The HELLAS2XMM survey
III. Multi-component analysis
of the spectral energy distribution of obscured AGN

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ABSTRACT

Aims. We combine near-to-mid-IR Spitzer data with shorter wavelength observations (optical to X-rays) to get insights on the properties of a sample of luminous, obscured Active Galactic Nuclei (AGN). We aim at modeling their broad-band Spectral Energy Distributions (SEDs) in order to estimate the main parameters related to the dusty torus which is assumed responsible for the reprocessed IR emission. Our final goal is to estimate the intrinsic nuclear luminosities and the Eddington ratios for our luminous obscured AGN.

Methods. The sample comprises 16 obscured high-redshift (0.9 < z < 2.1) X-ray luminous quasars (L_{2–10 keV}~10^{44} erg s^{-1}) selected from the HELLAS2XMM survey in the 2–10 keV band. The optical-IR SEDs are described by a multi-component model including a stellar component to account for the optical and near-IR emission, an AGN component which dominates in the mid-IR (mainly emission from a dusty torus heated by nuclear radiation) and a starburst to reproduce the far-IR bump. A radiative transfer code to compute the spectrum and intensity of dust reprocessed emission was extensively tested against our multiwavelength data. While the torus parameters and the BH accretion luminosities are a direct output of the SED-fitting procedure, the BH masses are estimated indirectly, by means of the local M_{BH}-M_{bulge} relation.

Results. The majority (~80%) of the sources show moderate optical depth (τ_{γ, 70 μm}≤5) and the derived column densities N_{H} are consistent with the X-ray inferred values (10^{22} ≤ N_{H} ≤ 3×10^{23} cm^{-2}) for most of the objects, confirming that the sources are moderately obscured Compton-thin AGN. Accretion luminosities in the range 5×10^{43} ≤ L_{edd} ≤ 4×10^{44} erg s^{-1} are inferred from the multiwavelength fitting procedure. We compare model luminosities with those obtained by integrating the observed SED, finding that the latter are lower by a factor of ~2 in the median. The discrepancy can be as high as an order of magnitude for models with high optical depth (τ_{γ, 70 μm} = 10). The ratio between the luminosities obtained by the fitting procedure and from the observed SED suggest that, at least for Type 2 AGN, observed bolometric luminosities are likely to underestimate intrinsic ones and the effect is more severe for highly obscured sources. Bolometric corrections from the hard X–ray band are computed and have a median value of k_{X–10keV}~1. The obscured AGN in our sample are characterized by relatively low Eddington ratios (median k_{Edd}=0.08). On average, they are consistent with the Eddington ratio increasing at increasing bolometric correction (e.g. Vasudevan & Fabian 2009).

Key words. quasars: general — galaxies: nuclei — galaxies: active

1. Introduction

A robust determination of Active Galactic Nuclei (AGN) Spectral Energy Distributions (SEDs) is of paramount importance to better understand the accretion processes onto supermassive black holes (SMBHs) and their cosmological evolution. According to our present knowledge, the bulk of accretion luminosity is emitted in the optical-UV range with a quasi-thermal spectrum originating in an optically thick, geometrically thin, accretion disk. Electrons with temperatures of the order of a few hundreds of keV form a hot corona which upscatters disk photons to X-ray energies with a power law spectrum and an exponential high-energy cut-off corresponding to the electron temperature (e.g., Haardt & Maraschi 1991). Dusty material, possibly with a toroidal geometry, intercepts a fraction of the primary continuum which depends on the cover-
The optical-UV spectrum rises steeply towards the shortest wavelengths, characterized by the slope $\alpha_{\text{opt}}$ of the power law connecting the rest-frame luminosities, increasing with increasing UV luminosity (e.g., Vignali et al. 2003; Steffen et al. 2006).

The average SEDs for radio-loud and radio-quiet Type 1 AGN presented in Elvis et al. (1994) allow the estimation of bolometric corrections, which are a key parameter to determining the bolometric luminosity from observations at a given frequency, and the Eddington ratio, once the SMBH mass is known. By including the $\alpha_{\text{opt}}$ vs. dusty torus seen almost face-on. The ratio between UV (at 2500 Å) and X-ray luminosity (at 2 keV), parameterized by the slope $\alpha_{\text{IR}}$ of the power law connecting the rest-frame luminosities, increases with increasing UV luminosity (e.g., Vignali et al. 2003; Steffen et al. 2006).

The bolometric correction correlates with the predictions of accretion disk models (e.g., Witt et al. 1997) where higher blue-bump to X-ray ratios for sources with higher Eddington ratios are expected.

While important progress has been made towards a better determination of Type 1 AGN SEDs, our knowledge of Type 2 broad-band spectra is much more limited despite the fact that most of the accretion-driven energy density in the Universe is expected to occur in obscured AGN (e.g., Fabian 1999, Gilli et al. 2007 and references therein). Therefore, a robust estimate of their bolometric luminosity is extremely important to properly address the issue of SMBH evolution over cosmic time.

Nuclear accretion luminosity in Type 2 AGN is very faint in the optical-UV and soft X-rays. Moreover, the host galaxy stellar light often dominates in the optical making it difficult to disentangle nuclear emission from starlight. Infrared emission is only marginally affected by dust obscuration and has proved to be a powerful indicator of dust obscured AGN. In particular, the thermally reprocessed nuclear emission of obscured Type 2 AGN is expected (e.g., Fritz et al. 2006, hereafter F06, and references within) to peak around a few tens of microns.

Mid-IR (MIR) observations, and especially those obtained in the last few years with the Spitzer satellite, are extremely efficient in the study of obscured AGN (e.g. Rieby et al. 2008, Martínez-Sansigre et al. 2005, Weedman et al. 2006, Fiore et al. 2008). In a previous paper (Pozzi et al. 2007) we presented the first analysis of the mid-IR data of a Spitzer program devoted to a systematic study of the broad-band properties of X-ray selected, luminous obscured quasars. In Pozzi et al. (2007), the SEDs were reproduced by means of SED templates from Silva et al. (2004).

Here we present the observational data for our final sample of 16 obscured quasars and the detailed modeling of their broad-band SED using a more complete multi-component model, with goodness of fit estimated via a $\chi^2$ analysis.

The outline of the paper is as follows: in §2 the X-ray selected quasar sample is presented, along with all the available multi-band (optical, near-IR (NIR) and sub-mm) and spectroscopic follow-up. The Spitzer data are presented in §3, along with data reduction and analysis. In §4, the complete multi-component model is described. In §5, the best-fitting solutions are discussed, while in §6 focus is on the black hole physical properties that can be constrained from the best-fitting procedure. Finally, the main results are summarized in §7.

Hereafter, we adopt the concordance cosmology $(H_0 = 70 \text{ km sec}^{-1} \text{ Mpc}^{-1}, \Omega_m=0.3 \text{ and } \Omega_{\Lambda}=0.7)$ (Spergel et al. 2003). Magnitudes are expressed in the Vega system.

### 2. The sample

The sample presented in this work comprises 16 X-ray obscured quasars detected in the HELLAS2XMM survey (Baldi et al. 2002) and observed by Spitzer in 2006. The HELLAS2XMM survey is a shallow, large-area hard X-ray survey ($S_{2-10\text{ keV}} > 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$) over a final area of 1.4 deg$^2$. The catalogue comprises 232 X-ray sources; ~92% of the sample is optically identified down to R~25, while ~70% of the sources have a spectroscopic classification (Fiore et al. 2003, Maiolino et al. 2006, Cocchia et al. 2007).

The 16 sources were selected from the original survey in order to include the most luminous obscured quasars. The selection was primarily based on the X-ray-to-optical flux ratio (hereafter $X/O$) which has been proved to be an efficient way to select high-redshift (z > 1), obscured quasars (see Fiore et al. 2003). All but one of the sources were selected to have $X/O$ greater than 1 (see Fig. 1 and Table I; the only exception is a Galaxy (X/O~0.63) which was included in the sample for its peculiar properties (see Vignali et al. 2008, hereafter V09). We note, however, that not all of the HELLAS2XMM sources matching this selection criterion are present in this work.

