

# The cosmological properties of AGN in the *XMM-Newton* Hard Bright Survey<sup>★,★★</sup>

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## ABSTRACT

**Aims.** We investigate here the X-ray luminosity function (XLF) of absorbed ( $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $10^{24}$   $\text{cm}^{-2}$ ) and unabsorbed ( $N_{\text{H}} < 4 \times 10^{21}$   $\text{cm}^{-2}$ ) AGN, the fraction of absorbed AGN as a function of  $L_{\text{X}}$  (and  $z$ ), the intrinsic  $N_{\text{H}}$  distribution of the AGN population, and the XLF of Compton thick ( $N_{\text{H}} > 10^{24}$   $\text{cm}^{-2}$ ) AGN.

**Methods.** To carry out this investigation, we have used the *XMM-Newton* Hard Bright Serendipitous Sample (HBSS), a complete sample of bright X-ray sources ( $f_{\text{x}} \gtrsim 7 \times 10^{-14}$   $\text{erg cm}^{-2} \text{s}^{-1}$ ) at high galactic latitude ( $|b| > 20^\circ$ ) selected in the 4.5–7.5 keV energy band. The HBSS sample is now almost completely identified (97% spectroscopic identifications) and it can be safely used for a statistical investigation. The HBSS contains 62 AGN out of which 40 are unabsorbed (or marginally absorbed;  $N_{\text{H}} < 4 \times 10^{21}$   $\text{cm}^{-2}$ ) and 22 are absorbed ( $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $\sim 10^{24}$   $\text{cm}^{-2}$ ).

**Results.** Absorbed and unabsorbed AGN are characterised by two different XLF with the absorbed AGN population being described by a steeper XLF, if compared with the unabsorbed ones, at all luminosities. The intrinsic fraction  $F$  of absorbed AGN (i.e., the fraction of sources with  $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $10^{24}$   $\text{cm}^{-2}$  divided the sources with  $N_{\text{H}}$  below  $10^{24}$   $\text{cm}^{-2}$ , corrected for the bias due to the photoelectric absorption) with  $L_{2-10 \text{ keV}} \gtrsim 3 \times 10^{42}$   $\text{erg s}^{-1}$  is  $0.57 \pm 0.11$ ; we find that  $F$  decreases with the intrinsic luminosity, and probably, increases with the redshift. Our data are consistent with a flat Log  $N_{\text{H}}$  distribution for  $N_{\text{H}}$  between  $10^{20}$  and  $10^{24}$   $\text{cm}^{-2}$ . Finally, by comparing the results obtained here with those obtained using an optically-selected sample of AGN we derive, in an indirect way, the XLF of Compton thick AGN; the latter is well described by a XLF similar, in shape, to that of absorbed AGN, but having a normalization of about a factor of 2 above. The density ratio between Compton thick AGN ( $N_{\text{H}} \geq 10^{24}$   $\text{cm}^{-2}$ ) and Compton thin AGN ( $N_{\text{H}} \leq 10^{24}$   $\text{cm}^{-2}$ ) decreases from  $1.08 \pm 0.44$  at  $\sim 10^{43}$   $\text{erg s}^{-1}$  to  $0.57 \pm 0.22$  at  $\sim 10^{44}$   $\text{erg s}^{-1}$  to  $0.23 \pm 0.15$  at  $\sim 10^{45}$   $\text{erg s}^{-1}$ .

**Conclusions.** The results presented here on the anti-correlation between  $F$  and  $-L_{\text{x}}$  are fully consistent with the hypothesis of a reduction of the covering factor of the gas as a function of the luminosity and are clearly inconsistent with the simplest unified scheme of AGN. These results strongly support the recently proposed radiation-limited clumpy dust torus model although alternative physical models are also consistent with the observations.

**Key words.** surveys – galaxies: active – galaxies: evolution – X-rays: diffuse background – X-ray: galaxies – quasars: general

## 1. Introduction

For many years the study of the cosmological and statistical properties (e.g. luminosity function, cosmological evolution, mean spectral properties) of active galactic nuclei (AGN) was principally limited to the optical (see, e.g., Boyle et al. 1988; Croom et al. 2004) or soft X-rays (see e.g. Maccacaro et al. 1991; Della Ceca et al. 1992; Miyaji et al. 2001; Hasinger et al. 2005) bands and essentially dealt with complete and unbiased samples of optically-unabsorbed (type 1) AGN. Indeed the selection and identification of sources hosting obscured accreting nuclei is a difficult task: in the optical domain, the active nuclei

appear very dim and their luminosity could be comparable to that of their host galaxies, while in the soft X-ray band (up to few keV) their selection is difficult since even hydrogen column densities ( $N_{\text{H}}$ ) of the order of  $10^{21}$ – $10^{22}$   $\text{cm}^{-2}$  strongly reduce the flux from the nuclear source.

However, despite their elusiveness, obscured AGN are fundamental for our understanding of the history of super-massive black holes (SMBHs) as the large majority of the energy density generated by accretion of matter in the Universe seem to take place in obscured AGN (Fabian et al. 1998), as testified by the integrated energy density contained in the cosmic X-ray background (XRB; Setti & Woltjer 1989; Madau et al. 1994; Comastri et al. 1995; Gilli et al. 2007). Even more important, the discovery of quiescent SMBH in the nuclei of non-active nearby galaxies with prominent bulges (Kormendy & Richstone 1995; Magorrian et al. 1998), along with the presence of scaling relations between the central BH mass and galaxy properties

\* Appendix A is only available in electronic form at <http://www.aanda.org>

\*\* Table 1 is only available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](http://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/487/119>

(e.g., bulge luminosity/mass and velocity dispersion, Ferrarese & Merritt 2000) strongly suggest that AGN are leading actors in the formation and evolution of galaxies and, in general, of cosmic structures in the Universe (see Begelman 2004, and references therein). Missing a large fraction of the AGN population could thus bias our understanding of the evolution of cosmic structure in the Universe.

Hard X-rays (photon energies between a few keV and  $\sim 10$  keV) can directly probe AGN activity, since they are almost uncontaminated by star formation processes at the X-ray luminosities of interest ( $L_X \gtrsim 10^{42}$  erg s $^{-1}$ ), and they are sensitive to absorbed AGN up to an intrinsic absorbing column density of  $N_H \sim 10^{23.5-24}$  cm $^{-2}$ , that is to say, they detect all but the most absorbed sources. Thus, hard X-ray surveys in the 2–10 keV range, as pioneered by ASCA and BeppoSAX (Cagnoni et al. 1998; Ueda et al. 1998; Della Ceca et al. 1999; Fiore et al. 1999; Ueda et al. 2003), and now routinely performed with *Chandra* and *XMM-Newton*<sup>1</sup>, provide among the most complete and unbiased samples of AGN presently possible (although they still miss Compton thick sources, i.e., the sources with absorbing column densities  $\geq 10^{24}$  cm $^{-2}$ ). In spite of this, a significant fraction of the AGN found in medium and deep fields is too faint to provide good X-ray spectral information. Furthermore, the extremely faint magnitudes of a large number of optical counterparts of these X-ray faint sources make the spectroscopic identifications very difficult, or even impossible, with the present day ground-based optical telescopes.

Here we use the bright ( $f_X \gtrsim 10^{-13}$  erg cm $^{-2}$  s $^{-1}$ ), hard (4.5–7.5 keV selection band), almost completely identified (97% spectroscopic ID) *XMM-Newton* Hard Bright Serendipitous Sample (HBSS) to discuss a few issues that are currently the subject of intense research activity, namely: a) the statistical properties (e.g. X-ray luminosity functions) of absorbed and unabsorbed AGN; b) the intrinsic ratio of absorbed and unabsorbed AGN as a function of the X-ray luminosity; c) the intrinsic absorption column density distribution of the AGN population for hydrogen column density up to  $\sim 10^{24}$  cm $^{-2}$ ; and d) the X-ray luminosity function of Compton thick AGN. These are fundamental issues both to study and to follow the accretion history in the Universe and to test the unification models of AGN. We stress that the high identification rate of the HBSS sample is fundamental to investigating these issues since interesting and important classes of X-ray emitting sources (e.g. the type 2 QSOs) could be more difficult to identify, and therefore, could be under-represented even in samples with an identification rate of the order of 90%. Furthermore, good optical and X-ray spectral data are available for almost all the sources in the HBSS sample. In particular, the results of a complete X-ray spectral analysis will be efficiently used here to separate absorbed AGN from the unabsorbed ones and to compute  $k$ -corrections.

This paper is organized as follows: in Sect. 2, we give a short account of the *XMM-Newton* Bright Survey (XBS, hereafter) and a description of the AGN sample selected in the 4.5–7.5 keV range (the HBSS AGN sample). In Sect. 3, we study the cosmological evolution properties of the HBSS AGN sample and derive the X-ray luminosity function (XLF) of the total AGN population as well as the XLF of absorbed and unabsorbed AGN separately. The intrinsic fraction of absorbed AGN as a function of the X-ray luminosities is discussed in Sect. 4, while in Sect. 5

we discuss the intrinsic  $N_H$  distribution of the AGN population. In Sect. 6, we compare our results with the prediction of AGN unification models. In Sect. 7, we compare our results on the intrinsic fraction of absorbed AGN as a function of luminosity with those obtained using an optically-selected sample of AGN; this comparison will be used to estimate the luminosity function of Compton thick AGN and to derive the ratio between Compton thick and Compton thin AGN as a function of  $L_X$ . Finally, summary and conclusions are reported in Sect. 8. In Appendix A, we discuss the method used to take into account the photoelectric absorption in the computation of the luminosity functions. Throughout this paper, we consider the cosmological model with  $(H_0, \Omega_M, \Omega_\Lambda) = (65, 0.3, 0.7)$ ; results from other papers have been rescaled to this cosmological framework.

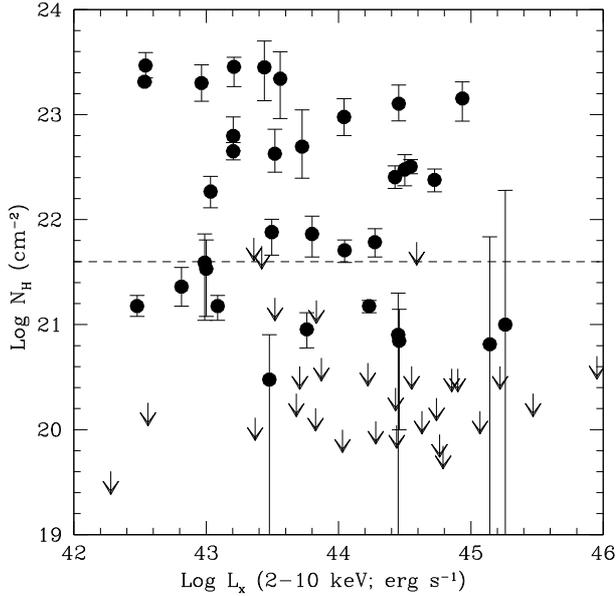
## 2. The XBS and the HBSS AGN sample

The *XMM-Newton* HBSS used here is part of a bigger survey project known as XBS<sup>2</sup>. This latter consists of two flux-limited serendipitous samples of X-ray selected sources at high galactic latitude ( $|b| > 20^\circ$ ): the XMM BSS sample (389 sources) and the XMM HBSS sample (67 sources, with 56 sources in common with the BSS sample) having an EPIC MOS2 count rate limit, corrected for vignetting, of  $10^{-2}$  cts/s ( $2 \times 10^{-3}$  cts/s) in the 0.5–4.5 keV (4.5–7.5 keV) energy band; the flux limit is  $\sim 7 \times 10^{-14}$  erg cm $^{-2}$  s $^{-1}$  in both energy selection bands. At the time of this writing the spectroscopic identification rate is 87% for the BSS sample and 97% for the HBSS sample. The details on the *XMM-Newton* fields selection strategy and the source selection criteria of the XMM BSS and HBSS samples are discussed in Della Ceca et al. (2004), while a description of the optical data and analysis, of the optical classification scheme, and of the optical properties of the extragalactic sources identified so far, is presented in Caccianiga et al. (2008). The optical and X-ray properties of the galactic population are discussed in López-Santiago et al. (2007).

