The XMM deep survey in the CDF-S

II. A 9–20 keV selection of heavily obscured active galaxies at $z > 1.7$

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ABSTRACT

We present results on a search of heavily obscured active galaxies $z > 1.7$ using the rest-frame 9–20 keV excess for X-ray sources detected in the deep XMM-CDFS survey. Out of 176 sources selected with the conservative detection criteria ($> 3\sigma$) in the first source catalogue of Ranalli et al. (in prep.), 46 objects lie in the redshift range of interest with the median redshift $\bar{z} = 2.5$. Their typical rest-frame 10–20 keV luminosity is $10^{44}$ erg s$^{-1}$, as observed. Among optically faint objects that lack spectroscopic redshift, four were found to be strongly absorbed X-ray sources, and the enhanced Fe K emission or absorption features in their X-ray spectra were used to obtain X-ray spectroscopic redshifts. Using the X-ray colour–colour diagram based on the rest-frame 3–5 keV, 5–9 keV, and 9–20 keV bands, seven objects were selected for their 9–20 keV excess and were found to be strongly absorbed X-ray sources with column density exceeding $10^{24}$ cm$^{-2}$, including two possible Compton thick sources. While they are emitting at quasar luminosity, $\sim 3/4$ of the sample objects are found to be absorbed by $N_{H} > 10^{23}$ cm$^{-2}$. A comparison with local AGN at the matched luminosity suggests an increasing trend of the absorbed source fraction for high-luminosity AGN towards high redshifts.

Key words. galaxies: active – X-rays: galaxies

1. Introduction

A population of heavily obscured active galactic nuclei (AGN) at cosmological distances, which might be missed by conventional quasar surveys, has been postulated by AGN synthesis models of the X-ray background (XRB, e.g., Gilli et al. 2007; Treister et al. 2009a, b) and the super-massive black hole mass function in the local Universe (Marconi et al. 2004). Various infrared selections have been employed extensively for searching for these objects in which strong re-radiation from obscuring dust is expected (Martínez-Sansigre et al. 2005; Alonso-Herrero et al. 2006; Daddi et al. 2007; Fiore et al. 2008, 2009; Bauer et al. 2010; Vignali et al. 2010; Alexander et al. 2011; Luo et al. 2011; Donley et al. 2012). Although X-ray observations should, in principle, also be effective for the search on account of the intrinsic X-ray loudness of AGN (relative to galaxy emission) and the penetrating power against obscuration, the low throughput of the existing X-ray telescopes limits the accessibility to high redshift. However, dedicated deep surveys with extremely long exposures, for example, in the Chandra Deep Field South (CDFS) conducted by XMM-Newton (Comastri et al. 2011) and Chandra (Giacconi et al. 2002; Xue et al. 2011) X-ray observatories now allow us to pursue this approach. Here, we present a study of X-ray selected heavily obscured active galaxies using the 3 Ms XMM-Newton survey of CDFS.

X-ray absorption is measured by the low energy cut-off of an X-ray spectrum, which moves to higher energies as absorbing column density increases. When $N_{H}$ approaches $10^{24}$ cm$^{-2}$, the cut-off occurs above 10 keV. As demonstrated for nearby examples, such as NGC 4945 (Iwasawa et al. 1993), the Circinus Galaxy (Matt et al. 1999a), and NGC 6240 (Vignati et al. 1999), detection of emission above 10 keV plays a key role in discoveries of heavily obscured AGN in those galaxies with absorbing column density exceeding $10^{24}$ cm$^{-2}$. This method works as long as the optical depth is not too large, that is, when a source becomes fully Compton thick with $N_{H} \geq 10^{25}$ cm$^{-2}$. Compton down-scattering suppresses the hard X-rays, leaving only reflected light, as observed in NGC 1068 (e.g., Matt et al. 1997). While a direct access is not possible for nearby objects with XMM-Newton, this crucial energy-band is redshifted into its bandpass for high redshift objects at $z \geq 2$. Given the shape of an absorbed X-ray spectrum, a negative K-correction sustains the detectability of absorbed sources to high redshift. Utilizing these properties, we searched for the rest-frame 9–20 keV excess sources to identify heavily obscured AGN candidates in the sources detected in the XMM-CDFS field.
we set the lower bound of the redshift range of our sample (details will be described in Ranalli et al., in prep.). Since X-ray spectra verified for use for a spectral analysis are available from all the three EPIC cameras of XMM-Newton, we set the lower bound of the redshift range of our sample to z = 1.7, for which rest-frame 20 keV corresponds to observed-frame 7.4 keV.