The selected sources are relatively faint in the optical band, with an R-band magnitude in the range 21.8-25.1 (the brightest of them is the peculiar source GD 158#19 (X/O~0.63) which was included in the sample for its peculiar properties (see Vignali et al. 2008, hereafter V09). The link between high $X/O$ ratios and optical-to-near colours was

\[ X/O = \log \frac{\Delta f_{\lambda}}{f_{\lambda}(0)} \]

used $f_{\lambda}(0) = 1.74 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ and $\Delta \lambda = 2200 \text{ Å}$ (Zombeck 1990).
redshift was estimated in Pozzi et al. (2007), where the data reduction and a preliminary SED analysis were presented. This is diluted and hidden by the host galaxy up to at least 2.2 for a nuclear point-like source (which would be expected to 

In Table 1, the R and K bands (from 3.6\mu m up to 160\mu m) with the Spitzer satellite (see § 3). The sub-mm flux densities are reported in Table I along with the fluxes obtained in the IR bands (in 2.2\mu m up to 160\mu m) with the Spitzer satellite (see § 3).

Almost all the sources have column densities N_H in the range 10^{22.0}−10^{23.4} cm^{-2} and 2−10 keV rest-frame luminosities in the range 10^{43.8}−10^{47} erg s^{-1}, placing them among the Type 2 quasar population.

3. The Spitzer data

The targets were observed by Spitzer in 2006 with both IRAC and MIPS instruments in photometry mode. All the sources were observed with the same total integration time in the IRAC bands (480s), while different strategies were followed in the MIPS bands taking into account the different optical-NIR properties. While all the objects were observed at 24\mu m for a total integration time of 1400s, only a sub-sample of sources with relatively bright R-band magnitudes (R<24) and spectroscopic redshifts were observed at longer wavelengths, with integration times of 300s and 600s at 70 and 160\mu m, respectively. PKS 0537#91 (see Table 1) was not observed at 70 and 160\mu m since it had no redshift at the epoch of the Spitzer observations.

The reduction method is described in detail in Pozzi et al. (2007) and in V09 and it is briefly summarized here. The IRAC flux densities of the sources were measured from the post-basic calibrated data (post-BCD) images in the Spitzer archive. Aperture fluxes were measured on the background subtracted maps within a 2.45″ aperture radius using aperture corrections of 1.21, 1.23, 1.38 and 1.58 for the four IRAC bands (following the IRAC Data Handbook). For the MIPS bands, we started the analysis from the basic calibrated data (BCD) at 24\mu m and from the median high-pass filtered BCD (tBCD) at 70 and 160\mu m, as suggested for faint sources. At 24\mu m, the BCD were corrected for a residual flat fielding dependent on the scan mirror position (see Fadda et al. 2006; Pozzi et al. 2007). We constructed then our own mosaics using the SSC MOPEX software (Makovoz & Marleau 2005). Aperture fluxes were measured within a 7″ aperture radius for the 24\mu m band and 16″ aperture radius for the 70 and 160\mu m band. The aperture corrections used were 1.61, 2.07 and 4.1, respectively (see the MIPS Data Handbook). A small aperture radius was used at longer wavelengths (at 160\mu m the adopted radius is comparable to half of the PSF FWHM) to exclude the contamination of nearby far-infrared sources (see V09). At 24\mu m, thanks to a better PSF...
Table 1. Properties of our luminous obscured quasars

| Complete Name | Name | 2–10 keV flux | $K_s$ | X/O | $\zeta$ | $N_H$ | $L_{2-10 \text{keV}}$ |
|---------------|------|---------------|------|------|-------|-------|-----------------|
| HELLS2XMM 054022.0-283139 | PKS 0537#43 | 3.35 | 22.70 | 17.50 | 1.10 | 1.797 | 10.5^{+6}_{-4} | 6.8 |
| HELLS2XMM 053920.4-283721 | PKS 0537#11a | 4.19 | 23.40 | 18.25 | 1.48 | 0.981 | 1.1^{+0.8}_{-0.9} | 1.9 |
| HELLS2XMM 053917.1-283819 | PKS 0537#164 | 1.50 | 23.60 | 19.02 | 1.12 | 1.824 | 3.1 |
| HELLS2XMM 053851.3-283949 | PKS 0537#123 | 2.97 | 23.10 | 17.94 | 1.21 | 1.153 | 6.6^{+4.6}_{-2.0} | 2.0 |
| HELLS2XMM 003413.8-115559 | GD 158#66 | 3.59 | 23.30 | 21.83 | 1.38 | 1.568 | 26.3^{+13.7}_{-4.9} | 4.9 |
| HELLS2XMM 003357.2-120046 | GD 158#19 | 2.43 | 21.80 | – | 0.61 | 1.957 | 7.3^{+7.1}_{-6.3} | 6.3 |
| HELLS2XMM 204428.7-105629 | Mrk 509#01 | 2.10 | 23.85 | 17.88 | 1.3 | 6.104 | 2.5^{+2.2}_{-2.6} | 2.6 |
| HELLS2XMM 204349.7-103243 | Mrk 509#13 | 3.10 | 23.99 | 18.79 | 1.56 | 1.261 | 2.5^{+2.2}_{-2.6} | 2.6 |
| HELLS2XMM 235956.6-251019 | Abell 2690#75 | 3.30 | 24.60 | 18.33 | 1.85 | 1.3 | 26.3^{+13.7}_{-4.9} | 4.9 |
| HELLS2XMM 054021.1-283721 | PKS 0537#91 | 4.2 | 23.70 | 18.99 | 1.6 | 0.981 | 1.5^{+0.9}_{-0.5} | 1.0 |
| HELLS2XMM 031343.5-765426 | PKS 0312#36 | 1.90 | 24.70 | 19.13 | 1.66 | 0.9 | 1.5^{+0.9}_{-0.5} | 1.0 |
| HELLS2XMM 054022.0-283139 | PKS 0537#43 | 3.35 | 22.70 | 17.50 | 1.10 | 1.797 | 10.5^{+6}_{-4} | 6.8 |
| HELLS2XMM 054021.1-283721 | PKS 0537#91 | 4.2 | 23.70 | 18.99 | 1.6 | 0.981 | 1.5^{+0.9}_{-0.5} | 1.0 |
| HELLS2XMM 000111.6-251202 | Abell 2690#29 | 2.8 | 25.10 | 18.91 | 1.85 | 1.0^{+3.9}_{-1.7} | 3.1 |
| HELLS2XMM 031018.9-765957 | PKS 0537#43 | 3.35 | 22.70 | 17.50 | 1.10 | 1.797 | 10.5^{+6}_{-4} | 6.8 |
| HELLS2XMM 005030.7-520046 | BPM 16274#69 | 2.27 | 24.08 | 17.87 | 1.48 | 1.35 | 2.5^{+2.2}_{-2.6} | 2.6 |

(1) Source complete name;
(2) source abbreviated name (adopted throughout the paper);
(3) 2–10 keV X-ray fluxes in units of 10^{-12} erg cm^{-2} s^{-1} from Perola et al. (2004) (with the exception of BPM 16274#69, from Lanzuisi et al., in preparation);
(4) $K_s$-band magnitude from Fiore et al. (2003) (with the exception of source BPM 16274#69, from Cocchia et al. 2007);
(5) $K_s$-band magnitudes. For a sub-sample of sources, the $K_s$-band analysis can be found in Mignoli et al. (2004);
(6) X-ray-to-optical flux ratio;
(7) source redshifts. Spectrophotometric redshift from optical spectroscopy (Fiore et al. 2003) and, for three sources, from near-IR spectroscopy (Abell 2690#29 and BPM 16274#69 from Maiolino et al. 2006; PKS 0537#91 from Sarria et al., in preparation); photometric redshifts (symbol), and corresponding 1σ errors, from Pozzi et al. (2007);
(8) column densities in source rest-frame in units of 10^{22} cm^{-2} measured from X-ray spectral fitting (see Perola et al. 2004 and Lanzuisi et al., in preparation); for the sources with photometric redshifts, values are taken from Pozzi et al. (2007). For PKS 0537#164 the X-ray spectral fitting is prevented by the few X-ray counts; for Mrk 509#01, only an upper limit was derived (Perola et al. 2004); for PKS 0537#54, the column density is 9.3×10^{22} cm^{-2} for $z = 1.3$. Galactic absorption column densities adopted in the spectral fitting are: 8×10^{19} cm^{-2} for the field PKS 0312–77; 2×10^{20} cm^{-2} for the field Abell 2690; 2.1×10^{20} cm^{-2} for the field PKS 0537–28; 4×10^{19} cm^{-2} for the field Mrk 509; 2.5×10^{20} cm^{-2} for the field GD 158–100 (see Stark et al. 1992);
(9) rest-frame 2–10 keV absorption-corrected X-ray luminosity in units of 10^{44} erg s^{-1} from Perola et al. (2004) and from Pozzi et al. (2007) for sources with photometric redshifts. Luminosities are computed using $H_0$=70 Km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$.}

