Sub-mm detection of a high redshift Type 2 QSO

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ABSTRACT
We report on the first SCUBA detection of a Type 2 QSO at z=3.660 in the Chandra Deep Field South. This source is X-ray absorbed, shows only narrow emission lines in the optical spectrum and is detected in the sub-mm: it is the ideal candidate in an evolution scheme for AGN (e.g. Fabian (1999); Page et al. (2004)) of an early phase corresponding to the main growth of the host galaxy and formation of the central black hole. The overall photometry (from the radio to the X-ray energy band) of this source is well reproduced by the spectral energy distribution (SED) of NGC 6240, while it is incompatible with the spectrum of a Type 1 QSO (3C273) or a starburst galaxy (Arp 220). Its sub-mm (850 µm) to X-ray (2 keV) spectral slope ($\alpha_{SX}$) is close to the predicted value for a Compton-thick AGN in which only 1% of the nuclear emission emerges through scattering. Using the observed flux at 850 µm we have derived a SFR=550–680 $M\odot/yr$ and an estimate of the dust mass, $M_{\text{dust}} = 4.2 \times 10^8 M\odot$.

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

1 INTRODUCTION
The presence of massive black holes (MBHs) at the centers of most galaxies appears by now firmly established. A number of correlations have been observed between the masses of MBHs and the properties of the galactic bulges hosting them (e.g. Kormendy & Gebhardt (2000), Merritt & Ferrarese (2001)). Since these correlations extend well beyond the direct dynamical influence of the MBH, it seems likely that a close link exists between the growth of the MBH and the formation of their host galactic bulges.

If these two events are co-eval then we would expect that powerful black holes are hosted in the centers of the most massive galaxies. SCUBA galaxies show a strong redshift clustering thus indicating that they are hosted by very high mass halos (Blain et al. (2002)). This is confirmed by CO molecular gas emission line widths and possible rotation curves (Frayer et al. (1999); Genzel et al. (2003); Neri et al. (2003)). The combination of deep X-ray observations and spectroscopic follow-up campaigns of SCUBA sources (Alexander et al. (2004)) led to the discovery that at least 38% of the SCUBA sources host an AGN, although in the majority of the cases the contribution of the nucleus is not bolometrically significant (i.e., < 20%).

A possible scenario would predict that the black hole grows within a SCUBA galaxy until the obscuring gas is blown away revealing an AGN (e.g. Fabian (1999)). A similar evolution argument has been proposed for ULIRGs (Sanders & Mirabel (1996)), which can be considered the closest local analogs to SCUBA galaxies. We have started to investigate this scenario using a unique sample of heavily X-ray absorbed ($\log(N_{\text{H}}) > 22$ cm$^{-2}$) and very luminous ($\log(L_X) > 44$ 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). In this letter we report on the first sub-mm detection of a high redshift ($z=3.660$) Type 2 QSO and discuss the implications for its nature. We will discuss in a future paper the properties of the full sample of Type 2 QSOs once our observational programme is completed.

We assume a cosmology with parameters $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 SUB-MM OBSERVATION
The Submillimetre Common User Bolometer Array (SCUBA, Holland et al. (1999)) was employed in photometry mode, with the wide 850:450 filter set, and a standard 60
with one another using a Kolmogorov-Smirnov test, rejecting the individual datasets have been tested for consistency.

Figure 1. Left: cutout in the z (F850LP) ACS band of 11″ across. The big dashed circle is the 5-arcsec radius from which the 850 μm flux can be originated, while the smaller continuum circle in the center indicates the Chandra 3 σ positional error. Right: a zoom of the central part (5″ across) in the ISAAC Ks band, the isointensity X-ray contours at 3, 11, 12, 13, 14 σ above the local background are shown.

arcsec chop in azimuth at 7.8Hz. The source was placed in the central bolometer (H7) and the median of the remaining bolometers was used for additional sky removal. Flux calibration was performed using Uranus. Telescope pointing was checked frequently while sky opacity was monitored via regular skydips at 850 and 450μm and continuously via the JCMT Water Vapour Monitor and the CSO Tau Meter. τ225 ranged from 0.05 to 0.13. The data were reduced using the SURF (SCUBA User Reduction Facility) software package. A linear interpolation between consecutive skydips was used, and the nearest calibration source in time ter. The bolometer time-stream was clipped at the 3-

Figure 2. VLT FORS spectrum of CDFS-263 (z= 3.660) from Szokoly et al. (2004).