Since the HBSS sample is now almost completely identified it will be used in this paper for a statistical investigation. We note that among the ongoing surveys performed with *Chandra* and *XMM-Newton*, the HBSS currently covers one of the largest areas ( $\sim 25$  deg $^2$ ) and, unlike deep pencil beam surveys, is unbiased by problems connected to the cosmic variance. The current classification breakdown of the HBSS sample is as follows: 62 AGN, 1 cluster of galaxies (XBS J 141830.5+251052), and 2 X-ray emitting stars (XBS J 014100.6-675328 and XBS J 123600.7-395217). Two X-ray sources (XBS J 080411.3+650906 and XBS J 110050.6-344331) are still unidentified at the time of this writing. The redshift of the 62 AGN are reported in Table 1 along with their basic X-ray spectral properties, which will be used in this paper (e.g., photon index, intrinsic absorbing column density  $N_H$ , intrinsic 2–10 keV luminosity). A full account of the X-ray spectral properties for all the sources in the *XMM-Newton* Bright Survey will be reported in a forthcoming paper.

<sup>2</sup> The XBS is one of the research programs conducted by the *XMM-Newton* Survey Science Center (SSC, see <http://xmmssc-www.star.le.ac.uk>), a consortium of 10 international institutions, appointed by the European Space Agency (ESA) to help the *XMM-Newton* Science Operations Centre (SOC) in developing the software analysis system, to pipeline process all the *XMM-Newton* data, and to exploit the *XMM-Newton* serendipitous detections. The *Osservatorio Astronomico di Brera* is one of the Consortium Institutes.

<sup>1</sup> A compilation of the main extragalactic surveys executed with *Chandra* and *XMM-Newton* is reported at the web address <http://cxc.harvard.edu/xraysurveys/>



**Fig. 1.** Intrinsic 2–10 keV luminosity versus intrinsic absorption column densities  $N_{\text{H}}$  (both quantities derived from a complete X-ray spectral analysis) for the AGN belonging to the HBSS sample (filled circles: objects for which we have measured the  $N_{\text{H}}$ ; downward arrows: objects for which we have only an upper limit on  $N_{\text{H}}$ ).

### 2.1. Absorption properties

The intrinsic 2–10 keV luminosities versus intrinsic absorption column densities for the HBSS AGN sample are shown in Fig. 1. We have directly measured the intrinsic absorbing column density for 34 AGN, while for the remaining 28 AGN we have only an upper limit. However, the measured upper limits are such that we can easily divide the sample into absorbed and unabsorbed AGN, using a value of  $N_{\text{H}} = 4 \times 10^{21} \text{ cm}^{-2}$ . Assuming a Galactic  $A_{\text{V}}/N_{\text{H}}$  ratio of  $5.27 \times 10^{-22} \text{ mag cm}^{-2}$  (Bohlin et al. 1978),  $N_{\text{H}} = 4 \times 10^{21} \text{ cm}^{-2}$  corresponds to  $A_{\text{V}} \sim 2$ ; as shown and discussed in Caccianiga et al. (2008) (e.g., see their Fig. 6) an  $A_{\text{V}}$  value of  $\sim 2$  mag seems to be the best dividing value between optically-type 1 (Sey1, Sey1.5, QSO, NLSy1) and optically-type 2 (Sey1.8, Sey1.9, Sey2, QSO2) AGN in the XBS survey. Therefore, the choice of  $N_{\text{H}} = 4 \times 10^{21} \text{ cm}^{-2}$  as a dividing line between X-ray absorbed and unabsorbed AGN has a direct physical link to the optical classification. Three objects (XBS J041108.1-711341, XBS J205635.2-044717 and XBS J220601.5-015346) have an upper limit between  $N_{\text{H}} = 4 \times 10^{21} \text{ cm}^{-2}$  and  $N_{\text{H}} \sim 7 \times 10^{21} \text{ cm}^{-2}$  (see Fig. 1), so the current X-ray data does not allow a firm classification as absorbed or unabsorbed AGN. On the other hand, these three objects are classified as broad-line (type 1) AGN in the optical domain (Caccianiga et al. 2008); based on their optical properties these three objects will be considered here as unabsorbed AGN. With these choices, the sample of unabsorbed (or marginally absorbed) AGN is composed of 40 objects, while the sample of absorbed AGN is composed of 22 objects. As shown in Sect. 4, the specific choice of the dividing line between absorbed and unabsorbed AGN does not affect the main results reported in this paper.

For the sake of clarity, we call, *unabsorbed AGN*, those AGN with an intrinsic absorbing column density  $N_{\text{H}}$  below  $4 \times 10^{21} \text{ cm}^{-2}$ ; *absorbed AGN*, those objects with  $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $\approx 10^{24} \text{ cm}^{-2}$ ; and, *Compton thick AGN*, those sources with  $N_{\text{H}}$  above  $10^{24} \text{ cm}^{-2}$ .

At the flux limit of the HBSS survey the measured surface densities of absorbed (unabsorbed) AGN is  $0.87^{+0.23}_{-0.18}$  ( $1.59^{+0.25}_{-0.25}$ )  $\text{deg}^{-2}$  and the observed fraction of absorbed AGN is  $37 \pm 7\%$ . If we split the sample according to an intrinsic luminosity of  $10^{44} \text{ erg s}^{-1}$ , we find that the fraction of absorbed AGN is  $29^{+10}_{-9}\%$  in the high-luminosity regime and  $42^{+11}_{-10}\%$  in the low-luminosity regime, thus confirming first results based on a complete sub-sample of 28 HBSS objects fully identified reported in Caccianiga et al. (2004). However, this crude comparison between low- and high-luminosity AGN is biased since it does not take into account selection effects due to the absorption, i.e., we are able to observe unobscured sources within a larger volume compared to the obscured sources since the intrinsic luminosity of the latter sources is depressed by photoelectric absorption. We will derive and discuss the unbiased intrinsic fraction of absorbed AGN as a function of the intrinsic X-ray luminosity in Sect. 4. It is worth noting that the selection strategy of the HBSS survey is extremely efficient in finding type two QSO, i.e., absorbed AGN with an intrinsic luminosity above  $10^{44} \text{ erg s}^{-1}$ . We have 9 of these sources in the HBSS sample (7 with  $N_{\text{H}} > 10^{22} \text{ cm}^{-2}$ ); they represent  $15^{+6}_{-5}\%$  of the total AGN population and  $41^{+13}_{-12}\%$  of the absorbed ones. At the flux limit of the HBSS survey the measured surface density of type 2 QSOs is  $0.36^{+0.13}_{-0.12} \text{ deg}^{-2}$ ; this latter surface density of type 2 QSO combined with the surface density of type 2 QSOs reported in Perola et al. (2004) ( $\sim 48 \text{ deg}^{-2}$  at a 2–10 keV flux limit of  $\sim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ ) implies a slope in the integral  $\text{Log } N - \text{Log } S$  of type 2 QSOs of  $\sim -2.1$  between  $\sim 10^{-13}$  and  $\sim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ .

Finally, we have not found Compton thick AGN, which are a fundamental population for producing the shape of the XRB around its emissivity peak ( $\sim 30 \text{ keV}$ , e.g., Gilli et al. 2007). As discussed in Appendix A, even the 4.5–7.5 keV HBSS survey is quite inefficient in selecting this kind of AGN. Given their large flux depression due to the absorption, X-ray surveys above 10 keV are needed to select these sources (see Della Ceca et al. 2007, for a recent review of this topic). We discuss Compton thick AGN in Sect. 7 where we derive, in an indirect way, their X-ray luminosity function.

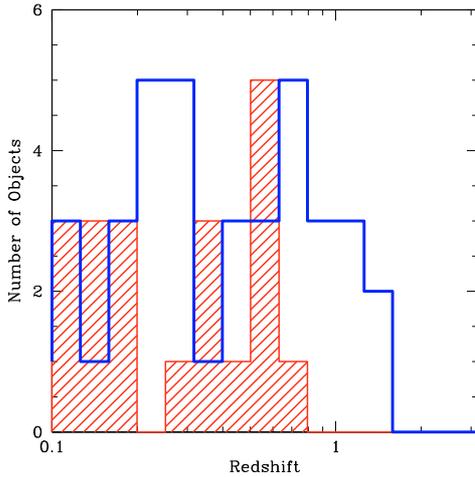
### 2.2. Redshift and luminosity distribution

The redshift and intrinsic 2–10 keV luminosity distribution for the AGN belonging to the HBSS sample are reported in Figs. 2 and 3, respectively. The shaded histogram indicates the distribution for absorbed AGN, while the empty histogram indicates the distribution for the unabsorbed ones. Both classes of AGN show a rather flat  $z$  distribution with the unabsorbed AGN population sampled up to  $z \sim 1.5$  while the absorbed AGN population is sampled up to  $z \sim 0.8$ . Intrinsic 2–10 keV luminosities are distributed over 4 order of magnitude for the unabsorbed AGN population (from  $10^{42}$  to  $10^{46} \text{ erg s}^{-1}$  with a median logarithmic luminosity of  $\sim 44.2$ ) and over about 2.5 order of magnitudes for the absorbed AGN population (from  $\sim 7 \times 10^{42}$  to  $10^{45} \text{ erg s}^{-1}$  with a median logarithmic luminosity of 43.7).