All 16 sources were clearly detected in the IRAC bands. At 24µm, 14 sources (out of 16) were detected above the 5σ level and span almost two orders of magnitude in flux, from ~7000 µJy down to the faintest source, close to the 5σ detection level (~100 µJy). For the two sources without detection, an upper limit (3σ) was estimated from the average noise of the map, derived by making multiple aperture measurements at random locations throughout the residual mosaic after source extraction. The typical average noise (1σ) is 20 µJy. At 70 and 160µm, as said before, only the brightest R-band sources were observed; among them, only the two most luminous (in the optical band) were detected, PKS 0537#43 and GD 158#19, the latter being the source described in V09. For the remaining 6 sources, an upper limit (3σ) was estimated from the residual mosaic (see also Frayer et al. 2006) after source extraction, as done at 24µm. The typical average noise (1σ) is 1.2 mJy and 8 mJy at 70 and 160µm, respectively (consistent with the results obtained in the COSMOS field from Frayer et al. 2009, taking into account the different integration time).

Table 2 reports the target flux densities provided by Spitzer. To compute uncertainties, the noise map was added in quadrature to the systematic uncertainties, assumed to be 10 per cent in the IRAC and MIPS 24µm bands and 15 per cent at 70 and 160µm (see IRAC and MIPS Data Handbook).

### 4. Modeling the spectral energy distribution

The observed optical-to-MIR (or FIR/sub-mm) SEDs can be modelled as the sum of three distinct components: a stellar component, which emits most of its power in the optical/NIR, an AGN component, whose emission peaks in the MIR for obscured quasars, and is due to hot dust heated by UV/optical radiation from gas accreting onto the central SMBH, and a star...
burst component, which represents the major contribution to the FIR spectrum. In this work, we considered all the three components (see Sec. 4.1, 4.2 and [Hatziminaoglou et al. 2008]). Since the focus of the paper is on the AGN contribution to the SED, we discuss in some more detail the hot dust modeling and its uncertainties.

The hot dust emission in AGN is reproduced using the F06 model. This model follows the formalism developed by different authors (e.g., Pier & Krolik 1992; Granato & Danese 1994; Efstathiou & Rowan-Robinson 1995), where the IR emission in AGN originates from dusty gas around the SMBH with a smooth distribution. The dust grains are heated by high-energy photons coming from the accretion disk, and their thermal and scattering re-emission, mostly at IR wavelengths, is computed by means of the radiative transfer equations. For what concerns the dust distribution geometry, different possibilities (i.e. “classical” torus shape, tapered or flared disk), are explored in the literature.

More recently, models considering a clumpy distribution for the dust have been developed (e.g., Nenkova et al. 2002; Hönig et al. 2006; Nenkova et al. 2008). These models successfully explain many recent observations in the mid-IR, such as the strength of absorption and emission features at 9.7 µm and the X-ray variability (Risaliti et al. 2002).

A further possibility to the torus models described above are the disk-wind models (see Elitzur & Shlosman 2006 and references therein), involving a completely different distance from the central source can be intercepted by the line of sight, including

### Table 2. Spitzer and SCUBA flux densities

| Source name               | 3.6µm [µJy] | 4.5µm [µJy] | 5.8µm [µJy] | 8.0µm [µJy] | 24µm [µJy] | 70µm [µJy] | 160µm [µJy] | 450µm [µJy] | 850µm [µJy] |
|---------------------------|-------------|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|
| PKS 0537#43              | 423 ± 42    | 918 ± 92    | 1750±175    | 3202 ± 320  | 6879 ± 688| 27.0±4.5  | 39.6±7.8  |           |           |
| PKS 0537#11a             | 57 ± 6      | 69 ± 7      | 95 ± 10     | 168 ± 17    | 517 ± 57  | <6.0      | <2.4      |           |           |
| PKS 0537#164             | 21 ± 2      | 18 ± 2      | 19 ± 4      | 23 ± 5      | <6.0      | <2.4      |           |           |           |
| PKS 0537#123             | 84 ± 9      | 96 ± 10     | 113 ± 13    | 165 ± 17    | 747 ± 81  | <3.6      | <2.4      |           |           |
| GD 158#62                | 60 ± 6      | 91 ± 9      | 155 ± 17    | 339 ± 35    | 1608 ± 164| <3.6      | <2.4      | <7.4      | <6.1      |
| GD 158#19                | 226 ± 23    | 387 ± 39    | 756 ± 76    | 1547 ± 155  | 5326 ± 534| 27.0±4.5  | 37.7±7.8  | <94.3      | 8.6±2.1   |
| Mrk 509#01               | 63 ± 7      | 51 ± 6      | 60 ± 11     | 59 ± 10     | <6.0      | <2.4      | <8.2      | <6.6      |           |
| Mrk 509#13               | 51 ± 6      | 69 ± 7      | 110 ± 11    | 215 ± 17    | 866 ± 94  | <3.6      | <2.4      | <7.5      | <6.2      |
| Abell 2690#75            | 51 ± 5      | 56 ± 6      | 89 ± 11     | 139 ± 15    | 565 ± 62  |           |           |           |           |
| PKS 0312#36              | 41 ± 4      | 44 ± 5      | 40 ± 8      | 710 ± 9     | 236 ± 30  |           |           |           |           |
| PKS 0537#91              | 28 ± 4      | 35 ± 4      | 42 ± 8      | 800 ± 10    | 301 ± 40  |           |           |           |           |
| PKS 0537#54              | 31 ± 4      | 35 ± 4      | 50 ± 10     | 470 ± 8     | 279 ± 45  |           |           |           |           |
| PKS 0537#111             | 88 ± 9      | 75 ± 8      | 41 ± 6      | 460 ± 7     | 148 ± 28  |           |           |           |           |
| Abell 2690#29            | 141 ± 14    | 185 ± 19    | 260 ± 27    | 371 ± 38    | 1012 ± 106|           |           |           |           |
| PKS 0312#45              | 50 ± 6      | 62 ± 7      | 69 ± 10     | 780 ± 10    | 249 ± 35  |           |           |           |           |
| BPM 16274#69             | 86 ± 9      | 92 ± 9      | 97 ± 11     | 120 ± 13    | 286 ± 34  |           |           |           |           |

The upper limits are given at the 3σ confidence level.

![Fig. 2. χ² distribution. The red hatched and the empty distributions represent the best-fitting solutions and all the solutions at 1σ, respectively. PKS 0537#43 is not reported given the high χ² value (Table 3).](image-url)
the innermost clouds, where the silicate feature is in emission given the higher temperature of the dust grains.

A systematic comparison of the two model predictions is beyond the scope of the present paper and should be performed on high-quality IR data (i.e. a Spitzer IRS spectroscopic sample).

Notwithstanding these limitations, with the present work we aim at extracting the maximum information using the available photometric data. The F06 model adopted in this work is one of the models best tested against both broad-band photometry (F06; Berta et al. 2004; Rodighiero et al. 2007; Hatziminaoglou et al. 2008, 2009; Agol et al. 2009; V09) and Spitzer mid-infrared spectra (F06). Moreover, the F06 model was the first able to reproduce the quasar mid-IR spectra, considered a very important constraint to characterize the dust properties in AGN and probe the Unified Model.