Table 1. Optical emission line properties of CDFS-263. FWHM and EW are rest frame

| line          | flux [10^{-18} erg cm^{-2} s^{-1}] | FWHM [km s^{-1}] | EW [Å] |
|---------------|-----------------------------------|------------------|-------|
| Lyα λ1216     | 2.96±0.04                         | 1000±10          | 29.6±3.0 |
| N V λ1240     | 0.17±0.03                         | 1580±140         | 2.4±0.6 |
| C IV λ1548    | 0.40±0.03                         | 1400±50          | 5.7±0.9 |

area of the sky imaged in the Ks band with ISAAC/VLT shows only the ‘B’ counterpart (right panel of Fig. 1) reinforcing its chances to be the real sub-mm source.

3 OPTICAL AND X-RAY SPECTROSCOPY

To help assign a reliable classification of CDFS-263 as a Type 2 quasar we have determined its optical emission line and X-ray spectral properties.

VLT FORS1 spectra of CDFS-263 were taken in 2000 during the spectroscopic identification programme of the CDF-S field (Szokoly et al. 2004). The object was observed with a multi-slit mask using 1.2 arcsec wide single slits and grism 150I with a spectral dispersion of ~5.5 Å/pixel, which corresponds to a spectral resolution of ~11 Å. The seeing was about 0.5–0.6 arcsec. The total integrated exposure time of the spectrum (see Fig. 2) is about 3.3 hours. The measured redshift is z = 3.660 ± 0.005.

The optical spectrum of CDFS-263 shows a strong Lyαλ1216 emission line and the two fainter lines of N V λ1240 and C IV λ1548, whereas no further lines as e.g. Lyβλ1026 or SI IV λ1397 are visible. Each emission line was fitted with a single Gaussian profile applying the Levenberg-Marquardt algorithm (Press et al. 1992). The four adjustable parameters are the total line flux, the central wavelength, the FWHM in Å and the flux of a local linear continuum. From this set of parameters we have calculated the FWHM in km s^{-1} (corrected for instrumental resolution) and the rest frame EW in Å. The line flux, the rest frame FWHM and the rest frame EW of the visible lines are given in Table 1.

1 XID from Giacconi et al. 2002.
Table 2. Best fit spectral model parameters for CDFS 263 (9.359G6E+05 sec) Galactic $N_H = 9.13 \times 10^{20}$ cm$^{-2}$. If we include the galactic $N_H$ there is only a marginal change of the intrinsic $N_H$ value.

| parameter | PL + intrinsic absorption | model 1 | model 2 |
|-----------|---------------------------|---------|---------|
| $N_H$ (10$^{22}$ cm$^{-2}$) | 0$^{+1.00}_{-0.00}$ | 88$^{+95}_{-75}$ |
| $z$ | - | - |
| $\Gamma$ | 0.34$^{+0.59}_{-0.59}$ | 1.90 (frozen) |
| $F_{0\,15}$ | 1.04$^{+0.66}_{-0.52}$ | 1.71$^{+1.37}_{-1.42}$ |
| $\chi^2$/doF | 1.19/4 | 3.37/5 |
| $f_{0.5-10.0}$ (absorbed) | 1.93E-15 | 1.04E-15 |
| $f_{0.5-10.0}$ (unabsorbed) | - | 2.00E-15 |
| $L_{0.5-10.0}$ (absorbed) | 0.19E-44 | 0.37E-44 |
| $L_{0.5-10.0}$ (unabsorbed) | - | 7.64E-44 |

Fit parameters are shown with 90% errors ($\Delta \chi^2 = 2.7$). The model and parameter definitions are: Model Components—PL: Power-law with a photon index of $\Gamma$ and a 0.5-7 keV flux of $F_{0\,15}$ in units of 10$^{-15}$ erg cm$^{-2}$ s$^{-1}$ using the XSPEC model pegpwrlw. Intrinsic absorption: Photo-electric absorption using Wisconsin cross-sections $\sigma_{\text{HS}}$ (Morrison & McCammon 1983), where $N_H$ is the equivalent Hydrogen column in units of 10$^{22}$ atoms cm$^{-2}$ and $z$ is the redshift. The luminosities reported in the table are in the rest frame [0.5-10] keV energy band.