There are 47 objects with z > 1.7 for which spectral data are available from all the three EPIC cameras, pn, MOS1 and MOS2, apart from two objects which are located outside the field of view of the pn but within the two MOS cameras (see Table 1). Spectroscopic redshifts are available for 33 objects, while photometric redshifts were estimated by various papers (Luo et al. 2010; Cardamone et al. 2008; Raftery et al. 2011; Wuyts et al. 2008; Santini et al. 2009; Taylor et al. 2009) for other 14 objects.

For some objects with photometric redshifts, more constrained redshift estimates could be obtained using the Fe K feature in their X-ray spectra when they have a strongly absorbed X-ray spectrum. We use these X-ray redshifts for five sources, while photometric redshifts were estimated using the Fe K feature in their X-ray spectra when they have a strongly absorbed X-ray spectrum.

Hereafter we use “PID” for the identification number of X-ray sources listed in Ranalli et al., and the basic information of the 46 objects in the sample is presented in Table 1. The redshift distribution of the sample is shown in Fig. 1. The median redshift is $\bar{z} = 2.5$. The background-corrected counts obtained from the three EPIC cameras range from 400 to 8000 in the respective rest-frame 3–20 keV band, while the typical counts are ~1400. The typical source fraction of the total (source plus background) counts is ~0.4 in both EPIC pn and MOS cameras.

Since the exposure time for each source varies, the observed flux in the observed-frame 1–4 keV band, which is shared by all the sources with various redshifts, is given in Table 1 as an objective measure of source brightness. Median values of the observed frame 1–4 keV flux, $f_{1-4}$, the rest-frame 2–10 keV and 10–20 keV luminosities, $L_{2-10}$ and $L_{10-20}$, are $2.5\times10^{43}$ erg s$^{-1}$ cm$^{-2}$, $9.1\times10^{43}$ erg s$^{-1}$, and $8.7\times10^{43}$ erg s$^{-1}$, respectively.

These luminosities are corrected for the Galactic extinction, $N_{H} = 9\times10^{19}$ cm$^{-2}$ (Dickey & Lockman 1990). Figure 2 shows how the objects in our sample are distributed in the $L_{10-20} - z$ plane. The spread of the 10–20 keV luminosity is relatively narrow with a logarithmic dispersion of 0.3 (or a factor of ~2).

3. Results

3.1. X-ray colour analysis

For selecting sources with various degrees of absorption, three rest-frame energy bands: $s$ (3–5 keV); $m$ (5–9 keV); and $h$ (9–20 keV), are defined and two X-ray colours: $s/m$ and $h/m$ are computed. At energies above 3 keV, little contribution from soft X-ray emission originating from the extranuclear region is expected. As the intrinsic continuum slope in the 3–20 keV band is not expected to vary wildly between objects, absorption would be the main driver of changes in the X-ray colours. For the adopted rest-frame energy range, these X-ray colours are sensitive to column densities larger than $N_{H} = 10^{23}$ cm$^{-2}$.