4.1. The AGN-torus component

The F06 code assumes a smooth dust distribution around the central source consisting of a Galactic mixture of silicate and graphite grains. The presence of silicate dust grains is clear from the absorption feature at 9.7 μm seen in most of Type 2 AGN. The graphite grains are, instead, responsible for the rapid decline of the emission at wavelengths shortwards of a few microns, corresponding to a blackbody emission of about 1500 K, the sublimation temperature of these grains (see F06).

The assumed dust geometry is a flared disk (see Efstathiou & Rowan-Robinson 1995.), that is a sphere with the polar cones removed. The internal radius of the dust distribution is defined in the 10−3 regime (from soft X-rays, i.e. 1.25 keV, to mid-IR) and is parameterized by broken power laws in F06. The specific indices of the power laws are adapted from the Granato & Danese (1994) and the Nenkova (2002) models and are consistent with the broad-band SEDs of a sample of Type 1 AGN from the SDSS survey (Hatziminaoglou et al. 2008; see their Figs. 8 and 9).

Along with the thermally re-processed light, the F06 provides, as a function of the line-of-sight and optical depth, the fraction of the inner accretion disk light not intercepted by the torus and the scattered light. In the following, with AGN component we will refer to the sum of all the three contributions.

4.2. The stellar and starburst components

The stellar component is modelled as the sum of Simple Stellar Populations (SSP) models of different age, all assumed to have common (solar) metallicity. A Salpeter (1955) initial mass function (IMF) with mass in the range (0.15-120 Μ⊙) is assumed. The SSP spectra have been weighted by a Schmidt-like law of star formation (see Berta et al. 2004):

$$SFR(t) = \frac{T_G - t}{T_G} \times \exp\left(-\frac{T_G - 1}{T_G \tau_H}\right)$$

where $T_G$ is the age of the galaxy (i.e. of the oldest SSP) and $\tau_H$ is the duration of the burst in units of the oldest SSP (see V09). As in Hatziminaoglou et al. (2008) and V09, a common value of extinction is applied to stars at all ages, adopting the extinction law of our Galaxy ($R_V = 3.1$; Cardelli et al. 1989).

In order to keep the number of free parameters as low as possible, emission from cold dust, which dominates the bolometric emission at wavelengths longer than 30μm rest-frame, is included only when far-IR/sub-mm data allow us to constrain that part of the SED (two sources of the sample). For the same reason, additional components, such as the cold absorber detached from the torus (i.e. Polletta et al. 2008), which might improve the fit but would increase the complexity of the overall modeling, is not included. To reproduce the starburst component, a set of semi-empirical models of well known and studied starburst galaxies is used, similarly to V09.

4.3. SED fitting procedure

The quality of the fitting solutions is measured using a standard $\chi^2$ minimization technique (as also done in Hatziminaoglou et al. (2008), where the observed values are the photometric flux densities (from optical-to-MIR/FIR) and the model values are the “synthetic” flux densities obtained by convolving the sum of stars, AGN and starburst components through the filter response curves.

Before starting the general fitting procedure, we test which torus parameters mainly influence the global model SED and are more sensitive to our data sets. Parameters which are not constrained by our data were then frozen.

The F06 torus model is described by six parameters: the ratio $R_{max}/R_{min}$ between the outer and the inner radius of the torus (the inner radius being defined by the sublimation temperature of the dust grains); the torus full opening angle $\Theta$; the optical depth $\tau$ at 9.7μm ($\tau_{9.7}$); the line of sight $\theta$ with respect to the equatorial plane, and two parameters, $\gamma$ and $\alpha$, describing the law for the spatial distribution of the dust and gas density $\rho$ inside the torus (Eq. 1).

$$\rho(r, \theta) = \rho_0 \cdot r^\alpha \cdot e^{-\gamma |\cos(\theta)|}$$

In our approach, we let free to vary, inside the pre-constructed grid of torus models the following parameters: the torus full opening angle $\Theta$, the optical depth $\tau_{9.7}$ and the parameter $\alpha$ describing the radial dependence of the density. We fix $R_{max}/R_{min}=30$, which translates into compact tori of a few tens of parsecs (given that $R_{min}$ is directly connected to the sublimation temperature and to the accretion luminosity of the central BH). Recent high-resolution IR observations support a compact dust distribution in nearby luminous AGN. Using the interferometry at VLTI in the 8-13 μm band, a torus of size ~2-3 pc was detected in NGC 1068 (Laffie et al. 2004). Similar compact tori were also found in other local AGN, as Circinus and NGC 4151 (see the review by Elitzur 2008).
Fig. 3. a. Observed-frame SEDs for 14 sources with data from the R-band to the 24µm (black dots) compared with the best-fit model obtained as the sum (solid black line) of a stellar component (red dotted line) and an AGN component (blue dashed line). The nuclear Ks-band upper limits (downward-pointing arrows) were derived from the morphological analysis carried out by Mignoli et al. (2004).

Regarding the density distribution, we allow power-law profiles decreasing with the radius with different coefficients $\alpha$. We do not allow any dependence on the distance from the equatorial plane by fixing $\gamma=0$. As a result, different angles for the lines of sight $\theta$ (with respect to the equatorial plane) give the same SED, once the torus is intercepted.

Given the F06 grid of models, the discrete values, allowed for our free parameters, are: $\Theta = [60, 100, 140^\circ]$, $\tau_{9.7} =$
5. Results from SED fitting

In Fig. 2 we show the $\chi^2$ distribution. The hatched histogram represents the distribution of the best-fitting solutions for our 16 targets, while the empty histogram shows the $\chi^2$ distribution of all the solutions within 1$\sigma$, satisfying the criteria $\chi^2<\chi^2_{\text{min}}+\Delta\chi$. Given our adopted grid for the fitted parameters, the total number of solutions at 1$\sigma$ (constructed by adding all the solutions at 1$\sigma$ of each object) is 137, 8 solutions on average per source (including the best-fitting one).

The two distributions do not show a significant difference, and this reinforces our choice of considering, in the analysis of the parameter space and degeneracy, all the solutions at 1$\sigma$ as a unique statistical sample.

In terms of the absolute values of the $\chi^2$, only 7 sources (out of 16) give a formally acceptable fit ($P(\chi^2>\chi^2_{\text{obs}})>90\%$, see Table 3); the remaining sources have a best-fit model with large $\chi^2_{\text{obs}}$. While we use the $\chi^2$ to assign a relative goodness of different parameter combinations inside the parameter grid, we will not take the absolute probabilities at face value. Overestimated $\chi^2$ are, in fact, a common problem of most SED fitting techniques, resulting from a combination of two different reasons: the limited grid of models (72 torus models with the adopted choice of parameters, see §4.3) with no uncertainties associated, and the photometric measurements with often underestimated uncertainties (see Gruppioni et al. 2008 for a detailed description of this issue).

In Fig. 3.b the observed SEDs, from the R-band to the IR (or sub-mm), are reported with the best-fitting models overplotted (solid line). All the sources need a host galaxy component (red dotted line) and an AGN one (blue long-dashed line). The stellar component dominates in the R and Ks bands, while the nuclear one at 24$\mu$m. In the IRAC bands, both components contribute, the fraction depending on the properties of the individual sources. For PKS 0537$\#43$ and G158$\#19$, where data points at longer wavelengths are available, an additional starburst component is needed (green dot-dashed line in Fig. 3b).

In Fig. 4 the relative contributions of the thermal, direct and scattered light to the total AGN light are shown for two sources characterized by a low ($\tau_{9.7}=0.1$, PKS 0537$\#123$) and a high ($\tau_{9.7}=10$, PKS 0537$\#111$) optical depth, respectively. While for $\tau_{9.7}=10$, the AGN emission is dominated by the reprocessed emission in all the UV/optical/IR bands, for $\tau_{9.7}=0.1$ the direct and scattered components account for the optical/UV AGN emission. Nevertheless, the contribution of the components mentioned above never exceeds the 20% of the observed flux in the R-band. For a sample of highly polarized red active galactic nuclei selected from the 2MASS survey, a larger contribution of the scattered nuclear component to the optical and near-IR emission was found (Cutri et al. 2002, Kuraszkiewicz et al. 2009). The different result obtained from our analysis is probably due to the different degree of obscuration of the two samples: the 2MASS sample is characterized by column densities around $10^{22}$ cm$^{-2}$, while the present sample has a median column density of $7\times10^{22}$ cm$^{-2}$.