$N\,\text{V} \lambda 1240$ is observed at the 4$\sigma$ level. The line fluxes are a factor of $\sim 20 - 100$ lower compared to those of the prototype Type 2 QSO CDFS-202 (Norman et al. 2002). The emission line widths are narrow with a FWHM of $< 1500$ km s$^{-1}$, whereas the mean line width of the permitted lines for X-ray selected Seyfert 1 and QSO1 ranges from $\sim 3000$ to $\sim 5000$ km s$^{-1}$ (see Lehmann et al. 2001). The narrow line widths and the observed 0.5-10 keV luminosity of $\sim 1.6 \times 10^{44}$ erg s$^{-1}$ indicate a Type 2 QSO (Szokoly et al. 2004).

The analysis of the X-ray spectrum of CDFS-263 is essential to determine its amount of intrinsic X-ray absorption and its unabsorbed X-ray luminosity. We have used the public Chandra ACIS-I data of the 1 Msec CDF-S survey (Giacconi et al. 2002). The total integrated exposure time is about 936 ksec for CDFS-263. The ACIS-I spectrum of the source was extracted from a circular region of $\sim 5$ arcsec in radius and the background spectrum was obtained from a source free region. The source spectrum contains 120 counts. The spectra were grouped to have at least 10 photons per bin.

Due to the small number of source photons we can only get an estimate of the X-ray spectral properties. The spectrum was analysed using XSPEC 11.3. A simple absorbed powerlaw model (1 in Table 2) gives a reasonable fit. The photon index of $\Gamma = 0.34$ is low compared to that of $\Gamma \sim 1.9$ found for most Seyfert galaxies and quasars. This points to a large intrinsic absorption of CDFS-263. Therefore we have frozen the photon index to 1.9 (model 2). The results of both models are shown in Table 2. All the errors quoted we calculated at 90% confidence level for two interesting parameters. As expected, the best fit model 2 shows a large $N_H$ of $\sim 10^{24}$ cm$^{-2}$, which implies nearly Compton-thick absorption. If we correct for intrinsic absorption the 0.5-10 keV rest frame luminosity of CDFS-263 increases by a factor of $\sim 20$ (see Table 2). The best fit model (2) and the X-ray data points are shown in Fig. 3. Whereas the quality of the ACIS-I spectrum is low, the strong intrinsic absorption of CDFS-263 (at least $N_H > 1 \times 10^{23}$ cm$^{-2}$) is fairly well constrained.

The narrow optical emission lines (FWHM<1500 km s$^{-1}$), the large intrinsic absorption (log $N_H > 22$) and the large absorption corrected X-ray luminosity (log $L_X > 44$) in the 0.5-10 keV energy band favour the Type 2 quasar nature of CDFS-263.

4 DISCUSSION

4.1 Spectral energy distribution

CDFS-263 has been observed in a wide range of energy bands. Photometry of extraordinary quality in the BVJ bands has been obtained with the ACS camera on board of HST as part of the GOODS survey, (Giavalisco et al. 2004)$^2$. As part of the same survey, ESO carried out deep near-IR imaging with ISAAC/VLT in J, H and K$_s$ bands$^3$. Finally, we have a radio upper limit from VLA observations at 20 cm of $F_r < 100$ µJy (K. Kellerman, private communication). The available photometry for CDFS-263 is summarized in Table 3.

According to the radio-power criterion given by Stocke et al. (1992), we can classify this AGN as radio-quiet. Hence, a non-thermal (synchrotron) contribution to the sub-mm flux is expected to be small (Carleton et al. 1987, Hughes et al. 1994). We compare the photometry of CDFS-263 with the SED of several well-studied local sources. We choose 3C273 as a template of an unabsorbed quasar, NGC 6240 a well-studied

$^2$ These data are publicly available at: http://www.stsci.edu/science/goods/

$^3$ These data are publicly available at: http://www.eso.org/science/goods/
Table 3. Photometry of CDFS-263.

| Observed Band | Rest-frame Band | Observed AB Magnitude | $\nu F_\nu$ [W/m$^2$] |
|---------------|-----------------|-----------------------|----------------------|
| 2-10 keV      |                  |                       | 2.6E-19              |
| 0.5-2 keV     |                  |                       | 8.1E-20              |
| F335W         |                  | 927Å                  | 27.7±0.4             | 2.9E-19 |
| F606W         |                  | 1277Å                 | 25.67±0.05           | 1.4E-18 |
| F775W         |                  | 1654Å                 | 25.38±0.08           | 1.3E-18 |
| F850LP        |                  | 1957Å                 | 25.08±0.08           | 1.6E-18 |
| J             |                  | 2690Å                 | 24.5±0.1             | 1.4E-18 |
| H             |                  | 3550Å                 | 23.9±0.4             | 1.8E-18 |
| K$_s$         |                  | 4660Å                 | 22.46±0.04           | 5.0E-18 |
| 850µm         |                  | 1.6E3 GHz             | ...                  | 1.6E-17 |
| 20 cm         |                  | 6.9 GHz               | ...                  | <1.5E-21 |