Since our objects have a wide range of redshift (1.7–3.8 in z), these X-ray colours are derived using photon spectra, i.e., spectral data corrected for the detector response and the Galactic absorption as a function of the rest-frame energy. The correction method employed here is practically the same as that used in the XMM-COSMOS spectral stacking analysis (Iwasawa et al. 2012). The photon counts in each band are the weighted mean of the three EPIC cameras, where we adopted the signal-to-noise ratio in the rest-frame 3–20 keV band as the weight.
Table 1. Properties of the sample.

| PID  | RA   | Dec  | z    | Net      | s/m  | h/m  | f1−4 | L_{20} | L_{10−20} |
|------|------|------|------|----------|------|------|-------|--------|-----------|
| 26   | 53.21484 | -27.97884 | 3.198 | sp a    | 618  | 0.35 ± 0.17 | 0.97 ± 0.33 | A   | 1.7c-15 | 9.2e+3    | 9.7e+3    |
| 30   | 05.03737 | -27.97493 | 1.830 | sp x    | -1344 | 0.29 ± 0.08 | 2.06 ± 0.27 | V   | 2.5c-15 | 4.5e+3    | 1.3e+4    |
| 31   | 28.28854 | -27.97376 | 2.583 | sp a    | 789  | 1.05 ± 0.15 | 1.07 ± 0.19 | M   | 3.9c-15 | 2.1e+4    | 1.4e+4    |
| 33   | 25.25708 | -27.97188 | 1.843 | sp a, b | 8112 | 1.20 ± 0.04 | 0.77 ± 0.05 | U   | 2.5c-14 | 6.8e+4    | 4.0e+4    |
| 49   | 52.97654 | -27.94723 | 2.298 | sp c    | 1474 | 1.09 ± 0.14 | 1.07 ± 0.18 | M   | 2.8c-15 | 1.0e+4    | 8.4e+3    |
| 57   | 29.0941 | -27.93768 | 2.571 | sp a    | 1891 | 1.49 ± 0.14 | 0.68 ± 0.12 | U   | 2.8c-15 | 1.9e+4    | 5.7e+3    |
| 62   | 30.30284 | -27.93094 | 2.561 | sp a    | 3642 | 1.40 ± 0.08 | 0.60 ± 0.07 | U   | 6.1c-15 | 3.8e+4    | 1.7e+4    |
| 63   | 17.0001 | -27.92967 | 3.350 | x       | -1277 | 0.23 ± 0.11 | 1.95 ± 0.31 | V   | 2.5c-15 | 8.7e+3    | 2.5e+4    |
| 68   | 25.35773 | -27.92238 | 2.005 | sp d    | 3023 | 1.30 ± 0.10 | 0.75 ± 0.11 | U   | 5.5c-15 | 2.0e+4    | 8.4e+3    |

Notes.
1) Source identification number in the XMM-CDFs catalogue of Ranalli et al.: (2) XMM position of source (degrees, J2000): (4) redshift; (5) source of redshift, sp: optical spectroscopic; ph: photometric; x: X-ray spectroscopic; (6) references for the redshift estimates: a: Treister et al. (2008b); h: Raﬀerty et al. (2011); i: Balestra et al. (2010); (7) net counts in the rest-frame 3–20 keV band from all the three EPIC cameras. † MOS1+MOS2 only; (8) X-ray colour, s/m: photon ratio of the rest-frame 3–5 keV and 5–9 keV; (9) X-ray colour, h/m, photon ratio of the rest-frame 9–20 keV and 5–9 keV; (10) X-ray colour category; (11) observed-frame 1–4 keV flux in units of erg s\(^{-1}\) cm\(^{-2}\); (12) rest-frame 2–10 keV luminosity in units of erg s\(^{-1}\); (13) rest-frame 10–20 keV luminosity in units of erg s\(^{-1}\). The luminosities given here are corrected for the Galactic absorption.

X-ray colours, s/m and h/m, for individual sources are listed in Table 1, and the colour–colour diagram is shown in Fig. 3.