## 3. Cosmological properties

### 3.1. Evolution

For the sample of unabsorbed AGN (40 objects) we find that, according to the  $V_e/V_a$  test (Schmidt 1968; Avni & Bahcall 1980), the hypothesis of a uniform distribution of the objects in the Universe is rejected at a confidence level



**Fig. 2.** Redshift distribution of the AGN belonging to the HBSS sample (shaded histogram: absorbed AGN; empty histogram: unabsorbed AGN).

of  $\sim 98\%$  ( $\langle V_e/V_a \rangle = 0.616 \pm 0.046$ ). Assuming a pure luminosity evolution model with an evolutionary form  $\propto (1+z)^C$ , we find a best fit parameter of  $C \simeq 2.7$  with an associated 68% confidence interval of 1.9–3.0. This value of cosmological evolution is consistent, within the errors, both with the results obtained in the soft ( $E \leq 3$  keV) energy band using the *Einstein* Extended Medium Sensitivity Survey ( $C = 2.56 \pm 0.17$ ; Maccacaro et al. 1991; Della Ceca et al. 1992) and the EMSS+Rosat AGN samples ( $C = 2.6 \pm 0.1$ ; Page et al. 1997) and with the results in the 2–10 keV energy range reported in Ueda et al. (2003;  $C = 2.70^{+0.17}_{-0.25}$ ) and La Franca et al. (2005;  $C = 3.22^{+0.13}_{-0.26}$ ).

However it is now well established that a luminosity dependent density evolution (LDDE) model provides a better description of the evolutionary properties of AGN, both in the X-ray energy range (Hasinger et al. 2005; Ueda et al. 2003; La Franca et al. 2005; Silverman et al. 2007) and in the optical domain (Bongiorno et al. 2007).

To test this evolutionary behavior, we assume here an LDDE model with the parametrization as introduced by Ueda et al. (2003),

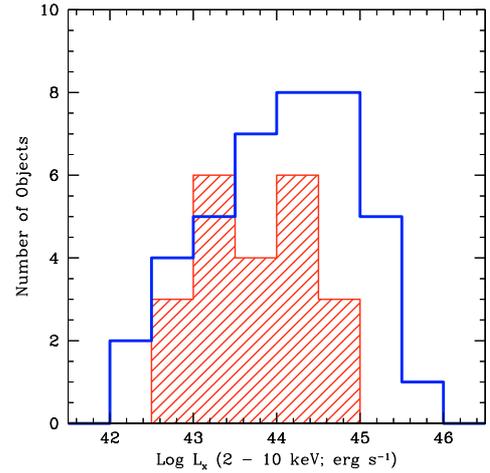
$$\frac{d\Phi(L_x, z)}{d\text{Log}L_x} = \frac{d\Phi(L_x, 0)}{d\text{Log}L_x} \times e(z, L_x)$$

$$e(z, L_x) = \begin{cases} (1+z)^{p1}, & (z < z_c) \\ e(z_c, L_x) [(1+z)/(1+z_c)]^{p2}, & (z \geq z_c) \end{cases}$$

$$z_c(L_x) = \begin{cases} z_c^*, & (L_x \geq L_a) \\ z_c^* (L_x/L_a)^\alpha, & (L_x < L_a). \end{cases}$$

where  $z_c$  corresponds to the redshift where the direction of the evolution changes sign. It is worth noting that  $z_c$  is a function of the intrinsic luminosity of the object; if we assume the best fit parameters of  $p2 = -1.15$ ;  $z_c^* = 2.49$ ;  $\alpha = 0.20$ ;  $\text{Log} L_a = 45.80$  (adapted to  $H_0 = 65$ ) as reported in La Franca et al. (2005), then  $z_c$  is  $\sim 0.7, 1.1, 1.7$  for AGN with  $L_x \sim 10^{43}, 10^{44}, 10^{45}$  erg s $^{-1}$ , respectively. Given the coverage in the luminosity-redshift plane of the HBSS unabsorbed AGN sample, for each luminosity the objects are below  $z_c$ , implying that we are unable to derive  $p2$ ,  $z_c^*$ ,  $\alpha$  and  $\text{Log} L_a$ . For these reasons, we have taken these parameter values from La Franca et al. (2005) and we have used the  $V_e/V_a$  test to constrain  $p1$ .

We obtain a best fit  $p1 = 6.5$  with an associated 68% confidence interval of 3.5–10.0. The distribution of the derived  $V_e/V_a$



**Fig. 3.** Intrinsic 2–10 keV luminosity distribution of the AGN belonging to the HBSS sample (shaded histogram: absorbed AGN; empty histogram: unabsorbed AGN).

values is consistent with being uniformly distributed between 0 and 1 according to a KS test (KS probability  $\sim 95\%$ ). We have also checked that, given the coverage of the luminosity-redshift plane of the HBSS AGN sample, the best fit  $p1$  is virtually insensitive to the other parameters of the model; i.e.,  $p1$  does not change by varying all the other parameters within their  $1\sigma$  range as derived from La Franca et al. (2005).

The derived best fit value for  $p1$  is consistent, within the errors, with that reported in La Franca et al. (2005) ( $p1 = 4.62 \pm 0.26$ ) and is in very good agreement with those recently obtained, in the optical domain, by Bongiorno et al. (2007) using a sample of 130 broad-line AGN with redshift up to  $z = 5$  from the VIMOS-VLT Deep Survey ( $p1 = 6.54$ ) and from Hopkins et al. (2007) using a large data set of AGN selected in the mid-IR, optical, soft X-ray, and hard X-ray ( $p1 = 5.95 \pm 0.23$ ).

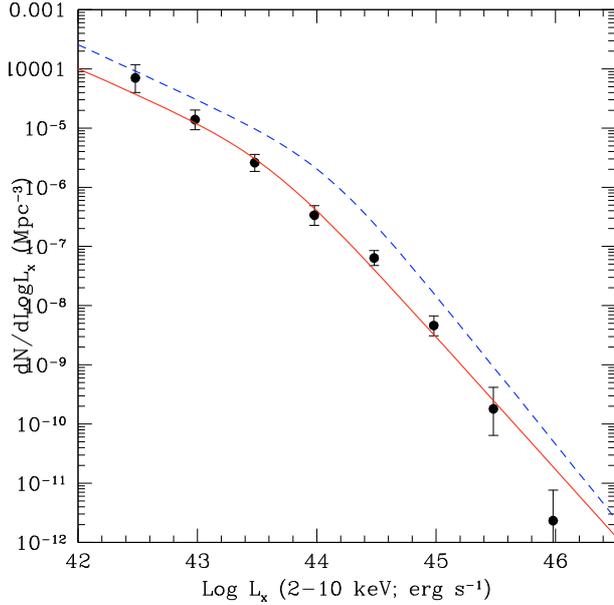
Because of their number statistics (22 objects in total) and their distribution in the  $L_x$ – $z$  plane the cosmological evolution is unconstrained for the absorbed AGN sample (note that the absorbed AGN are sampled only up to  $z \sim 0.8$ ). Therefore, in the following, and in line with the unification scheme of AGN, we make the assumption that this class of sources evolve with cosmic time (and within the redshift range sampled at the HBSS flux limit) in a similar way to the unabsorbed ones.

### 3.2. X-ray luminosity functions of absorbed and unabsorbed AGN

In this section, we will derive the *intrinsic* (i.e., corrected for the selection bias due to the intrinsic absorption) local X-ray luminosity function of absorbed and unabsorbed AGN. For comparison with other survey projects, the XLF will be derived in the 2–10 keV energy range (with the  $1/V_a$  method; see Avni & Bahcall 1980) as follows.

For each AGN we have computed the maximum redshift ( $z_{\text{max}}$ ) at which the source (characterized by the observed count rate in the 4.5–7.5 keV energy band, by the X-ray spectral shape, and by the redshift) can still be detected above the MOS2 count rate limit of the HBSS sample ( $= 2 \times 10^{-3}$  cts/s in the 4.5–7.5 keV band). The X-ray spectral shape of each AGN, as derived from the X-ray spectral analysis (reported in Table 1), has been used to take properly into account  $k$ -corrections.

This  $z_{\text{max}}$  combined with the solid angle covered by the HBSS survey (25.17 deg $^{-2}$ ) and the best fit LDDE model



**Fig. 4.** De-evolved ( $z = 0$ ) X-ray luminosity function (2–10 keV) obtained using the total HBSS AGN sample (filled circles). We have also reported for comparison the local XLF for the total AGN population as derived by Shinozaki et al. (2006) (HEAO1 AGN sample; dashed line) and by Sazonov & Revnivtsev (2004) (RXTE AGN sample; solid line). See Sect. 3.2 for details.

described in the previous section allow us to compute, for each object  $i$ , the *density-weighted volume*  $V'_{a_i}$  (see Avni & Bahcall 1980):

$$V'_{a_i} = 25.17 \times \int_0^{z_{\max}} e(z, L_x) \times dV/dz \times dz.$$

The XLFs computed with these volumes are the so called de-evolved XLF at  $z = 0$ .

In order to obtain the differential 2–10 keV X-ray luminosity function, we bin the individual contributions in bins of equal logarithmic width  $\Delta \text{Log } L_x$  according to the intrinsic 2–10 keV luminosity as derived from the X-ray spectral analysis of each source. For each luminosity bin we have

$$\frac{d\Phi}{d\text{Log } L_x} = \sum_{i=1}^n \left[ \frac{1}{V'_{a_i} \Delta \text{Log } L_x} \right]$$

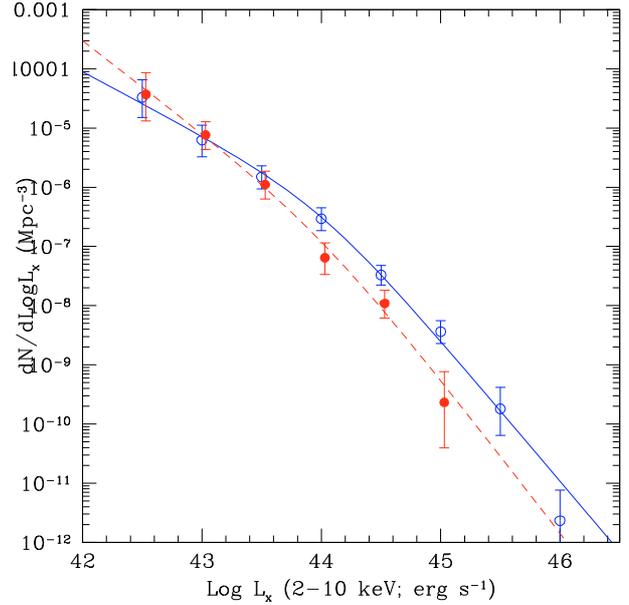
where  $n$  is the number of objects in that bin. Poissonian errors bars have been computed using the Gehrels (1986) prescriptions.

In summary, in the XLF computation we have used:

- the observed count rate in the selection 4.5–7.5 keV band; the count rate limit of the HBSS survey; and the best fit LDDE model in estimating the *available* co-moving density weighted volume  $V'_{a_i}$  of each source. The spectral shape of each individual source, as derived from the X-ray spectral analysis, has been used to properly take into account  $k$ -corrections;
- the intrinsic (2–10 keV) luminosities (as derived from the X-ray spectral analysis of each source) to divide the sources into luminosity bins.

In Appendix A we discuss a few simulations we have carried out to prove the validity of this approach.