The negligible contribution of the AGN component, relative to the stellar one, at short wavelengths, is consistent with the upper limits to the AGN emission derived by Mignoli et al.
respectively. In this Figure, the 3 different components that contribute to the AGN emission are reported: direct nuclear light (long-dashed line), scattered light (dashed-dot line) and thermally re-emitted light (dashed-dot-dot-dot line).

The finding of a preferred range of optical depths by the SED-fitting analysis, even with relatively sparse photometric data, comes from the overall shape of the NIR/MIR continuum. In fact, once the stellar component is determined by the optical/NIR data, the slope of the torus component is directly linked to the amount of absorption (i.e., to the optical depth) and is relatively well constrained by the available data.

As shown in Fig. 3ab, for the very low values of the optical depth (see bottom panel), there is a small number of solutions with high optical depths while the majority of the solutions (~80%) are characterized by 'moderate' τ9.7 (τ9.7≤5) and 50% by low τ9.7 (τ9.7≤1). The median value for τ9.7 is 2.

Regarding the density profile, about 65% of the solutions have α = 0, while α = -0.5 and α = -1.0 represent 20% and 15% of the solutions, respectively. This is reflected also in the 16 best-fitting solutions, where only 2 sources (Mrk 0509#1 and PKS 0537#111) are fitted with α = -0.5, one with α = -1.0 (PKS 0537#43), and the remaining ones with α = 0 (see Table 3).

Solutions with a moderate optical depth τ9.7 are favoured by the SED-fitting analysis. As shown in Fig. 5, there is a small number of solutions with high optical depths while the majority of the solutions (~80%) are characterized by 'moderate' τ9.7 (τ9.7≤5) and 50% by low τ9.7 (τ9.7≤1). The median value for τ9.7 is 2.

In Table 3 the χ^2 values (and the corresponding degree of freedom) of the best-fitting solutions are reported for each source.

5.1. Torus parameters

In the following section, we discuss how the model torus parameters are constrained by our data set. As anticipated, we will consider all the 137 solutions at the 1σ level.

First of all, the torus is seen almost edge-on in all the solutions (i.e., the line of sight always intercepts the obscuring material), in agreement with the Type 2 X-ray and optical classification of our sources.

The torus model parameters which are left free to vary within the grid of models are: the torus opening angle Θ, the slope α of the dust density profile and the optical depth τ9.7.

By converting the torus opening angle into a covering factor (CF) representing the fraction of solid angle covered by the dusty material, we find that solutions with high and low CF are possible, with a slight preference towards tori with large CF; the mean CF value is 0.65 (1σ~0.25), corresponding to a torus opening angle of ~110°.

According to Maiolino et al. (2007), the covering factor of the circum-nuclear dust decreases for increasing optical luminosity at 5100 Å (L5100). This relation is explained in terms of a “receding-torus”. In Maiolino et al. (2007) the luminosities at 5100 Å were derived from optical spectroscopy and the CF values from the ratios between the 6.7μm and the 5100 Å luminosities for a sample of Type 1 quasars spanning five orders of magnitude in optical luminosity. In our approach, L5100 is estimated, for each solution, from the input accretion-disk spectrum (see Sec. 4.1), once the normalization is found (see Sec. 6.1). The average value of CF and L5100 for our sample lies, within 1σ, on the relation found by Maiolino et al. (2007).

Unfortunately, given the limited range of L5100, we cannot investigate the validity of the CF vs. L5100 relation over the range probed by Maiolino et al. (2007).

Perola et al. 2004 for details and Table 1), the two independent estimates give a consistent picture for the majority of the sources, once the 1σ uncertainties, derived from the SED and X-ray fitting procedure, are taken into account. By excluding the two sources without a measured NH from the X-rays analysis.

Fig. 4. Observed-frame spectral energy distribution as in Figs. 3a,b for 2 sources characterized by extreme values of the optical depth: τ9.7mu=0.1 and 10 for PKS 0537#123 and PKS 0537#111 respectively. In this Figure, the 3 different components that contribute to the AGN emission are reported: direct nuclear light (long-dashed line), scattered light (dashed-dot line) and thermally re-emitted light (dashed-dot-dot-dot line).
analysis (see Table 1), the median values for N_H are ~7×10^{22} cm^{-2} and ~5.5×10^{22} cm^{-2}, from the X-rays analysis and the dust optical depths, respectively. Therefore, the SED-fitting method confirms the X-ray classification of the sources as moderately obscured Compton-thin AGN.

Two sources have a significantly different N_H (by an order of magnitude) derived from the two methods, PKS 0537#111 and Mrk 509#01. These objects are those characterized by the highest optical depths (τ_{9.7} = 6, 10, which are converted into N_H=5.3×10^{23} cm^{-2} and N_H=8.7×10^{23} cm^{-2}, respectively). Since Mrk 509#01 has only an upper limit for the N_H inferred from X-ray analysis (< 1.1×10^{23} cm^{-2}, see Table 1), the observed discrepancy for this object might be explained if the source is Compton-thick (N_H≥10^{24} cm^{-2}) and the observed X-ray spectrum is due to a reflection component. However, we cannot draw any firm conclusion on this issue.

5.2. Host galaxy parameters

In the spectral procedure, the host galaxy accounts for the optical/near-IR photometric data points, where the AGN contribution, given the obscured nature of our sources, is presumably low. We use the SSP spectra weighted by a Schmidt-like law of star formation (see Sec. 4.2). The extinction E(B-V) and τ_{sf} are free parameters. Once the best-fitting values for these two parameters are found, the stellar mass (obtained by integrating the star formation history over the galaxy age and subtracting the fraction due to mass loss during stellar evolution, ~ 30%, from it) is estimated from the SED normalization. At the end of the SED fitting procedure, stellar masses are well constrained, for a given pair of E(B-V) and τ_{sf}, with a typical 1σ uncertainty for the normalization of ~ 20%.

We note that all but one of the stellar masses derived in this work are within 30% from the values estimated by Pozzi et al. (2007; eight sources in common), where the same data were used but different stellar libraries and a simpler approach was adopted (see Sects. 4.1 and 5.2 of Pozzi et al. 2007).

The stellar masses found are in the range 4×10^{10} up to 5×10^{11} M_{⊙} with three very massive galaxies (> 10^{12} M_{⊙}, see Table 3), implying that our obscured AGN are hosted by massive galaxies at high redshift. As said in Sec. 4.2, the masses are obtained using a Salpeter (1955) initial mass function (IMF) with mass in the range (0.15-120 M_{⊙}). The assumption of a Chabrier (2003) IMF (see Renzini 2006) would produce a factor of ~ 1.7 lower stellar masses.

In Table 3, the best-fitting value for the free host galaxy parameters (τ_{sf} and E(B-V)) and the stellar masses are reported for each source.
6. Black hole physical properties

6.1. Black hole accretion luminosities

The accretion-disk luminosity $L_{\text{acc}}$ is a direct output of the fitting procedure and is obtained by integrating the code input energy spectrum once the best-fitting torus components and their normalization are found (see Sect. 4.3).

The input spectrum is defined in the $10^{-3}$ to 20 $\mu$m regime. Although this wavelength range provides the largest contribution to the nuclear AGN luminosity, we have also included in the $L_{\text{acc}}$ computation the hard X-ray luminosity ($L_{\text{1.25-500 keV}}$). This luminosity is estimated from the de-absorbed, k-corrected $L_{2-10 \text{keV}}$ luminosity, assuming a photon index $\Gamma=1.9$ (typical of AGN emission) and an exponential cut-off at 200 keV (e.g., Gilli et al. 2007). A different choice for the energy cut-off (e.g., at 100 keV) would produce a difference by $\approx 20\%$ in the total X-ray luminosity for $\Gamma=1.9$ sources (see Vasudevan et al. 2009).

We note that dust grains are almost transparent to hard X-ray photons, therefore the output of the code is not affected by the fact that the accretion-disk model spectrum does not extend above soft-X-ray energies.