With the two X-ray colours, a column density range of log N\(_{HI}\) = 22–24 (cm\(^{-2}\)) can be probed, as s/m covers the lower N\(_{HI}\) regime and h/m does the higher. In Fig. 3, a locus of spectral evolution when a power-law continuum of photon index \(\Gamma = 1.8\) is modified by various absorbing columns of log N\(_{HI}\) between 21 and 24 (cm\(^{-2}\)) is drawn. As the s/m represents softness of a spectrum below 9 keV, objects at the bottom-right in Fig. 3 are populated by sources with little absorption. The s/m colour moves to the left as absorption increases. Two divisions were made along the s/m axis, at s/m = 0.6 and 1.1. In the lowest interval, the model locus turns upwards as increasing absorption at log N\(_{HI}\) ≥ 23.5 (cm\(^{-2}\)) and a few sources indeed
spread towards higher \( h/m \) values, which indicates an excess of 9–20 keV emission.

PID 144 \((z = 3.70)\) is a previously known, heavily obscured AGN with an X-ray absorbing column of \( N_H \sim (0.6–0.9) \times 10^{24} \text{ cm}^{-2}\) (Norman et al. 2002; Comastri et al. 2011), located in this interval. We take this object with \( h/m = 1.46 \) as the reference and sources that have \( h/m \) larger than this object were classified as 9–20 keV excess sources.

According to the three intervals along \( s/m \) and two intervals along \( h/m \), four zones, V: Very absorbed; A: Absorbed; M: Modestly absorbed; and U: Unabsorbed, are defined in the colour–colour diagram, as shown in Fig. 3. The degree of absorption thus increases in the order of U, M, A, and V, and typical column densities for these X-ray colour categories would be \( \log N_H \) of \( \leq 22, 22.7, 23.4, \) and 23.8 (cm\(^{-2}\)), respectively.

For a comparison, the X-ray colours of nearby, well-studied heavily obscured AGN, NGC 6240 \((N_H \sim 2 \times 10^{24} \text{ cm}^{-2})\), NGC 4945 \((N_H \sim 5 \times 10^{24} \text{ cm}^{-2})\), and NGC 1068 \((N_H \geq 10^{25} \text{ cm}^{-2})\) were computed, based on the spectra presented in Vignati et al. (1999), Guainazzi et al. (2002), and Matt et al. (1997), respectively, obtained from the BeppoSAX observations (see Fig. 3). In these low luminosity systems, non AGN components, e.g., a circumnuclear starburst, flaring X-ray binaries (e.g., Brandt et al. 1996), can make a significant contribution to their spectra in the lower energy range, altering the \( s/m \) colour in particular, more than in high luminosity AGN like our sample.

\section*{3.2. X-ray redshift measurements}

Redshift was measured with X-ray spectra for five objects, PID 30, 64, 116, 245, and 352, which have only photometric redshifts (Table 3). These objects are too faint in the optical band to obtain a reliable spectroscopic redshift. The photometric redshifts reported by various authors for each object spread over a significant range, while they can serve as a guide for a redshift range to be searched in. The Fe K features in their spectra gave improved accuracy in the redshift measurements.

Despite of this spectral complexity, \( h/m \) serves as a good indicator of the strong absorption seen in sources like NGC 6240 and NGC 4945. The \( h/m \) colour moves back to a lower value for a fully Compton thick source, e.g., NGC 1068, but it still remains in a zone of hard spectrum sources.

Two sources, PID 84 and PID 366, have \( h/m \) values similar to the reference PID 144 but softer \( s/m \) colours (see Table 1). An inspection of their spectra shows that PID 84 has a moderately absorbed spectrum with \( N_H \sim 1 \times 10^{23} \text{ cm}^{-2}\) as expected for the M category, while PID 366 in the U interval shows a relatively soft spectrum but with a deficit at the rest-frame 7–10 keV (observed 2.2–3 keV range), causing the large value of \( h/m \). This could be attributed to a strong Fe K edge caused by absorption of \( N_H \sim 6 \times 10^{23} \text{ cm}^{-2}\), where a spectral complexity might play a role to mask the strong absorption.