In Fig. 4, we show (filled dots) a binned representation of the de-evolved (2–10 keV) XLF obtained using the total AGN



**Fig. 5.** Comparison between the de-evolved ( $z = 0$ ) X-ray luminosity function (2–10 keV) for the unabsorbed ( $N_{\text{H}} < 4 \times 10^{21} \text{ cm}^{-2}$ ; open circles) and absorbed ( $4 \times 10^{21} < N_{\text{H}} \leq 10^{24} \text{ cm}^{-2}$ ; filled circles) AGN in the HBSS sample. The solid and dashed lines represent the best fit two power-law function of the unabsorbed and absorbed AGN XLF, respectively (best fit parameters as reported in Table 2). Please note that for comparison reasons the XLF of absorbed AGN has been computed with a small shift ( $\Delta \text{Log } L_x = 0.03$ ) with respect to that of unabsorbed AGN. See Sect. 3.2 for details.

HBSS sample (62 objects). The derived XLF (at  $z = 0$ ) is compared with the 2–10 keV XLF obtained using *local* AGN samples, the latter being independent from cosmological evolution. In particular, in Fig. 4 we compare our XLF with that obtained from Shinozaki et al. (2006) using the 2–10 keV selected AGN in the HEAO1 survey (49 objects in total, dashed line) and by Sazonov & Revnivtsev (2004) using the 3–20 keV selected AGN sample (95 AGN in total; solid line) in the Rossi X-ray Timing Explorer (RXTE) slew survey. This last XLF has been converted from the 3–20 keV to the 2–10 keV energy range using a power-law model with photon index equal to 1.9 ( $\frac{L_{2-10 \text{ keV}}}{L_{3-20 \text{ keV}}} = 0.8$ ). As can be seen in Fig. 4, the best fit AGN XLF (at  $z = 0$ ) derived here is in excellent agreement with that derived using the RXTE slew data, while its normalization is a factor between 2.5 to 5 times below that derived using the HEAO1 AGN sample (Shinozaki et al. 2006). This discrepancy in the normalization of the local (2–10 keV) XLFs was already discussed by Sazonov & Revnivtsev (2004) and by Shinozaki et al. (2006) and it is currently an open issue. It is worth noting that a similar shift between our computation of the XLF and the Shinozaki et al. (2006) XLF is also present when we consider only the unabsorbed AGN population, suggesting that the possible different distribution of the absorption properties of the two samples cannot explain the different observed normalizations of the XLFs. Despite the different normalizations, the shapes of the different XLFs seem to be in satisfactory agreement.

More important is the comparison between the XLF of the absorbed and unabsorbed AGN population in the HBSS sample reported in Fig. 5 (unabsorbed population: open circles; absorbed population: filled circles). It is clear that the two populations are characterized by two different XLF with the absorbed AGN population being described by a steeper XLF, if compared with the unabsorbed ones, at all luminosities. The binned

**Table 2.** Best fit parameters of the 2–10 keV XLF.

Sample	Objects	Log A	Log $L_\star$	$\gamma_1$	$\gamma_2$	KS-prob
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Unabsorbed AGN	40	$-6.21^{+0.12}_{-0.12}$	44.0 (fixed)	$1.08^{+0.19}_{-0.19}$	$2.38^{+0.17}_{-0.18}$	0.44; 0.24; –
Absorbed AGN	22	$-6.62^{+0.17}_{-0.16}$	44.0 (fixed)	$1.55^{+0.31}_{-0.24}$	$2.61^{+0.43}_{-0.52}$	0.10; 0.49; 0.34

Columns are as follows: (1) sample; (2) number of objects in the sample; (3) XLF normalization, A, is in units of  $h_{65}^3 \text{ Mpc}^{-3}$ ; (4) XLF break luminosity  $L_\star$  in units of  $h_{65}^{-2} \text{ erg s}^{-1}$ ; (5) low-luminosity XLF slope; (6) high-luminosity XLF slope; (7) the three values are the probabilities (1D-KS test) that the observed  $z$ ,  $L_x$  and, in the case of absorbed AGN,  $N_{\text{H}}$  distributions are consistent with being derived from the the best fit XLF plus cosmological evolution plus intrinsic  $N_{\text{H}}$  distribution derived here. See Sect. 3.2 for details.

representation of the XLFs reported in Fig. 5 have been fitted by a smoothly connected two power-laws function of the form

$$\frac{d\Phi(L_x, z=0)}{d\text{Log } L_x} = A \left[ \left( \frac{L_x}{L_\star} \right)^{\gamma_1} + \left( \frac{L_x}{L_\star} \right)^{\gamma_2} \right]^{-1}$$

taking into account the error bars of each data point and by minimizing  $\chi^2$  using the routines in the QDP<sup>3</sup> software package. Since  $L_\star$  is not well constrained we have fixed it to  $10^{44} \text{ erg s}^{-1}$  close to that found for the total AGN population in Sazonov & Revnivtsev (2004;  $L_\star = 10^{43.6} \text{ erg s}^{-1}$ ) and in Shinozaki et al. (2006;  $L_\star = 10^{44.02} \text{ erg s}^{-1}$ ). Best fit XLF parameters and  $1\sigma$  errors are reported in Table 2.

For the unabsorbed AGN population the value of  $\gamma_1$  and  $\gamma_2$  are consistent, within the errors, with those reported in Sazonov & Revnivtsev (2004) and in Shinozaki et al. (2006). For the absorbed AGN population the  $\gamma_1$  ( $\gamma_2$ ) derived here is slightly steeper (flatter) than that reported in Shinozaki et al. (2006) ( $\gamma_1 = 1.12^{+0.17}_{-0.19}$ ,  $\gamma_2 = 3.34^{+0.90}_{-0.65}$ ). Sazonov & Revnivtsev (2004) do not quote the XLF parameters for the absorbed AGN population.

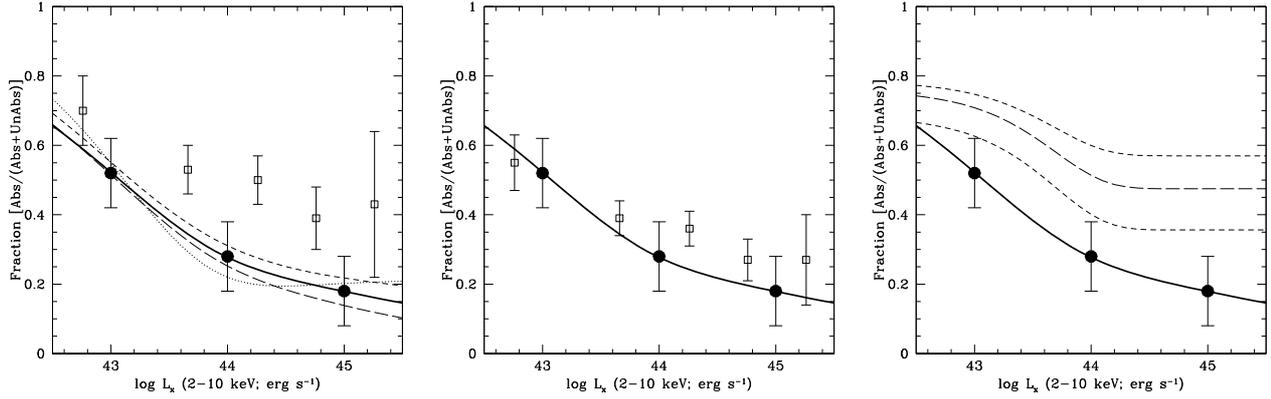
As discussed in Sect. 2, two HBSS sources (XBS J080411.3+650906 and XBS J110050.6-344331) are still unidentified at the time of this writing. Can their inclusion in the AGN sample substantially change the results discussed above? In particular, their inclusion could be important if these sources were high-luminosity absorbed AGN where we measure a deficit of absorbed sources. To answer to this question we have examined in detail their X-ray spectral properties as well as the optical (photometric) properties of the most likely optical counterpart. The source XBS J110050.6-344331 is well described (fixing  $z = 0$ ) by a power-law model having  $\Gamma = 1.80 \pm 0.16$  and  $N_{\text{H}} = 1 \pm 0.5 \times 10^{21} \text{ cm}^{-2}$ . Its 2–10 keV X-ray flux ( $\sim 3 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ ), optical magnitude ( $m_R = 18.0$ ), X-ray to optical flux ratio ( $X/O \sim 1$ ), and X-ray spectral properties strongly suggest a type 1 (unabsorbed) object. On the contrary, XBS J080411.3+650906 is most likely an absorbed AGN. Its X-ray spectra is described (at  $z = 0$ ) by a power-law model having  $\Gamma = 1.7 \pm 0.4$  and  $N_{\text{H}} = 8.4 \pm 4.3 \times 10^{21} \text{ cm}^{-2}$ , so with an intrinsic  $N_{\text{H}}$  (at the source  $z$ ) well above  $4 \times 10^{21} \text{ cm}^{-2}$ . The optical magnitude of the counterpart ( $m_R = 21.10$ ) combined with its 2–10 keV X-ray flux ( $\sim 2.1 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ ) implies an X/O flux ratio of  $\sim 17.5$ , strongly supporting the absorbed AGN hypothesis (e.g., Severgnini et al. 2006). If we use the relationship between X/O flux ratio and intrinsic luminosity reported in Fiore et al. (2003) the most likely redshift of this object is  $\sim 0.55$  (consistent with a poor quality optical spectrum of the optical counterpart) and its intrinsic luminosity is  $L_x \simeq 1.9 \times 10^{44} \text{ erg s}^{-1}$ . The addition of this object to the HBSS absorbed AGN sample produce an increase

of  $\sim 8\%$  of the space density of the absorbed AGN population at  $L_x \simeq 10^{44} \text{ erg s}^{-1}$ , a very marginal difference that is well within the error bar reported in Fig. 5. It is also worth noting that there are four objects (see Fig. 1), which have a best fit  $N_{\text{H}}$  value below  $4 \times 10^{21} \text{ cm}^{-2}$  but with error bars crossing this  $N_{\text{H}}$  dividing line. The two objects (with large error bars) with a luminosity around  $2 \times 10^{45} \text{ erg s}^{-1}$  are optically classified as broad-line QSO; so their optical properties are fully consistent with the unabsorbed classification. The two objects with a luminosity around  $1 \times 10^{43} \text{ erg s}^{-1}$  are instead optically-elusive AGN (Caccianiga et al. 2007) and their unabsorbed classification was based on their best fit  $N_{\text{H}}$  value. On the other hand, their inclusion in the absorbed AGN sub-sample will increase the difference between absorbed and unabsorbed AGN at luminosities of about  $L_x \simeq 10^{43} \text{ erg s}^{-1}$ , strengthening our conclusions of different XLF of the two populations. To conclude, the results presented and discussed in this section are stable also taking into account all the uncertainty about the two unidentified sources and about our present classification (absorbed or unabsorbed AGN) break down. Finally, as a consistency test, we have compared the observed  $z$ ,  $L_x$  and  $N_{\text{H}}$  distributions with those predicted by the best fit cosmological evolution model derived here (XLF + cosmological evolution) folded with the  $N_{\text{H}}$  distribution discussed in Sect. 5. The 1D-KS probabilities reported in Table 2 confirms the goodness of our modeling of the AGN cosmological properties.