$^a$Chandra/ACIS; $^b$HST/ACS; $^c$VLT/ISAAC; $^d$NTT/SOFI; $^e$JCMT/SCUBA; $^f$VLA

(U)LIRG which hosts a Compton-thick AGN, and Arp 220 as a starburst galaxy where X-ray binaries are the major source of its X-ray emission (Iwasawa et al. 2001). Due to the difference in redshift between our source and these templates, we have photometry for CDFS-263 in wavelength regions not covered for the local sources. In particular for CDFS-263, the V filter contains Lyα while the i band contains the CIV line. We have subtracted the contribution of these lines in the observed fluxes and compared them with the templates SED in Fig. 4. The wide-band energy distribution of CDFS-263 is inconsistent with the spectrum of an unabsorbed QSO (dash-dotted line in Fig. 4); if we anchor 3C273 to the X-ray observations, we underestimate the fluxes at the other wavelengths. Using the SED of NGC 6240, we can reproduce in a consistent way the observed sub-mm, optical, near-IR and X-ray fluxes of our source (solid thick line in Fig. 4). The observed flux in the B band is low compared with the expected one, this can be ascribed to absorption due to the Lyα forest for a source at $z = 3.660$ (see also Stern et al. 2002). Finally, the energy distribution of CDFS-263 does not resemble the SED of Arp 220 (dotted line in Fig. 4): if we fix the template at the observed sub-mm flux we underestimate the X-ray flux by two orders of magnitudes. We note that Arp 220 appears to be an order of magnitude underluminous in soft X-rays, given its FIR luminosity, if compared with other starbursts galaxies (see Fig. 3 of Iwasawa et al. 2001), but this is not enough to reconcile the photometry of CDFS-263 with a starburst template.

4.2 Sub-mm to X-ray spectral index

To further compare the properties of our source with local templates and other SCUBA observations of X-ray sources, we derive the sub-mm (850 µm) to X-ray (2 keV) spectral slope ($\alpha_{SX}$) of CDFS-263. Fig. 4 shows the expected values of $\alpha_{SX}$, as a function of redshift, for a number of template SEDs. Namely, a quasar with no absorption in the X-ray or with different amounts of absorption ($N_{HI} = 10^{23}, 10^{24}$ and Compton-thick with 1% of the nuclear emission scattered); a mean starburst template and Arp 220. These templates are described in detail in Almaini et al. (2003). CDFS-263 yields a value of $\alpha_{SX} = 1.29$ (star symbol in Fig. 4). This value is clearly incompatible with an unabsorbed AGN, as we already expected from the optical and X-ray spectral properties of the source. On the other hand, it is close to the spectral index of a Compton-thick AGN in which only 1% of the nuclear emission emerges through scattering. The X-ray spectral fit yields a column density of $\sim 10^{23}$ cm$^{-2}$ (see Table 2). One way to obtain this value of $\alpha_{SX}$ is a sub-mm flux due to starburst activity plus an absorbed AGN in the center of the host galaxy that accounts for the X-ray emission, which is higher than that expected for a starburst galaxy alone (dashed line in Fig. 4) (see also Fabian et al. 2001; Alexander et al. 2003; Almaini et al. 2003). For comparison we report in Fig. 5 other X-ray selected sources with sub-mm data measurements from the literature. Namely, the CDF-N sources from Alexander et al. (2003) (circles) the majority of which show $\alpha_{SX}$ values higher than CDFS-263, and compatible with the expected indices for a starburst galaxy, although all except one of them lack a precise redshift measurement. The X-ray absorbed (filled triangles) and X-ray unabsorbed (empty triangle) ROSAT BLAGN from Page et al. (2001) and Page et al. (2004) are sampling a different region in Fig. 5 with their $\alpha_{SX}$ values being closer to pure QSO tracks in agreement with their nature as unabsorbed AGN in the optical band. Finally, we show also the $\alpha_{SX}$ values of some $z > 4$ Type 1 QSOs (square) with X-ray (Kaspi et al. 2000) and sub-mm (McMahon et al. 1999) observations. The location of our source in the $\alpha_{SX}$ vs $z$ plot is peculiar: it has a lower $\alpha_{SX}$ than any source from Alexander et al. (2003) at high redshift and a higher value of the BLAGN from Page et al. (2001) & Page et al. (2004) and the Type 1 QSOs at $z > 4$. **Figure 4.** Detections and upper limits for CDFS-263 plotted over the SED of NGC 6240 (solid), Arp 220 (dotted) and 3C273 (dash-dotted). The dashed line shows where the photometry is not available and template is extrapolated. The CDFS-263 data have been shifted to the rest frame and the empty circles show the line subtracted magnitudes (see text).
Figure 5. Sub-mm to X-ray spectral index ($\alpha_{SX}$) as a function of redshift. The dotted and dashed lines are the expected values of $\alpha_{SX}$ for a set of SEDs (see text). The values for CDFS-263 (star), the sample from Alexander et al. (2003) (circles), Page et al. (2001) (filled triangles), Page et al. (2004) (empty triangle) and a sample of Type 1 QSOs at $z > 4$ (squares) are shown.