The sources in the V and A categories are absorbed by \( N_H \) of a few times of \( 10^{23} \text{ cm}^{-2}\) or larger, so that prominent Fe K features in the form of an emission line or an absorption edge can be observed. This offers a possibility to derive a reliable X-ray spectroscopic redshift. There are five objects in the two categories with only photometric redshifts. X-ray redshift (\( z_X \)) were obtained for these five objects and their X-ray colours were recomputed assuming the new redshifts. Details of the X-ray redshift measurements are described in Sect. 3.2.

\begin{table}[ht]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\textbf{Category} & \textbf{\( N \)} & \textbf{\( z \)} & \textbf{\( \log L_2-10 \)} & \textbf{\( \log L_{10-20} \)} & \textbf{\( \Gamma_{10-20} \)} \\
\hline
V & 7 & 2.68 & 43.59 & 44.04 & 0.3 ± 0.2 \\
A & 6 & 2.78 & 43.86 & 43.93 & 1.5 ± 0.3 \\
M & 19 & 2.56 & 43.96 & 43.93 & 1.3 ± 0.2 \\
U & 14 & 2.19 & 44.20 & 43.99 & 1.6 ± 0.1 \\
\hline
\end{tabular}
\caption{Properties of the four X-ray colour categories, V, A, M, and U.}
\end{table}
Table 3. X-ray redshift measurements.

| PID | Z_E | Photo-z |
|-----|-----|---------|
| 30  | 1.83 ± 0.07 | 2.123, 1.936, 1.84, 1.683 |
| 64  | 3.35 ± 0.04 | 3.528, 3.341, 3.301 |
| 116 | 3.74 ± 0.06 | 3.53, 3.39, 4.63, 4.14 |
| 245 | 2.68 ± 0.12 | 3.001, 2.4318, 2.28 |
| 352 | 1.60 ± 0.02 | 1.78 |

Notes. Z_E is the X-ray spectroscopic redshift with 1σ error. The Fe K features are assumed to arise from cold matter (see text for details).

References. References for photometric redshifts: a: Luo et al. (2010); b: Cardamone et al. (2008); c: Rafferty et al. (2011); d: Taylor et al. (2009); e: Wuyts et al. (2008); f: Wardlow et al. (2011); g: Wardlow et al. (2011, the second solution); h: Dahlen et al. (2010); k: Santini et al. (2009).
luminosity; (4) absorption correction factor for the 10 keV continuum modelled by a simple power-law with $\Gamma=2$. When a Thomson opacity approaches unity, as observed in these sources, the absorption correction depends on the geometry of absorbing clouds (e.g., Matt et al. 1999b). In this table, the values for a spherical geometry are given as the lower limits. These values can go up by a factor of $\sim 2$, as the covering factor of the absorber is reduced. 10 The spectra of these sources can also be described well by a reflection spectrum from cold matter.

hard X-ray colour $h/m$ (Fig. 6) although no obvious Fe line is seen. For these two objects, a pure reflection spectrum from cold matter, modelled by pexrav (Magdziarz & Zdziarski 1995) or pexmon (Nandra et al. 2007), provides a comparable fit to their spectra, compared to the absorption correction factor. This indicates that these two objects might be Compton thick AGN with a larger $N_{\rm H}$ than that given in Table 4, e.g., $\sim 10^{25}$ cm$^{-2}$.