#### 4. The intrinsic fraction of absorbed AGN

One of the most important open issues regarding absorbed AGN is to understand their relevance amongst the AGN population and if (and how) the fraction ( $F$ ) of absorbed AGN changes as a function of  $L_x$  and  $z$ . We define  $F$  as the intrinsic ratio between the AGN with  $N_{\text{H}}$  in the range  $4 \times 10^{21} - 10^{24} \text{ cm}^{-2}$  and all the AGN with  $N_{\text{H}}$  below  $10^{24} \text{ cm}^{-2}$ . This is a long-standing issue coming back to almost 26 years ago when Lawrence & Elvis (1982) reported an anti-correlation between the intrinsic luminosity of the AGN and the presence of absorption. This issue has recently re-emerged in many papers with contradicting results: several studies suggest that  $F$  decreases with  $L_x$  and increase with  $z$  (e.g., La Franca et al. 2005; Ballantyne et al. 2006; Treister & Urry 2006), while other studies suggest that  $F$  is independent of  $L_x$  and  $z$  (e.g., Dwelly & Page 2006) or that  $F$  is dependent from  $L_x$  but not from  $z$  (e.g., Ueda et al. 2003; Akylas et al. 2006; Gilli et al. 2007). Having computed the intrinsic de-evolved XLFs of absorbed and unabsorbed AGN, we can now use them to derive  $F$ . We stress that using the derived XLFs we should be free from the selection bias due to the absorption since the appropriate corrections have been already taken into account in the computation of the XLF itself. We also recall that we are not considering here Compton thick AGN, so the derived  $F$  ratio

<sup>3</sup> See in <http://heasarc.gsfc.nasa.gov/docs/software>



**Fig. 6.** *Left panel:* the thick solid line represents the intrinsic (i.e., the fraction of sources with  $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $10^{24}$   $\text{cm}^{-2}$  divided the sources with  $N_{\text{H}}$  below  $10^{24}$   $\text{cm}^{-2}$ , corrected for the bias due to the photoelectric absorption) differential fraction  $F$  of absorbed AGN as a function of the intrinsic luminosity obtained in this paper. The 68% confidence errors on this ratio are also reported at  $L_x = 10^{43}, 10^{44}, 10^{45}$   $\text{erg s}^{-1}$ . We have also reported the differential fraction of absorbed AGN obtained assuming no cosmological evolution (short dashed line), a cosmological evolution of the absorbed/unabsorbed ratio similar to that recently proposed by [Treister & Urry \(2006\)](#) (long dashed line) and that obtained using  $N_{\text{H}} = 10^{22}$   $\text{cm}^{-2}$  as the dividing value between absorbed and unabsorbed AGN (dotted line). The open squares represent the fraction of absorbed AGN as derived from [Akylas et al. \(2006\)](#). *Middle panel:* solid line as in the left panel. The [Akylas et al. \(2006\)](#) points have been rescaled to  $z = 0$  using the mean redshift in each luminosity bin and an evolution of the absorbed/unabsorbed ratio similar to that recently proposed by [Treister & Urry \(2006\)](#). *Right panel:* solid line as in the left panel. The long dashed line is the prediction from [Gilli et al. \(2007\)](#) on the synthesis model of the CXB. The two dashed lines enclose the uncertainty on the  $F$  ratio based on the CXB modeling. We stress that all the quantities reported in this figure refer to AGN with absorbing column density  $N_{\text{H}}$  below  $10^{24}$   $\text{cm}^{-2}$ . See Sect. 4 for details.

**Table 3.** Fraction of absorbed AGN with  $L_x \geq 3 \times 10^{42}$   $\text{erg s}^{-1}$  in different samples<sup>1</sup>.

Sample	$F$	NOTE
HBSS	$0.57 \pm 0.11$	XMM
<a href="#">Markwardt et al. (2005)</a>	$0.59 \pm 0.09$	SWIFT/BAT
<a href="#">Beckmann et al. (2006)</a>	$0.54 \pm 0.10$	INTEGRAL
<a href="#">Bassani et al. (2006)</a>	$0.56 \pm 0.09$	INTEGRAL
<a href="#">Ajello et al. (2008)</a>	$0.57 \pm 0.13$	SWIFT/BAT

Notes: <sup>1</sup> in deriving, from the original papers, the above reported quantities we have considered, as for the HBSS AGN sample, only the Compton thin AGN ( $N_{\text{H}} < 10^{24}$   $\text{cm}^{-2}$ ) and a dividing  $N_{\text{H}}$  line between absorbed and unabsorbed AGN fixed at  $4 \times 10^{21}$   $\text{cm}^{-2}$ .

is indeed a lower limit to the *true* fraction of absorbed AGN. Compton thick AGN will be discussed in Sect. 7.

Using the integral representation of the derived XLFs we have first computed  $F$  for AGN having an intrinsic luminosity above  $\sim 3 \times 10^{42}$   $\text{erg s}^{-1}$  (i.e., around the luminosity of the faintest obscured AGN in the HBSS sample). This fraction ( $F = 0.57 \pm 0.11$ ) is in excellent agreement with the fraction found using hard ( $E > 10$  keV) selected (local) samples of AGN from INTEGRAL/Swift surveys at a flux limit of  $\sim 10^{-11}$   $\text{erg cm}^{-2} \text{ s}^{-1}$ . This comparison is reported in Table 3<sup>4</sup>, where we have listed the value of  $F$  in the HBSS sample, in the SWIFT/BAT sample ([Markwardt et al. 2005](#); [Ajello et al. 2008](#)) and in the INTEGRAL samples ([Beckmann et al. 2006](#); [Bassani et al. 2006](#)). Please note that the local INTEGRAL/Swift samples are almost free from selection bias related to the absorption at least for  $N_{\text{H}}$  up to  $10^{24}$   $\text{cm}^{-2}$ . The good agreement implies that, after selection effect due to the absorption have been taken into account, the HBSS is sampling at a  $f_x \sim 10^{-13}$   $\text{erg cm}^{-2} \text{ s}^{-1}$ ,

<sup>4</sup> We have not reported in Table 3 the INTEGRAL results from [Sazonov et al. \(2007\)](#) since these authors do not report the absorbing column densities of their objects but simply split the objects into absorbed and unabsorbed according to an  $N_{\text{H}}$  value of  $10^{22}$   $\text{cm}^{-2}$ ; for comparison the fraction of absorbed AGN found from their sample using this  $N_{\text{H}}$  value is  $0.42 \pm 0.09$ .

the same population of absorbed AGN as the present surveys performed at  $E > 10$  keV. It is also worth noting that after the selection effect have been taken into account the fraction of obscured AGN increases from an observed value of  $0.37 \pm 0.07$  (see Sect. 2.1) to an intrinsic value of  $0.57 \pm 0.11$ .

The differential fraction  $F$  of absorbed AGN as a function of the intrinsic luminosity is reported in Fig. 6 left panel (solid line); we have also reported the  $1\sigma$  error bar on  $F$  (vertical solid line at  $L_x = 10^{43}, 10^{44}, 10^{45}$   $\text{erg s}^{-1}$ ), computed taking into account the current uncertainties on the XLFs.

Given the coverage in the luminosity-redshift plane of the HBSS AGN sample the results reported in Fig. 6 are quite stable, i.e. they do not depend strongly on the value of the cosmological evolution parameter. To prove this in Fig. 6 (left panel) we have also reported  $F$  as a function of  $L_x$  if we assume no cosmological evolution for absorbed and unabsorbed AGN (short dashed line) or if we assume a cosmological evolution of the absorbed population faster than that the unabsorbed ones according to the [Treister & Urry \(2006\)](#) model ( $F \propto (1+z)^{0.4}$ ; long dashed line). Finally we have also reported (dotted line) the fraction of absorbed AGN if we re-perform all the analysis but this time splitting the objects as absorbed or unabsorbed using  $N_{\text{H}} = 10^{22}$   $\text{cm}^{-2}$  as the dividing value (44 unabsorbed AGN, 18 absorbed AGN).

In the same left panel of Fig. 6, we have also reported the fraction of obscured AGN as recently computed by [Akylas et al. \(2006\)](#) using a sample of AGN selected in the hard 2–8 keV band down to a flux limit of  $6 \times 10^{-16}$   $\text{erg cm}^{-2} \text{ s}^{-1}$  (open squares), about a factor one hundred below our flux limit. The data points computed by [Akylas et al. \(2006\)](#) have been corrected for the different volumes sampled from absorbed and unabsorbed AGN (due to the absorption) in a similar way as done here. Although the HBSS sample and the [Akylas et al. \(2006\)](#) show a similar trend of decreasing  $F$  as a function of the intrinsic luminosity, the fractions computed at  $z = 0$  using the HBSS sample are systematically lower ( $\sim$  a factor 2 for  $L_x > 10^{43}$   $\text{erg s}^{-1}$ ) than those reported in [Akylas et al. \(2006\)](#). However, the data points reported in [Akylas et al. \(2006\)](#) have been computed

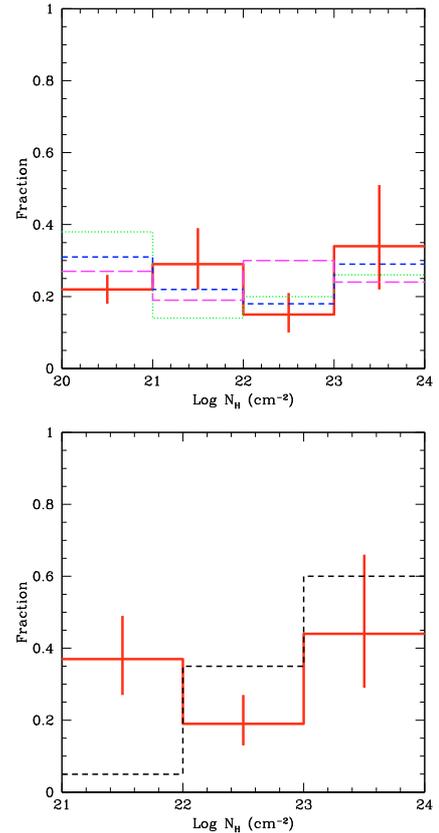
without taking into account possible differences in the cosmological evolution properties of the absorbed and unabsorbed AGN population. This effect, which we have already shown as of the second order for the HBSS AGN sample, could be very important for the Akylas et al. (2006) sample since their objects are at a significantly higher  $z$  compared to the HBSS AGN sample. To test this effect in Fig. 6 (middle panel) the Akylas et al. (2006) points have been rescaled to  $z = 0$  using the mean redshift in each luminosity bin (T. Akylas, private communication) and a cosmological evolution of  $F$ , according to the model proposed by Treister & Urry (2006) ( $F \propto (1+z)^{0.4}$ ). A much better agreement with our results is clearly evident, suggesting a possible evolution of the fraction of absorbed AGN with the redshift.

