing co-evol growth of their spheroid component while at the same time maintaining an accretion rate high enough to form a black hole of \( M_{BH} \sim 10^8 M_\odot \). Once this is achieved, the QSO will blow away the obscuring material revealing its luminous QSO and following a passive evolution into the present-day ellipticals. Future sensitive submillimetre observations are clearly needed to further strengthen this claim. Deep sensitive surveys at 250, 320 and 520 \( \mu \text{m} \) with HERSCHEL and SCUBA -2 (450 and 850 \( \mu \text{m} \)) will be crucial in delineating the shape of the far-infrared/submm part of the SED of type-2 QSOs and provide firm evidence of their submillimetre emission.

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SEDs of type 2 QSOs