In Table 3, $L_{\text{bol}}$, along with $L_{\text{acc}}$ and $L_{\text{1.25-500 keV}}$, are reported. $L_{\text{bol}}$ extends over two orders of magnitudes ($10^{41}$-10$^{43}$ erg s$^{-1}$), with the hard-X-ray luminosities ($1.25-500$ keV) contributing in the range 5-50% of the AGN power (see Table 3). The two sources with the highest optical depths ($\tau_{\text{9 \mu m}}=6.10$) are among the sources with the smallest hard-X-ray fraction (Mrk 509#01 and PKS 0537#111). In Table 3 we report also the range of bolometric luminosities as obtained by considering the full set of $1\sigma$ solutions. The uncertainties are, on average, of the order of 0.2 dex, but vary significantly from source to source, ranging from about 5% to about a factor 3 (see also Fig. 7).

We compare the computed bolometric luminosities with the luminosities derived by integrating the torus best-fitting templates from 0.1-1000$\mu$m (plus adding the hard X-ray luminosity for self-consistency). The two methods assume the same torus SED, hence the comparison can give important information on the systematics affecting the estimates of $L_{\text{bol}}$ derived by integrating the observed SED, which is the method widely used in literature. We refer to the first measures as the ‘model’ luminosities and to the latter as the ‘observed’ luminosities.

The ‘observed’ $L_{\text{bol}}$ (see Fig. 6) are lower (up to an order of magnitude) than the ‘model’ ones for all the solutions; the median value of the ratio is $R=2$ (the solid line in Fig. 6 represents the identity relation). An under-estimate of the luminosity in Type 2 sources is expected by torus models (e.g., Pier & Krolik 1992; Granato & Danese 1994); here, we quantify this effect and provide an empirical factor to correct the ‘observed’ luminosities, at least for this class of sources.

We underline how the observed discrepancy does not depend on the lack of observations at far-IR wavelengths. In fact, the two methods assume the same torus SED for self-consistency (i.e., the integrated torus SED to estimate the observed IR luminosity is the output of the code); under this hypothesis, an over(under)-estimate on one luminosity would introduce the same effect on the other. As a result, a poor sampling in the far-IR would have the same impact on both (i.e., ‘observed’ and ‘model’) luminosities. Our analysis takes into account this uncertainty by considering all the solutions (i.e., all torus models) at the $1\sigma$ confidence level. By means of this procedure, a broad range of model SED is associated to each source (on average, eight solutions; see Sec. 5), characterized by different emission in the mid/far-IR region, as a result of different torus geometry and absorption properties (see Fig. 3).

As explained in Pier & Krolik (1992), the low values of the ‘observed’ $L_{\text{bol}}$ depend on a combination of three factors: the torus opening angle $\Theta$ (geometrical factor), the observer viewing angle $\theta$ and the torus optical thickness $\tau_{\text{9 \mu m}}$. By erroneously assuming isotropic torus emission (as done to compute the ‘observed’ $L_{\text{bol}}$), the primary flux which does not intercept the obscuring material would not be included in the luminosity budget; moreover, as the thickness of the torus increases, more and more primary high-energy photons entering the torus are absorbed by the dust grains and re-emitted isotropically (hence also in directions escaping the torus itself). This effect is explained by the dust self-absorption, i.e., thermal dust emission absorbed by the dust itself. For high optical depth, the outer edges of the torus absorb the IR photons coming from the warmer dust at smaller radii and re-emit them isotropically, i.e. also in directions outside the line of sight. To better visualize this effect, we report in Fig. 6 the ‘observed’ versus ‘model’ luminosities, as predicted by Pier & Krolik (1992), as a function of the viewing angle $\theta$ and the torus optical thickness $\tau_{\text{9 \mu m}}$ for 4 sets of Type 2 configurations (as described in Fig. 6 caption).

Although there are some slight differences between the F06 model (adopted here) and the Pier & Krolik (1992) torus model (where the optical depth varies independently along the radial and the vertical axis), optically thinner models show less anisotropy (red dotted lines in Fig. 6 corresponding to two different viewing angles), than higher $\tau_{\text{9 \mu m}}$ models (blue dashed lines in Fig. 6 corresponding to the same viewing angles considered for the thinner model). The cold outer edges of the thicker models, in fact, radiate little and block the light coming from the inner torus radii.

To investigate these issues further, we apply a ‘conservative’ correction to our ‘observed’ luminosities, meant to correct only for the geometrical factor; in other words, we divided each ‘observed’ luminosity by the corresponding covering factor CF ($\sim$0.58 for $\approx 100^\circ$ and $\sim$0.88 for $\approx 140^\circ$). Although this correction increases the ‘observed’ luminosities, the ‘model’ ones are still higher ($R \sim 1.6$); the remaining discrepancy is mostly found for solutions with high optical depth, as expected ($R \sim 5$ for models with $\tau_{\text{9 \mu m}} \geq 3$; see Fig. 6 where the squares mark the 52 solutions with $\tau_{\text{9 \mu m}} \geq 3$).

An independent and consistent analysis was done also by Pozzi et al. 2007 (see their §5.1) where a first-order correction of $\sim 2$ to the ‘observed’ luminosities was estimated, accounting for geometrical and anisotropy effects; in that work, however, the correction was estimated using the ratio of obscured/unobscured quasars according to the Gilli et al. 2007 AGN synthesis models of the X-ray background and the different shape of Type 2 vs. Type 1 quasar SEDs as a function of the column density. In Pozzi et al. 2007, the SED fitting was done
Fig. 7. 2–10 keV bolometric corrections as a function of the ‘model’ bolometric luminosities (filled circles). Filled circles inside empty red squares represent the sources with a spectroscopic redshift. The red solid and dot-dashed lines represent the predictions from the Marconi et al. (2004) relation and its 1σ dispersions. Also the expectations from Hopkins et al. (2007) are reported as empty blue triangles. The red dotted line represents the Marconi et al. (2004) expectations at 5σ from the best-fitting relation.

using the Silva et al. (2004) AGN templates. Since the template choice was based on the X-ray N_H (and not on the N_H resulting from the torus modelling as in the present analysis), the correction corresponding to the thicker models (N_H > 10^{24} cm^{-2}) were not included since no Compton-thick objects were revealed in X-rays.

6.2. Hard X-ray bolometric corrections

In Fig. 7 the bolometric-to-X-ray luminosity ratio (k_{2–10keV}) as a function of L_{bol} is shown: for the bolometric luminosities we assume the model ones. The error bars on k_{2–10keV} are derived from the 1σ dispersion on L_{bol}.

A large spread in the k_{2–10keV} is found (6 < k_{2–10keV} < 80), as pointed out also by the pioneering work of Elvis et al. (1994) on Type 1 QSOs, due to the large dispersion in the AGN spectral shape. Our median value (k_{2–10keV} = 20, estimated on the 137 solutions), is marginally consistent with the mean value of Elvis et al. (1994), ~25 after removing the IR contribution (in order to not double-count the fraction of the nuclear emission absorbed by the circumnuclear dusty material seen almost face-on). We confirm the trend of higher k_{2–10keV} for objects with higher bolometric luminosities as predicted by Marconi et al. (2004) (red solid line in Fig. 7; red dot-dashed lines representing the 1σ model dispersion), but our k_{2–10keV} values are significantly lower (at least a factor 2 in normalization). They derive k_{2–10keV} by constructing an AGN reference template taking into account how the spectral index α_{ox} varies as a function of the luminosity (Vignali et al. 2003). Predictions consistent with Marconi et al. (2004) were obtained more recently by Hopkins et al. (2007, blue triangles in Fig. 7), considering the most recent determination of SED templates (i.e. Richards et al. 2006) and α_{ox} (i.e. Steffen et al. 2006).