Finally in Fig. 6 (right panel) we compare  $F$  with that required to produce the cosmic X-ray background according to the new synthesis model reported in Gilli et al. (2007) (long dashed line: best fit; short dashed lines: one  $\sigma$  error range; both computed and predicted  $F$  ratios refer only to absorbed AGN with  $N_{\text{H}}$  below  $10^{24}$   $\text{cm}^{-2}$ ); we discuss this comparison in Sect. 8.

## 5. The intrinsic $N_{\text{H}}$ distribution in AGN

A second important and debated issue on the AGN astrophysics is related to their intrinsic  $N_{\text{H}}$  distribution, i.e., the  $N_{\text{H}}$  distribution of the AGN family computed taking into account the selection effects related to the photoelectric absorption. To compute this distribution we have proceeded as follows. We have first split the HBSS AGN sample in four bins of absorbing column densities up to  $N_{\text{H}} = 10^{24}$   $\text{cm}^{-2}$  ( $N_{\text{H}} = 10^{20}$ – $10^{21}$ ;  $10^{21}$ – $10^{22}$ ;  $10^{22}$ – $10^{23}$ ;  $10^{23}$ – $10^{24}$   $\text{cm}^{-2}$ ). Second, we have computed the integral luminosity function with the objects in each bin of  $N_{\text{H}}$  and the  $1/V_a$  method as discussed in Sect. 3.2. Third, using these XLFs we have determined the density of objects in each  $N_{\text{H}}$  bin having a luminosity above  $\sim 3 \times 10^{42}$   $\text{erg s}^{-1}$  (i.e., around the luminosity of the faintest absorbed AGN in the HBSS sample). Finally, to obtain the  $N_{\text{H}}$  distribution (reported in Fig. 7 upper panel, as solid line) the density in each  $N_{\text{H}}$  bin has been normalized to the total density of AGN with  $N_{\text{H}}$  between  $10^{20}$  and  $10^{24}$   $\text{cm}^{-2}$ . One  $\sigma$  Poisson error bars have been computed with the Gehrels (1986) prescription and the objects in each bin of  $N_{\text{H}}$ . It is interesting to compare the rather flat  $\text{Log } N_{\text{H}}$  distribution obtained from the HBSS sample with other samples of AGN or with that required from the synthesis model of the CXB. In Fig. 7 (upper panel), we compare the  $N_{\text{H}}$  distribution derived using the HBSS sample with that computed using hard ( $E > 10$  keV) selected (local) samples of AGN from SWIFT/BAT and INTEGRAL surveys at a flux limit of  $\sim 10^{-11}$   $\text{erg cm}^{-2} \text{ s}^{-1}$ . We stress again that these latter samples are virtually free from selection bias related to the absorption for  $N_{\text{H}}$  below  $\approx 10^{24}$   $\text{cm}^{-2}$ . Clearly, the flat  $N_{\text{H}}$  distribution derived using the HBSS AGN sample is in agreement with that derived with local samples of X-ray selected ( $E > 10$  keV) AGN at a flux limit about a factor 100 higher, thus suggesting that we are indeed sampling a similar population of Compton thin AGN. The derived flat  $\text{Log } N_{\text{H}}$  distribution is also consistent with the flat  $\text{Log } N_{\text{H}}$  distribution assumed by La Franca et al. (2005). Finally, in Fig. 7 (lower panel) we compare the  $N_{\text{H}}$  distribution derived here with that required by Gilli et al. (2007) (up to  $N_{\text{H}} = 10^{24}$   $\text{cm}^{-2}$ ) to fit the spectra of the CXB; the current CXB synthesis modeling based on absorbed and unabsorbed AGN require an increasing fraction of absorbed AGN, which is clearly at odds with the results reported here.

Finally, it is worth noting that the flat  $\text{Log } N_{\text{H}}$  distribution derived here is also markedly different from that derived by

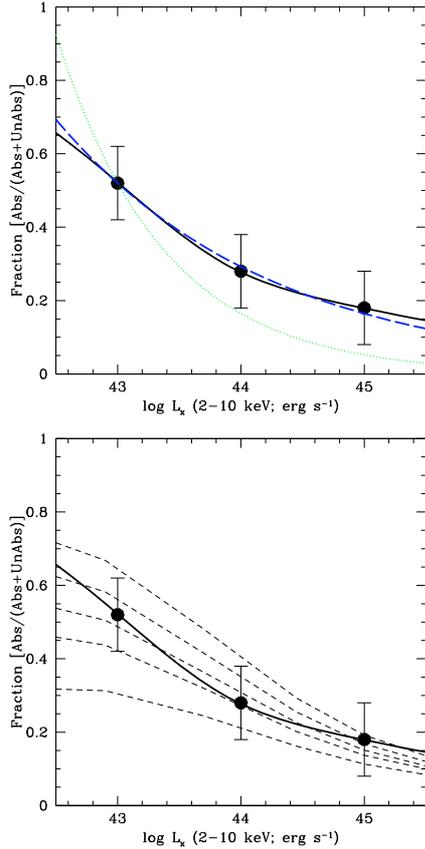


**Fig. 7.** Upper panel: intrinsic  $N_{\text{H}}$  distribution between  $10^{20}$  and  $10^{24}$   $\text{cm}^{-2}$  obtained using the HBSS AGN sample (see Sect. 5, for details), compared with  $N_{\text{H}}$  distribution from the SWIFT/BAT sample (Markwardt et al. 2005: long dashed line) and from the INTEGRAL samples (Beckmann et al. 2006: short dashed line; Bassani et al. 2006: dotted line). Lower panel: intrinsic  $N_{\text{H}}$  distribution between  $10^{21}$  and  $10^{24}$   $\text{cm}^{-2}$  obtained using the HBSS AGN sample, compared with that required from the synthesis model of the CXB (Gilli et al. 2007). In this panel, as done in Gilli et al. 2007, the number of objects in each  $N_{\text{H}}$  bin is normalized to the total number of AGN with  $N_{\text{H}}$  between  $10^{21}$  and  $10^{24}$   $\text{cm}^{-2}$ .

Risaliti et al. (1999) using a sample of optically-selected Seyfert 2 galaxies, with the optically-selected sample requiring an increasing fraction of absorbed AGN, increasing the  $N_{\text{H}}$ . This difference is expected and is due to the fact that we are considering in Fig. 7 both optically-type 1 and optically-type 2 AGN, thus providing the  $N_{\text{H}}$  distribution of the total AGN population. A good agreement with Risaliti et al. (1999) is indeed obtained as we consider only the HBSS optically-type 2 AGN. In other words, the  $\text{Log } N_{\text{H}}$  distribution reported in Risaliti et al. (1999) does not represent the  $N_{\text{H}}$  distribution of the total AGN population, but is probably more typical of that of optically-selected Seyfert 2 galaxies, which, with few exceptions, are absorbed sources with  $N_{\text{H}}$  usually above  $10^{22}$   $\text{cm}^{-2}$ .

## 6. Comparison with AGN unification models

The results of the fraction of absorbed AGN as a function of the intrinsic luminosity discussed in Sect. 4 can be now directly compared with the prediction(s) of the unification model of AGN. These results are inconsistent with the simplest unified scheme, where a similar thick molecular torus (at a distance of the order of one parsec from the central black hole) surrounds all the AGN, and which predicts that  $F$  is independent from  $L_{\text{X}}$ ;



**Fig. 8.** *Upper panel:* the thick solid line represents the fraction  $F$  of absorbed AGN as a function of the intrinsic luminosity obtained using the best fit de-evolved XLF of absorbed ( $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $10^{24}$  cm<sup>-2</sup>) and unabsorbed ( $N_{\text{H}}$  below  $4 \times 10^{21}$  cm<sup>-2</sup>) AGN in the HBSS sample. The dotted line represents the absorbed fraction expected from the original receding torus model discussed in Lawrence (1991;  $F \propto L^{-0.5}$ ), while the dashed line represents the absorbed fraction expected from the radiation-limited clumpy dust torus recently discussed in Höning & Beckert (2007;  $F \propto L^{-0.25}$ ); *Lower panel:* the thick solid line as in the upper panel. The dashed lines represent the expected behavior of the fraction of absorbed AGN for values of the galaxy central surface densities (from bottom to top) of 40, 80, 120, 200, and 400  $M_{\odot}/\text{pc}^2$ , according to the models discussed in Lamastra et al. (2006).

a modification to this simple zero order unification scheme is clearly required. In Fig. 8 (upper panel), we compare  $F$ - $L_{\text{X}}$  relationship derived here with that expected in the framework of the original *receding torus model* ( $F \propto L^{-0.5}$ , dotted line; Lawrence 1991) and in the framework of the *radiation-limited clumpy dust torus* ( $F \propto L^{-0.25}$ , dashed line; Höning & Beckert 2007); both these models have been normalized with our results at  $L_{\text{X}} = 10^{43}$  erg s<sup>-1</sup>. It is clearly evident the excellent agreement between our results and the prediction of the radiation-limited clumpy dust torus discussed in Höning & Beckert (2007).

Finally, in Fig. 8 (lower panel), we compare the  $F$ - $L_{\text{X}}$  relationship from the HBSS sample with the AGN absorption model recently discussed by Lamastra et al. (2006). According to this model, the absorption seen in Compton thin AGN is not related to the obscuring torus but to molecular gas in a disk located far away from the X-ray source (between 25 and 450 pc depending on the BH mass). As shown in Lamastra et al. (2006) the anti-correlation between the ratio of absorbed AGN and the luminosity can be reproduced if a) there is a sufficient number of molecular clouds within the radius where the BH gravitational influence is dominant; and b) there is a statistical correlation

between the BH mass and the AGN luminosity. We have reported in Fig. 8 (lower panel, dashed lines) the expected behavior of the fraction of absorbed AGN for values of the central surface densities of molecular clouds (from bottom to top) of 40, 80, 120, 200 and 400  $M_{\odot}/\text{pc}^2$  as reported in Fig. 4 (right panel) of Lamastra et al. (2006)<sup>5</sup>, based on the assumption  $L_{\text{Bol}}/L_{\text{Edd}} = 0.1$  and luminosity dependent-bolometric corrections (see Lamastra et al. 2006 for details). Our results on the  $F$ - $L_{\text{X}}$  relationship are fully consistent with this model if the surface density of molecular clouds in the central part of the galaxy is between 80 and 200  $M_{\odot}/\text{pc}^2$ , a condition that, as discussed in Lamastra et al. (2006), is consistent with the observations of local galaxies.

## 7. The X-ray luminosity function of Compton thick AGN

As discussed above *XMM-Newton* and *Chandra* data can be efficiently used to investigate the statistical properties of AGN with column densities below  $\sim 10^{24}$  cm<sup>-2</sup>. On the contrary, the statistical properties (e.g., XLF) of absorbed sources having  $N_{\text{H}}$  above  $\sim 10^{24}$  cm<sup>-2</sup>, the so called Compton thick AGN, are currently completely unconstrained. According to the latest versions of synthesis modeling of the XRB (Gilli et al. 2007), these sources should represent a substantial fraction of the total AGN population but only a few dozen of them (mostly local) have been found and studied so far in the X-ray domain (see Della Ceca et al. 2007, for a review).