Fe K emission is detected at $\sim 2\sigma$ or larger significance in these objects except for PID 252 (Table 5, see also Comastri et al. 2011). The spectrum of PID 252 does not show clear

**Notes.** (1) Source identification number; (2) absorption column density in unit of $10^{23}$ cm$^{-2}$; (3) absorption correction factor for the 2−10 keV luminosity; (4) absorption correction factor for the 10−20 keV luminosity. Spectral fits were performed for the observed-frame 1−7 keV data using an absorbed power-law with $\Gamma=1.8$. When a Thomson opacity approaches unity, as observed in these sources, the absorption correction depends on the geometry of absorbing clouds (e.g., Matt et al. 1999b). In this table, the values for a spherical geometry are given as the lower limits. These values can go up by a factor of $\sim 2$, as the covering factor of the absorber is reduced. **Table 5.**

| PID  | $EW_1$ (keV) | $EW_2$ (keV) |
|------|-------------|-------------|
| 30   | 0.76 ± 0.24 | 0.51 ± 0.19 |
| 64   | 0.57 ± 0.19 | 0.27 ± 0.11 |
| 114  | 1.40 ± 0.61 | 1.09 ± 0.53 |
| 144  | 1.13 ± 0.51 | 0.47 ± 0.23 |
| 180  | 0.65 ± 0.16 | 0.34 ± 0.12 |
| 245  | 1.10 ± 0.48 | 0.44 ± 0.28 |
| 252  | <0.5        | <0.2        |

Notes. $EW_1$ and $EW_2$ are measured with respect to the rest-frame 5−10 keV continuum modelled by a simple power-law and an absorbed power-law of $\Gamma=1.8$, respectively. For PID 252, $2\sigma$ upper limits are given. We remark that $EW_2$ is always smaller than $EW_1$ since part of the line is accounted for by the sharp continuum feature of an absorbed continuum carved by an Fe K edge.

Fe K emission with $EW \lesssim 0.5$ keV (2$\sigma$ upper limit of a narrow line at 6.4 keV). This weak-line source may be a high-redshift analogue of Mrk 231, a Compton thick AGN with a weak Fe K line in the local Universe (e.g., Braito et al. 2004; Gallagher et al. 2002; Iwasawa et al. 2011, and other references therein). The large EW observed in PID 114 (Table 5) agrees with an Fe K line expected from a reflection-dominated spectrum from cold medium, giving a support to the possibility of a Compton thick source.

**4. Discussion**

**4.1. X-ray selection of heavily obscured AGN**

Seven heavily obscured active galaxies with $N_{\rm H} \geq 0.6 \times 10^{24}$ cm$^{-2}$, including one previously known source (PID 144, Norman et al. 2002; Comastri et al. 2011), were selected by the rest-frame X-ray colour selection, primarily utilizing the
Fig. 7. Distribution of absorbing column density $N_H$, obtained by fitting an absorbed power-law to the EPIC spectra. The lowest bin represents the number of objects with no detection of absorption. The typical error bar of each bin is ±1.

excess emission in the 9–20 keV band relative to emission at lower energies. Two of them (PID 114 and PID 252) are possibly Compton thick AGN with a reflection-dominated spectrum. Given the limited bandpass available from XMM-Newton, this selection can be applied only for high redshift objects, but the a posteriori checks showed that this selection is reliable for sources with spectra of reasonable quality, and can pick up strongly absorbed sources with near Thomson-thick opacity.

This method is a pure X-ray selection, and these seven objects compose a sample of heavily obscured, moderate-luminosity quasars with $L_{20-10} \sim 10^{44}$ erg s$^{-1}$, selected by the hard X-ray emission above 10 keV beyond the local Universe.