Our low values for k_{2–10keV} are consistent with our previous analysis (median k_{2–10keV} ~ 25, Pozzi et al. 2007) based on a different method and on different AGN templates (Silva et al. 2004) and with other estimates found in literature for hard X-ray selected samples. Kuraskiewicz et al. (2003), considering a sample of X-ray selected luminous AGN (10^{43} < L_{2–10keV} < 10^{46} erg sec^{-1}) found a median k_{2–10keV} of 18; Ballo et al. (2007), analysing a sample of low-luminosity AGN (10^{42} < L_{2–10keV} < 10^{43.6} erg sec^{-1}), found a median k_{2–10keV} of 12. Low bolometric-to-X-ray ratios, consistent with our estimate (median k_{2–10keV} ~ 25, 1σ=53) were found recently by Lusso et al. (2009), where the statistical properties of a large (and complete) sample of 545 X-ray selected Type 1 QSO from the XMM-COSMOS survey (Hasinger et al. 2007) are presented.

The lower bolometric-to-X-ray luminosity ratios found in the present work (and in the above mentioned samples), in comparison to the Marconi et al. (2004) and Hopkins et al. (2007) predictions, are probably caused by a selection bias, since our sample (and most of the above cited ones) are hard-X-ray selected samples (i.e., sources with high X-ray luminosity are favored). Moreover, as discussed in § 2 our sources are among the most extreme X-ray sources, being characterized by red optical-to-NIR colours (R-K_s > 5) and high X-ray-to-optical ratio (X/O > 1). Our selection is likely the origin of the large deviation (at about the 5σ level) for a large fraction of the present sample (see Fig. 7 from the Marconi et al. (2004) relation. To further explore this issue, a larger (and complete) sample of X-ray sources (with optical identification up to the faintest X-ray fluxes) is needed, in order to correct for the selection bias and to derive the properties of the parent AGN population (see Lusso et al. 2009).

6.3. Black hole masses

The BH masses are not a direct output of the best-fitting procedure and cannot be derived using ‘standard methods’ (i.e. galaxy stellar kinematics, nuclear gas motions, reverberation). We estimate them indirectly using the Marconi & Hunt (2003), by assuming as M_{BH} the stellar mass derived from our best-fitting procedure. The main uncertainties affecting these estimates derive from the extrapolation of the local relation to higher z, where the behaviour of this relation is still a matter of debate (see discussion in Pozzi et al. 2007). As far as the stellar masses are concerned, they are quite well constrained by the SED-fitting procedure inside the pre-constructed grid of galaxy models (see Sec. 5.2).

The inferred black hole masses are typically in the range 10^{8} – 10^{10} M_{⊙}, with three sources (PKS 0537#/43, GD 158#/19, Abell 2690#/29) with higher masses (M_{BH} ~ 10^{9.5} – 10^{10} M_{⊙}).

The range of BH masses is consistent with the values reported by McLure & Dunlop (2004) for the SDSS quasars in the same redshift interval (0.9 < z < 2.1, see also Shen et al. 2008, where new BH masses are derived).
The Eddington ratios $\lambda_{Edd}$, defined as $\lambda_{Edd} = L_{bol}/L_{Edd}$ (with $L_{Edd} = 1.38 \times 10^{38} M_{BH}/M_\odot$), are reported as a function of redshift. The values are compared with those of the whole SDSS quasar sample (small grey crosses, McLure & Dunlop 2004) and those obtained by Lusso et al. (2009) for the sub-sample of 150 X-ray selected Type 1 AGN in COSMOS with an accurate black hole mass determination (blue triangles).

The $\lambda_{Edd}$ values of the present work cover slightly more than an order of magnitude (0.01-0.3), with a median value of $\lambda_{Edd} \sim 0.08$ (estimated considering all the 137 solutions at 1σ level, see Sec. 5). The derived values are within the 3σ confidence interval of the SDSS quasar $\lambda_{Edd}$ distribution, characterized by a median value of $\sim 0.3$ and with a dispersion of 0.35 dex at the same redshift interval sampled by our sources. However, almost all our data points lie towards the low $\lambda_{Edd}$ tail of the SDSS distribution (see Fig. 8), suggesting that X-ray selection is biased towards slightly lower $\lambda_{Edd}$ than optical selection. Our data are fully consistent with the results obtained from a much larger sample of X-ray selected Type 1 AGN in the COSMOS field (Lusso et al. 2009).

The results are robust against the uncertainties on the extrapolation, discussed above, of the local $M_{\text{bulge}} - M_{BH}$ relation, at the redshift of our sample. In fact, allowing for positive evolution with redshift of the $M_{BH}/M_{\text{bulge}}$ ratio by a factor of 2 (e.g., Hopkins et al. 2006, Shields et al. 2006, Merloni et al. 2010), the Eddington ratios $\lambda_{Edd}$ would decrease further by the same factor.

Finally, in Fig. 9 the bolometric corrections $k_{2-10keV}$ are plotted against the Eddington ratios $\lambda_{Edd}$ (following Vasudevan & Fabian 2009). The sources of the present work are reported as black filled circle (the error bars representing the 1σ confidence interval derived from the uncertainties on $L_{bol}$). Along with our data we show the Vasudevan & Fabian (2009) results, where simultaneous optical, UV and X-ray observations are included for the majority of the Peterson et al. (2004) reverberation mapped sample of AGN (blue empty circles). Our findings are in fairly good agreement with the trend of increasing $k_{2-10keV}$ for increasing $\lambda_{Edd}$. Vasudevan & Fabian (2009) interpret the observed trend as due to different black hole SED shape as a function of the Eddington ratio, with the high and low Eddington ratios corresponding to different fractions of the ionizing UV luminosity. A similar trend was recently found for a sample of 63 Type 1 and Type 2 AGN detected in the Swift/BAT 9-months catalog (see Vasudevan et al. 2009). At variance with the assumption in Vasudevan & Fabian (2009), where the bolometric luminosities were derived by integration over the observed optical/UV/X-ray SED, in this work the authors consider the reprocessed IR emission, reproduced by the empirical SEDs of Silva et al. (2004), as a proxy of the intrinsic AGN bolometric luminosity, as firstly suggested by Pozzi et al. (2007).

The dependence of bolometric corrections on Eddington ratios is expected by accretion-disk models, which predict an increasing hard X-ray bolometric corrections at increasing accretion rates (e.g. Witt et al. 1997). Recently also Bianchi et al. (2009), studying a large (156 sources) sample of Type 1 X-ray AGN from the XMM-Newton archive suggest that the bolometric correction must depend on Eddington ratio in order to allow the intrinsic power of AGN to scale linearly with black hole masses.

7. Summary

We analyzed the SEDs of a sample of 16 obscured quasars selected in the hard X-ray band. Spitzer mid/far-IR photometry (IRAC and MIPS), along with the data available in the literature, is modeled using a multi-component model, where the AGN re-processed emission is reproduced in the context of a flared disk model, as described by F06. Within the context of a flared disk torus model, the uncertainty in and degeneracy between the various derived parameters are accounted for by including all solutions within 1σ of the best- fit in the subsequent analysis.

The main results are summarized below:

- All the 16 quasars are detected up to 8 µm and all, but two sources, are detected at 24µm with flux densities in the range 100-7000 µJy at the 3σ level. The two most luminous sources of the sample are detected also at 70 and 160 µm.

- The observed broad-band spectral energy distributions are well reproduced by a multi-component model comprising a stellar, an AGN and a starburst components (when far-IR detections are available). The AGN component, modelled
| Source Name | α | τ9.7µm | Θ | L2−10 keV | L1.25−500 keV | Lbol/L2−10 keV | Lbol | Log(Lbol/Ledd) | Mgalaxy | Mbh | Ledd/Lbol |
|-------------|---|--------|----|-----------|-------------|--------------|------|---------------|--------|-----|----------|
| PKS 0312#36 | 9.6/5 | 0.0 | 0.1 | 140 | 0.85 | 0.79 | 3.0 | 2.5 | 0.7 | 2.7 | 5.7 [5.7-8.1] | 8.2 | 0.43 | 0.11 | 0.043 |
| PKS 0537#91 | 2.9/5 | 0.0 | 3.0 | 0.25 | 0.3 | 66.0 | 23.7 | 8.1 | 31.4 | 98.3 [40.2-326] | 12.1 | 1.48 | 0.35 | 0.224 |
| PKS 0537#54 | 2.9/5 | 0.0 | 0.1 | 140 | 0.05 | 0.17 | 5.6 | 4.6 | 2.0 | 7.8 | 13.3 [13.3-25.8] | 6.7 | 1.72 | 0.40 | 0.026 |
| PKS 0537#111 | 11.4/5 | -0.5 | 10.0 | 0.05 | 0.31 | 103.1 | 13.4 | 1.7 | 6.6 | 110 [34.1-110] | 64.4 | 4.61 | 1.03 | 0.084 |
| Abell 2690#29 | 0.5/2 | 0.0 | 1.0 | 0.15 | 0.55 | 168.8 | 94.7 | 8.4 | 32.6 | 201 [135-264] | 23.9 | 17.9 | 3.80 | 0.042 |
| PKS 0312#45 | 0.5/5 | 0.0 | 0.1 | 100 | 0.25 | 0.48 | 24.25 | 11.3 | 6.2 | 24.0 | 48.3 [37.4-239] | 7.8 | 3.61 | 0.81 | 0.047 |
| BPM 16274#69 | 0.5/5 | 0.0 | 0.6 | 140 | 0.05 | 0.25 | 11.4 | 7.3 | 2.4 | 9.3 | 20.7 [18.2-56.6] | 8.6 | 4.68 | 1.05 | 0.016 |