4.3 Star Formation Rate, dust mass and black hole mass

Under the hypothesis that the sub-mm flux is due to star formation activity, we estimate, using the measured flux at 850 $\mu$m, the dust-enhrouded Star Formation Rate (SFR) and the dust mass. We note that the temperature of the dust heated by the AGN would be too high ($\gtrsim 100$ K) to emit in the sub-mm. The far-infrared luminosity ($L_{FIR}$) provides a reasonable measure of the active formation of massive stars. Assuming a dust temperature of 40K and an emissivity index $\beta = 1.2$ (e.g. Dunne et al. 2000) we interpolate from the 850 $\mu$m luminosity and get an estimate of the 60 $\mu$m luminosity assuming an optically-thin greybody. The SFR is given by:

$$SFR = \epsilon 10^{-10} L_{60}/L_{sun}(M_\odot/yr)$$

where $\epsilon$ is the fraction of optical/UV light being radiated in the far-infrared and depends on the IMF and the fraction of the optical/UV light that is absorbed and re-radiated in the FIR. For $\epsilon = 0.6$ we get $SFR = 550 - 680M_\odot/yr$ (assuming $\Omega_\Lambda = 0.7$ and $H_0 = 70$).

The dust mass is given by:

$$M_{dust} = 1/(1+z)S_{850}D_L^2/k_{dust}(\nu_{rest}, T_d)$$

where $z$ is the redshift, $S_{850}$ is the observed flux density, $D_L$ is the luminosity distance, $k_{dust}$ is the rest frequency absorption coefficient and B is the Planck function. Using $k_{dust} = 0.15$ (Scott et al. 2002) we derive an $M_{dust} = 4.2 \times 10^8 M_\odot$. The dust mass estimate assumes optically thin thermal emission with no contribution from bremsstrahlung or synchrotron radiation.

Finally, we compute the rest frame absorption corrected $L_X [2-10 \text{ keV}] = 4.5 \times 10^{44} \text{ erg s}^{-1}$ and using the relation given by Marconi et al. (2004) estimate the bolometric luminosity, $L_{bol} = 2.4 \times 10^{46} \text{ erg s}^{-1}$. Assuming that $L_{bol} = L_{Edd}$, where $L_{Edd}$ is the Eddington luminosity, we derive a lower limit on the black hole mass: $M_{BH} = 1.9 \times 10^8 M_\odot$.

5 CONCLUSIONS

We have a firm (4$\sigma$) SCUBA detection of a Type 2 QSO at redshift $z = 3.660$ (CDFS-263). Its SED is consistent, from radio to X-ray wavelengths, with the shape of NGC 6240 while it can not be reproduced with the SED of 3C273 or Arp 220. Furthermore, we derive an $\alpha_{SX} = 1.29$. We conclude that CDFS-263 can be powered by a Compton thick AGN (we found $N_H \sim 1 - 2 \times 10^{23} \text{ cm}^{-2}$).

CDFS-263 is a strong candidate for an AGN in the initial phase (before the “X-ray absorbed phase”) described by Page et al. (2004) that corresponds to the main growth phase (before the “X-ray absorbed phase”) described by Page et al. (2004) that corresponds to the main growth phase described by Alexander et al. (2003) (circles), Page et al. (2001) (filled triangles), Page et al. (2004) (empty triangle) and a sample of Type 1 QSOs at $z > 4$ (squares) are shown.
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