There are various reports in the literature on Compton thick AGN candidates in the CDFS using whole or part of the Chandra 4 Ms data (e.g., Norman et al. 2002; Mainieri et al. 2005; Tozzi et al. 2006; Fiore et al. 2008; Gilli et al. 2011; Feruglio et al. 2011; Luo et al. 2011; Brightman & Ueda 2012; Fiore et al. 2012). Some of them lie in the redshift range of our sample, although they are expected faint and just a few of them entered in our sample of relatively bright sources. Fiore et al. (2012) investigated high-redshift sources at $z > 3$ in CDFS and selected several heavily obscured AGN. Their E537 (=PID 245), M5390 (=PID 144), M8273 (PID 180), M3320 (=PID107) and M4302 (=PID 120) are in our sample. Our results on the spectra of these sources agree except for PID 120 for which only moderate absorption of $N_H = 1.6^{+0.5}_{-0.6} \times 10^{22}$ cm$^{-2}$ is found. The smaller $N_H$ value for PID 245 obtained by us (Table 4) is explained by the lower redshift adopted for this source: the X-ray redshift $z_X = 2.68$ (Sect. 3.2, Table 3), instead of the photometric redshift $z = 4.29$ from the GOODS-ERS (Grazian et al. 2011) adopted by Fiore et al. (2012), which a close inspection of the X-ray/optical/infrared images suggests to be the redshift for another galaxy near the X-ray source.

4.2. Absorbed AGN fraction

In Fig. 3, when the model locus is used as a guide, 10 objects appear to have unobscured X-ray sources, i.e., their X-ray absorption is $N_H < 10^{22}$ cm$^{-2}$. That is, 3/4 of our sample objects host significantly obscured active nuclei. Fitting to the individual spectra verifies the above assessment with 12 objects having $N_H$ values smaller than $10^{22}$ cm$^{-2}$, and gives the $N_H$ distribution shown in Fig. 7. The distribution of log $N_H$ (cm$^{-2}$) is nearly flat between 22–24, although the two objects (PID 114 and 252) possibly move up to log $N_H > 24$ (cm$^{-2}$). For their typical 2–10 keV intrinsic luminosities [(0.8–5)×10^{44} erg cm$^{-2}$ s$^{-1}$], these active galaxies at $z \sim 2.5$ can all be considered to emit at quasar luminosity, and 74 ±8 per cent of them are absorbed X-ray sources. We have estimated this absorbed AGN fraction using a Bayesian approach and the binomial distribution (Wall & Jenkins 2008) with a 68 per cent confidence interval (Andreon, priv. comm.). It should be noted that, since the fraction of Compton thick AGN is not constrained, this value is considered to be the lower limit of the absorbed AGN fraction.

We compared our findings with the predictions of the XRB synthesis model by Gilli et al. (2007). Our sample spans the 2–10 keV flux range (2–54)×10^{-15} erg cm$^{-2}$ s$^{-1}$. Since the sensitivity of the XMM-CDFS observations strongly varies across the field, we computed the model predictions at the 2–10 keV limiting flux, $f_{2-10}^{\text{lim}} = 4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, which returns the same AGN surface density of our sample, i.e. 46 sources at $z > 1.7$ distributed over a ~0.27 deg$^2$ area. The predicted absorbed fraction (defined as the number of AGN with log $N_H > 22$ over the total number of AGN in the sample) is 0.54 ± 0.06, smaller than the observed value of 0.74 ± 0.08.

In the local Universe, the Swift/BAT and INTEGRAL surveys show that absorbed sources (with $N_H > 10^{22}$ cm$^{-2}$) consist ~55 per cent of hard X-ray selected AGN (e.g., Burlon et al. 2011, and references therein). It is also found that this fraction depends on X-ray luminosity, and at the luminosity matched to our sample, the fraction is 21 ± 8 per cent (Burlon et al. 2011, see also Ebrero et al. 2008). The absorbed quasar fraction ($L_{2-10} > 10^{44}$ erg s$^{-1}$) in our sample is higher than that of the local Universe, suggesting a positive evolution with redshift, as found in the previous work by La Franca et al. (2005), Treister & Urry (2006) and Ebrero et al. (2008). No evolution of the obscured AGN fraction was assumed in Gilli et al. (2007), yet the prediction comes close to the observation at $z > 1.7$ as discussed above. However, we note that the luminosity dependence of the absorbed AGN fraction assumed in Gilli et al. (2007) appears to be shallower than the observations (Hasinger 2008; Brusa et al. 2010; Burlon et al. 2011), and it overestimates the obscured fraction of quasi-stellar objects (QSOs) with $L_{2-10} > 10^{44}$ erg s$^{-1}$ in the local Universe by a factor of ~2.5. This excess number assumed for local obscured QSOs then compensates the lack of a redshift evolution of their fraction in the model.