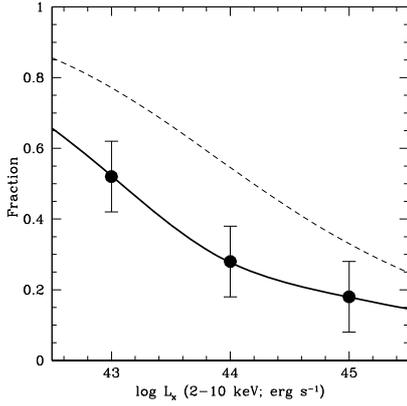
In Fig. 9, we show the fraction of optically-selected narrow-line AGN as a function of the X-ray luminosity (dashed line) as derived by Simpson (2005) using a complete, magnitude-limited, sample of active galaxies from the Sloan Digital Sky Survey and assuming the mean  $L_{[\text{OIII}]}/L_{(2-10 \text{ keV})} \simeq 0.015$  ratio for Seyfert galaxies obtained by Mulchaey et al. (1994) (fully consistent with the similar value reported in Heckman et al. 2005, for the unobscured view of Seyfert galaxies,  $L_{[\text{OIII}]}/L_{(2-10 \text{ keV})} \simeq 0.017$ ). The thick solid line (and the error bars) are the results derived here on the fraction of absorbed ( $4 \times 10^{21} < N_{\text{H}} \leq 10^{24}$  cm<sup>-2</sup>) AGN obtained using the HBSS AGN sample (see Sect. 4); we recall here that in the HBSS we are sampling only AGN with  $N_{\text{H}}$  below  $10^{24}$  cm<sup>-2</sup>.

The behavior of the fraction of optically-selected narrow-line AGN derived by Simpson (2005) is remarkable similar to the correlation between  $F$  and  $L_{\text{X}}$  found here. More important, since the Simpson (2005) sample should contain both Compton thin ( $N_{\text{H}} \leq 10^{24}$  cm<sup>-2</sup>) and Compton thick ( $N_{\text{H}} \geq 10^{24}$  cm<sup>-2</sup>) AGN (see also the results discussed in Heckman et al. 2005), the comparison between the results found by Simpson (2005) (dashed line in Fig. 9;  $F_{\text{optical}}$  hereafter) and those found here (solid line in Fig. 9) allow us to estimate the ratio between Compton thick AGN and AGN with  $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $\sim 10^{24}$  cm<sup>-2</sup> as a function of the luminosity.

Assuming that the number of Compton thick AGN is proportional to the number of AGN with  $N_{\text{H}}$  in the range between  $4 \times 10^{21}$  cm<sup>-2</sup> and  $10^{24}$  cm<sup>-2</sup>,  $N_{\text{Thick}} = C \times N_{4E21-E24}$ , thus from the comparison between  $F$  and  $F_{\text{optical}}$ , and recalling that the definition of  $F$  given in Sect. 4 does not include Compton thick AGN in either the numerator or denominator, we can derive

$$C = \frac{(F_{\text{optical}} - F)}{F \times (1 - F_{\text{optical}})}$$

<sup>5</sup> Lamastra has kindly provided us the expected behavior of their model for  $L_{\text{X}} \geq 3 \times 10^{44}$  erg s<sup>-1</sup>.



**Fig. 9.** The dashed line represents the fraction of optically-selected narrow-line AGN ( $F_{\text{optical}}$ ) as derived by Simpson (2005) using a complete, magnitude-limited, sample of active galaxies from the Sloan Digital Sky Survey and assuming the mean  $L_{[\text{OIII}]} / L_{(2-10 \text{ keV})}$  ratio for Seyfert galaxies derived by Mulchaey et al. (1994). The thick solid line represents the fraction  $F$  of absorbed AGN (sources with  $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $10^{24} \text{ cm}^{-2}$  divided by the sources with  $N_{\text{H}}$  below  $10^{24} \text{ cm}^{-2}$ ) as a function of the intrinsic luminosity obtained using the best fit de-evolved XLF of absorbed and unabsorbed AGN in the HBSS sample. The 68% confidence errors on this ratio are also reported at  $L_x = 10^{43}, 10^{44}, 10^{45} \text{ erg s}^{-1}$ .

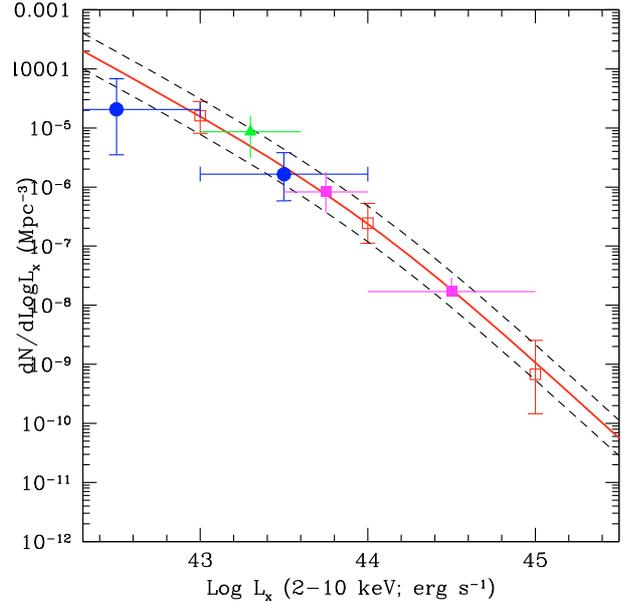
In order to derive an estimate of the density of Compton thick AGN as a function of the luminosity we have first computed  $C$  for three values of the intrinsic X-ray luminosity ( $L_x = 10^{43}$ ,  $L_x = 10^{44}$  and  $L_x = 10^{45} \text{ erg s}^{-1}$ ); thus we have multiplied them for the corresponding XLF of absorbed AGN with  $N_{\text{H}}$  between  $4 \times 10^{21}$  and  $\sim 10^{24} \text{ cm}^{-2}$  (i.e., second line of Table 2). The obtained results are reported in Fig. 10 as open squares (the errors have been computed taking into account the errors reported in Fig. 9).

These estimates of the density of Compton thick AGN at  $L_x = 10^{43}$ ,  $L_x = 10^{44}$  and  $L_x = 10^{45} \text{ erg s}^{-1}$  can be reproduced well assuming an XLF similar in shape to that of absorbed AGN reported in Table 2, but having a normalization  $A_{\text{Thick}} = 2 \times A_{4\text{E}21-\text{E}24}$ ; this XLF is shown in Fig. 10, along with the XLFs with  $A_{\text{Thick}} = A_{4\text{E}21-\text{E}24}$  and  $A_{\text{Thick}} = 4 \times A_{4\text{E}21-\text{E}24}$ .

In Fig. 10, we have also reported:

- the density of local Compton thick AGN (filled circles at  $L_x \sim 3 \times 10^{42}$  and  $\sim 3 \times 10^{43} \text{ erg s}^{-1}$ ) as derived using the three Compton thick AGN (NGC 4945, NGC 3281 and MKN 3) in the INTEGRAL all sky survey at  $|b| > 5^\circ$  (Sazonov et al. 2007)<sup>6</sup>. To convert the observed 17–60 keV fluxes into 2–10 keV intrinsic (i.e. unabsorbed) luminosities we have corrected the fluxes for intrinsic absorption and assumed  $\Gamma = 1.9$ ;
- the density of Compton thick AGN with  $L_x \sim (1 - 4) \times 10^{43} \text{ erg s}^{-1}$  (filled triangle) as derived by Daddi et al. (2007) using *Spitzer* and *Chandra* data in two GOODS fields with multiwavelengths information. Their estimated space density at  $z$  between 1.4 and 2.5 has been rescaled to  $z = 0$  using our best fit evolutionary model;
- the density of Compton thick AGN (filled squares) with  $L_x \sim (3 - 10) \times 10^{43} \text{ erg s}^{-1}$  ( $z$  between 0.7 and 1.0) and  $L_x \sim (1 - 10) \times 10^{45} \text{ erg s}^{-1}$  ( $z$  between 1.3 and 2.0) as derived by Fiore et al. (2008) using the *Spitzer* and *Chandra* data in

<sup>6</sup> We thank S. Sazonov to have provided us the sky coverage of this survey in a tabular form.



**Fig. 10.** The open squares represent the density of Compton thick AGN at  $L_x = 10^{43}, 10^{44}$  and  $10^{45} \text{ erg s}^{-1}$  derived as explained in Sect. 7. The thick solid line represents the proposed XLF of Compton thick AGN with  $A_{\text{Thick}} = 2 \times A_{4\text{E}21-\text{E}24}$  ( $\gamma_1 = 1.55$ ,  $\gamma_2 = 2.61$ ,  $\text{Log } L_\star = 44$ ,  $\text{Log } A_{\text{Thick}} = -6.32$ ), while the two dashed lines correspond to the XLFs with  $A_{\text{Thick}} = A_{4\text{E}21-\text{E}24}$  (lower dashed line) and  $A_{\text{Thick}} = 4 \times A_{4\text{E}21-\text{E}24}$  (upper dashed line). The filled circles at  $L_{(2-10 \text{ keV})} \sim 3 \times 10^{42}$  and  $\sim 3 \times 10^{43} \text{ erg s}^{-1}$  represent the density of local Compton thick AGN derived using the Compton thick AGN in the INTEGRAL all sky survey discussed in Sazonov et al. (2007). The filled triangle represents the density of Compton thick AGN with  $L_x \sim (1-4) \times 10^{43} \text{ erg s}^{-1}$  as derived by Daddi et al. (2007). The filled squares represent the density of Compton thick AGN with  $L_x \sim (3-10) \times 10^{43} \text{ erg s}^{-1}$  and  $L_x \sim (1-10) \times 10^{45} \text{ erg s}^{-1}$ , as derived by Fiore et al. (2008). The densities of Compton thick AGN reported in Daddi et al. (2007) and Fiore et al. (2008) have been rescaled to  $z = 0$  using our best fit evolutionary model. See Sect. 7 for details.

the COSMOS field. Their estimated space density has been rescaled to  $z = 0$  using our best fit evolutionary model.

As it is clear in Fig. 10 the different estimates of the space density of Compton thick AGN, derived using different selection criteria (and methods), are in remarkably good agreement with the suggested XLF of Compton thick AGN ( $\gamma_1 = 1.55$ ,  $\gamma_2 = 2.61$ ,  $\text{Log } L_\star = 44$ ,  $\text{Log } A_{\text{Thick}} = -6.32$ ) with a possible hint of a XLF flattening below few times  $10^{42} \text{ erg s}^{-1}$  (where, we point out, the XLF of absorbed AGN in the HBSS is not well defined since we have no objects in the sample).