(1) source name
(2) best-fitting minimum $\chi^2 (\chi^2_{\text{min}})$ and number of parameters to be fitted (degrees of freedom);
(3), (4), (5) best-fitting torus parameters ($\alpha$: exponent of the power law parameterizing the density profile; $\tau_{9.7\mu m}$: 9.7 $\mu m$ optical depth, $\Theta$: torus opening angle). The ratio parameter $R_{\text{max}}/R_{\text{min}}$ is frozen to 30; the density parameter $\gamma$ is frozen to 0;
(6), (7) best-fitting stellar parameters ($\tau_{s f}$: duration of the exponential decay of the burst in units of the oldest SSP; $E(B - V)$: extinction);
(8) accretion-disk model luminosity, $L_{\text{acc}}$ (from soft X-ray to IR frequencies) which represents the torus model input luminosity, in units of $10^{44}$ erg s$^{-1}$;
(9) integrated (1-1000$\mu m$) torus luminosity in units of $10^{44}$ erg s$^{-1}$ (not corrected, see [6.1]);
(10) absorption-corrected 2–10 keV luminosity in units of $10^{44}$ erg s$^{-1}$;
(11) hard-X-ray (1.25-500 keV) luminosity in units of $10^{44}$ erg s$^{-1}$ (derived from the 2–10 keV luminosity, see [6.2]);
(12) bolometric AGN luminosity ($L_{\text{acc}} + L_{1.25-500 keV}$) in units of $10^{44}$ erg s$^{-1}$; the 1$\sigma$ range derived from the SED-fitting analysis is reported;
(13) 2–10 keV bolometric correction ($L_{\text{bol}}/L_{2-10 keV}$);
(14) galaxy mass in units of $10^{11}$ M$_{\odot}$;
(15) black hole masses in units of $10^{9}$ M$_{\odot}$ (estimated from Marconi & Hunt 2003 relation);
(16) Eddington ratios ($L_{\text{bol}}/L_{\text{Edd}}$).
with the F06 radiative transfer code, accounts for the X-ray emission and for a fraction of the IR emission, mainly due to reprocessed emission from the putative dusty torus surrounding the central black hole.

- Solutions with a moderate optical depth \( \tau_{9.7} \) are favoured by the SED-fitting, with the majority of the sources having moderate optical depths (\( \tau_{9.7} \leq 3 \)). The derived gas column densities (\( N_H \)) are consistent, for most of the sources, with the values estimated from the X-ray analysis, both indicating that the sources are Compton-thin AGN (\( N_H \sim 10^{22} - 3 \times 10^{23} \text{cm}^{-2} \)).

- The model nuclear bolometric luminosities are in the range \( 5 \times 10^{44} - 4 \times 10^{46} \text{ erg s}^{-1} \). By comparing these values with those obtained by the integration of the nuclear observed SED, we conclude that the latter under-estimate the bolometric luminosities by a factor of 2. The difference may be explained by anisotropic torus emission and the effect of the torus optical depth (e.g., Pier & Krolik 1992).

- From the model nuclear SEDs, we estimate the bolometric-to-X-ray corrections (\( k_{2-10 \text{keV}} \)). The median \( k_{2-10 \text{keV}} \) is \( \sim 20 \) (6\% \( k_{2-10 \text{keV}} \sim 80 \)). The value is smaller than assumed by some models of BH evolution (\( k_{2-10 \text{keV}} \sim 40 \) at the median luminosity of our sample). The discrepancy is significant at 5\( \sigma \) level at low bolometric luminosity.

- By assuming the local \( M_{\text{bulge}} - M_{\text{BH}} \) relation, we estimate \( \lambda_{\text{Edd}} \) with a median value of 0.08 (0.01\% \( \lambda_{\text{Edd}} \sim 0.3 \)). The whole SDSS quasar sample, at the same redshift interval sampled by our objects, is characterized by a median value of 0.3. Our data are within the 3\( \sigma \) confidence level of the optically selected quasar distribution. However, almost all our sources lie towards the low \( \lambda_{\text{Edd}} \) tail of the SDSS distribution, suggesting that our X-ray selection is biased towards lower Eddington efficiencies than optical selection.

- The data are consistent with the correlation recently suggested by Vasudevan & Fabian (2007, 2009) between \( k_{2-10 \text{keV}} \) and \( \lambda_{\text{Edd}} \), where low bolometric corrections are found at low Eddington ratios.

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References

Agol, E., Gogarten, S. M., Gyorjian, V., & Kimball, A. 2009, ApJ, 697, 1010
Baldi, A., Molendi, S., Comastri, A., et al. 2002, ApJ, 564, 190
Ballo, L., Cristiani, S., Pasano, G., et al. 2007, ApJ, 667, 97
Berta, S., Fritz, J., Franceschini, A., Bressan, A., & Lonsdale, C. 2004, A&A, 418, 913
Bianchi, S., Bonilla, N. F., Guainazzi, M., Matt, G., & Ponti, G. 2009, A&A, 501, 915
Brusa, M., Comastri, A., Daddi, E., et al. 2005, A&A, 432, 69
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chabrier, G. 2003, PASP, 115, 763
Cocchia, F., Fiore, F., Vignali, C., et al. 2007, A&A, 466, 31
Dullemond, C. P. & van Bemmel, I. M. 2005, A&A, 436, 47
Efstathiou, A. & Rowan-Robinson, M. 1995, MNRAS, 273, 649
Elitzur, M. 2008, New Astronomy Review, 52, 274
Elitzur, M. & Shlosman, I. 2006, ApJ, 648, L101
Elvis, M., Wilkes, B. J., McDowell, J. C., et al. 1994, ApJS, 95, 1
Fabian, A. C. 1999, MNRAS, 308, L39
Fadda, D., Marleau, F. R., Storrie-Lombardi, L. J., et al. 2006, AJ, 131, 2859
Fiore, F., Brusa, M., Cocchia, F., et al. 2003, A&A, 409, 79
Fiore, F., Grazian, A., Santini, P., et al. 2008, ApJ, 672, 94
Frayer, D. T., Hynh, M. T., Chary, R., et al. 2006, ApJ, 647, L9
Frayer, D. T., Sanders, D. B., Surace, J. A., et al. 2009, ArXiv e-prints
Fritz, J., Franceschini, A., & Hatziminaoglou, E. 2006, MNRAS, 366, 767 (F06)
Gilli, R., Comastri, A., & Hasinger, G. 2007, A&A, 463, 79
Granato, G. L. & Danese, L. 1994, MNRAS, 268, 235

Fig. 9. \( k_{2-10 \text{keV}} \) as a function of \( \lambda_{\text{Edd}} \). Black filled symbols: sources of the present sample. Red squares as in Fig.7. The error bars represent the 1\( \sigma \) uncertainties on \( L_{\text{bol}} \) (as derived from the \( \chi^2 \) analysis) which affect both the \( k_{2-10 \text{keV}} \) and the \( \lambda_{\text{Edd}} \) values. Blue open symbols: sources from Vasudevan & Fabian (2009).