Contrary to the high-luminosity AGN, no strong evidence for a redshift dependence of the obscured AGN fraction at luminosities $<10^{44}$ erg s$^{-1}$ has been found. Gilli et al. (2010), for instance, showed that the increasing trend of the absorbed fraction as observed by Hasinger (2008) for AGN with $L_{2-10} < 10^{44}$ erg s$^{-1}$, can be accounted for by the K-correction effect, and is instead consistent with a non-evolving intrinsic absorbed fraction. Here we suggest that the obscured fraction increases with redshift only for luminous QSOs. The different behaviours in obscured fraction between low- and high-luminosity AGN may reflect their distinct accretion mechanisms, as argued in literature (Hasinger 2008; Hopkins et al. 2008; Hickox et al. 2009): merger-driven accretion for luminous AGN (e.g., Menci et al. 2008) and secular accretion for less luminous AGN, possibly mirroring their respective drivers of star formation (e.g., Elbaz et al. 2011). This may not be the whole story but qualitatively explains the different behaviours between AGN of the low and high luminosity ranges. If all QSOs originate from a major merger of gas-rich
galaxies (e.g., Sanders et al. 1988), the increase of merger rate at high redshift (with α(1+z)^2), e.g., Xu et al. 2012) naturally sees an increase in number of QSOs. A merger causes gas channeling to the nuclear region (Barnes & Hernquist 1991). This concentration of gas and the chaotic geometry left by a merger would lead to a high probability of the nuclear region to be seen obscured (e.g., Hopkins et al. 2006; but see Shawinski et al. 2012) until the radiation pressure of the buried QSO sweeps it away. In the context of this evolutionary scenario alone, the obscured fraction of QSOs is expected to be constant at all redshift, given the short duration of the QSO life-time (∼10^8 yr, Hopkins et al. 2005). The evolution we observed is probably driven by the increase in the gas fraction of a galaxy towards high redshift (e.g., Carilli et al. 2011), combined with the efficient inflow induced by a merger. A higher gas fraction of merger progenitor galaxies means more gas to be transported to the nuclear region to form heavier obscuration. This would result in a longer duration of the obscured phase, which can be translated to a higher obscured fraction of the QSO population at high redshift. At the same time, the elevated gas density by a merger increases the efficiency of star formation leading to a starburst (e.g., Barnes & Hernquist 1991; Elbaz et al. 2011). Kinetic energy injection from a starburst may help to maintain the obscuration by inflating gaseous wall around AGN (e.g., Fabian et al. 1998). Conversely, the lack of mergers may explain the little evolution of the obscured fraction in lower luminosity AGN. The gas fraction of galaxies hosting them also increases towards high redshift in the same way as for high-luminosity AGN. However, without a major merger, the gas reservoir is not transported to the nuclear region rapidly. This means that the nuclear obscuration condition remains little affected regardless the amount of gas contained in a galaxy (hence redshifts). The gas content is instead consumed to form stars over galaxy-wide as a secular process, and the feeding to the black hole from a large-scale disk remains relatively inefficient.

In summary, we present a result of a rest-frame 9–20 keV selection of heavily obscured AGN at z > 1.7, using the deep XMM-CDHS survey, and also show that the fraction of absorbed AGN at high luminosity may be higher at high redshift than in the local Universe. In the near future, a further advance in this area of research will benefit from even deeper observations of deep fields with Chandra and XMM-Newton, while NuSTAR and Astro-H which will provide us with useful templates and insights at lower redshifts. It is also useful to standardize various X-ray spectral models of strongly absorbed systems with improved physics incorporated for the community to share with.

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