The good agreement seem to suggest that, at the sampled X-ray luminosities, the space density of optically-elusive Compton thick AGN (e.g. objects like Arp 299, see Della Ceca et al. 2002) is, at most, similar to that of optically-selected Compton thick AGN, since the former population should be clearly missing in the optically-selected sample of active galaxies defined in Simpson (2005) but should be present in the infrared or X-ray selected samples. This fact is also supported by the consideration that the total number of Compton thick AGN cannot be increased arbitrarily but we have to take into account the limits imposed by the local black mass density derived by Marconi et al. (2004) from dynamical studies of local galaxy bulges ( $\rho_{\text{BH}} = 4.0_{1.2}^{1.6} h_{65}^2 \times 10^5 M_\odot \text{ Mpc}^{-3}$  for  $H_0 = 65$ ). Using the formalism described in La Franca et al. (2005) (see their Eqs. (15)–(17)), assuming a radiative efficiency  $\sim 0.1$ , a

bolometric conversion factor equal to 25 (Pozzi et al. 2007), and integrating the XLFs of AGN (unabsorbed, absorbed, and Compton thick) from  $z = 4.5$  to  $z = 0$  and from  $L_X \sim 3 \times 10^{42} \text{ erg s}^{-1}$  to  $\sim 10^{49} \text{ erg s}^{-1}$ , the limit of  $\rho_{\text{BH}} = 5.6h_{65}^2 \times 10^5 M_\odot \text{ Mpc}^{-3}$  is violated if the XLF of Compton thick AGN is more the  $\sim 4$  times that of absorbed AGN, e.g., the upper envelope reported in Fig. 10. We stress that this is probably an upper envelope since we have not considered in the computation of the local black mass density the objects with luminosity below  $\sim 3 \times 10^{42} \text{ erg s}^{-1}$ .

Finally, the comparison of  $F_{\text{optical}}$  and  $F$  reported in Fig. 9 can be used to evaluate the ratio,  $Q$ , between Compton thick and Compton thin ( $N_{\text{H}} < 10^{24} \text{ cm}^{-2}$ ) AGN. Assuming, as above, that the number of Compton thick AGN is proportional to the number of AGN with  $N_{\text{H}}$  in the range between  $4 \times 10^{21} \text{ cm}^{-2}$  and  $10^{24} \text{ cm}^{-2}$ , thus

$$Q = \frac{(F_{\text{optical}} - F)}{(1 - F_{\text{optical}})}.$$

We derive that the density ratio between Compton thick AGN and Compton thin AGN decreases from  $Q = 1.08 \pm 0.44$  at  $\sim 10^{43} \text{ erg s}^{-1}$  to  $Q = 0.57 \pm 0.22$  at  $\sim 10^{44} \text{ erg s}^{-1}$  to  $Q = 0.23 \pm 0.15$  at  $\sim 10^{45} \text{ erg s}^{-1}$ .

## 8. Summary and conclusions

We have discussed here the cosmological properties of the 62 AGN belonging to the XMM-Hard Bright Serendipitous Survey, a complete and representative sample of bright ( $f_X \geq 7 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ ) serendipitous *XMM-Newton* sources selected in the 4.5–7.5 keV energy band on a sky area of  $\sim 25 \text{ deg}^{-2}$ . Since the HBSS sample is almost completely spectroscopically identified (ID rate  $\sim 97\%$ ), it allows us to have an unprecedented and unbiased view of the extragalactic 4.5–7.5 keV sky in the bright flux regime. Using an  $N_{\text{H}}$  dividing value of  $4 \times 10^{21} \text{ cm}^{-2}$  (see Sect. 2.1), the HBSS AGN sample is composed of 40 unabsorbed (or marginally absorbed) AGN and 22 absorbed AGN.

The main results reported and discussed in this paper are:

1. The HBSS survey is extremely efficient in finding type 2 QSO, i.e., absorbed AGN with an intrinsic luminosity above  $10^{44} \text{ erg s}^{-1}$ . They represent  $(15 \pm 6)\%$  of the total AGN population and  $(41 \pm 13)\%$  of the absorbed ones. At the flux limit of the HBSS survey ( $\sim 7 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the 4.5–7.5 keV energy range) the measured surface density of type 2 QSOs is  $0.36^{+0.13}_{-0.12} \text{ deg}^{-2}$  ( $0.28^{+0.15}_{-0.10} \text{ deg}^{-2}$  if we consider only the 7 type 2 QSO with  $N_{\text{H}} > 10^{22} \text{ cm}^{-2}$ ). At the same flux limit the measured surface density of absorbed (unabsorbed) AGN is  $0.87^{+0.23}_{-0.18}$  ( $1.59^{+0.25}_{-0.25} \text{ deg}^{-2}$ ) and the observed fraction of absorbed AGN is  $(37 \pm 7)\%$ .
2. The de-evolved ( $z = 0$ ) 2–10 keV X-ray luminosity function of the total AGN population derived using the AGN HBSS sample is in very good agreement with the local AGN XLF obtained by Sazonov & Revnivtsev (2004) using the data from the Rossi X-ray Timing Explorer survey. A smaller normalization (a factor between 2.5 to 5 times depending on  $L_X$ ) is observed if compared with the local HEAO1 AGN XLF as recently computed from Shinozaki et al. (2006).
3. Absorbed and unabsorbed AGN are characterized by two different XLF with the absorbed AGN population being described by a steeper XLF, if compared with the unabsorbed ones, at all luminosities.

4. The intrinsic fraction of absorbed AGN with  $L_X \gtrsim 3 \times 10^{42} \text{ erg s}^{-1}$  (i.e., around the luminosity of the faintest absorbed AGN in the HBSS sample) is  $0.57 \pm 0.11$ . This is in excellent agreement with the fraction found using hard ( $E > 10 \text{ keV}$ ) selected (local) samples of AGN from INTEGRAL/Swift surveys at a flux limit of  $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ .
5. The fraction  $F$  of absorbed AGN is a function of luminosity. A comparison of our results with those reported in Akylas et al. (2006) (obtained using a source sample at fainter fluxes and thus at higher  $z$ ) seem to suggest an evolution of the fraction of absorbed AGN with  $z$ . This evolution is consistent with that recently discussed in Treister & Urry (2006) and in Ballantyne et al. (2006).
6. We find a flat  $\text{Log } N_{\text{H}}$  distribution for  $N_{\text{H}}$  between  $10^{20}$  and  $10^{24} \text{ cm}^{-2}$ , still in very good agreement with local samples of hard ( $E > 10 \text{ keV}$ ) selected AGN at a flux limit of  $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ .
7. The shape of the  $F-L_X$  relationship and the derived flat  $\text{Log } N_{\text{H}}$  distribution (both in good agreement with the assumptions and the results of La Franca et al. 2005) are not consistent with the current models for the production of the cosmic X-ray background based on the absorbed AGN. This disagreement, probably due to the fact that we are not sampling the X-ray source population producing the bulk of the CXB, may require a revision in the current model's parameters, e.g. an increase of the fraction of absorbed sources with redshift and/or a  $N_{\text{H}}$  distribution, which depends on the source luminosity, redshift or both.
8. By comparing the results obtained here with the behavior of the fraction of optically-selected narrow-line AGN, derived by Simpson (2005) using a complete, magnitude-limited, sample of active galaxies from the Sloan Digital Sky Survey, we have derived, in an indirect way, the X-ray luminosity function of Compton thick AGN; it is described by a smoothly connected two power-law function (see Sect. 3.2) having  $\gamma_1 = 1.55$ ,  $\gamma_2 = 2.61$ ,  $\text{Log } L_\star = 44$ ,  $\text{Log } A_{\text{Thick}} = -6.32$ . The density ratio,  $Q$ , between Compton thick AGN ( $N_{\text{H}} \geq 10^{24} \text{ cm}^{-2}$ ) and Compton thin AGN ( $N_{\text{H}} \leq 10^{24} \text{ cm}^{-2}$ ) decreases from  $Q = 1.08 \pm 0.44$  at  $\sim 10^{43} \text{ erg s}^{-1}$  to  $Q = 0.57 \pm 0.22$  at  $\sim 10^{44} \text{ erg s}^{-1}$  to  $Q = 0.23 \pm 0.15$  at  $\sim 10^{45} \text{ erg s}^{-1}$ .
9. Finally, the decreasing fraction of absorbed AGN as a function of the luminosity is fully consistent with the hypothesis of a reduction of the covering factor of the *gas* component as a function of the luminosity. A similar reduction with the luminosity of the covering factor of the circumnuclear *dust* component has been recently pointed out by Maiolino et al. (2007) using a sample of AGN observed with *Spitzer*. These results are clearly inconsistent with the simplest unified scheme of AGN. Indeed, we found an excellent agreement between our results and the predictions of the radiation-limited clumpy dust torus discussed in Hönig & Beckert (2007). An alternative model, which also explains our results well has been recently discussed by Lamastra et al. (2006) and is based on the obscuration due to molecular gas in a disk located far away from the X-ray source (between 25 and 450 pc depending on the BH mass).

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## Appendix A: Computation of the intrinsic 2–10 keV XLF using the HBSS AGN sample

In Sect. 3, we have derived the intrinsic 2–10 keV XLF of absorbed and unabsorbed AGN using the HBSS AGN sample selected in the 4.5–7.5 keV energy band. To this end, we have used the  $1/V_a$  method, a well-established procedure to derive space densities of interesting astronomical objects (Avni & Bahcall 1980).

However, to apply this method to the absorbed AGN population the following considerations have to be taken into account. Given an intrinsic count rate (i.e., the count rate we would have observed without intrinsic absorption), the observed count rate is a function of the absorbing column density  $N_H$  (at the source redshift) and of the energy selection band. Therefore, a given source with an intrinsic count rate above the survey threshold could have been missed in the survey since, because of the absorption, its observed count rate falls below the survey count rate threshold.

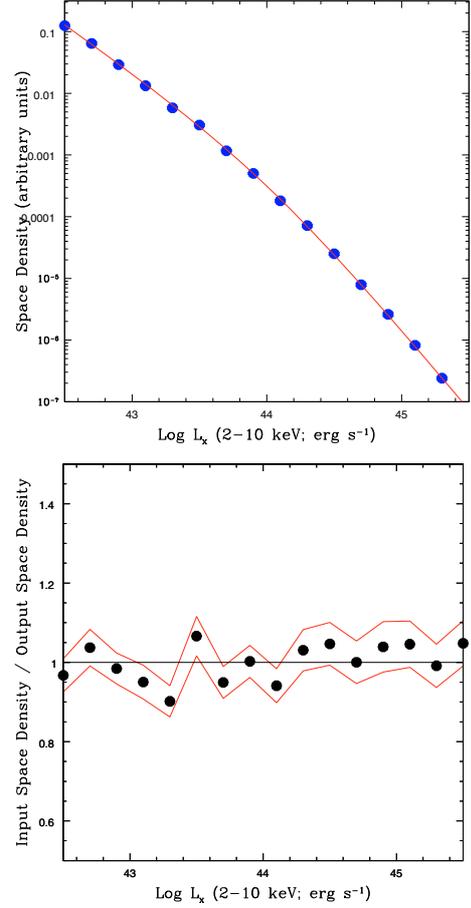
In order to compute the  $z_{\max}$  of each source (absorbed or not), in Sect. 3 we have used the observed MOS2 count rate in the selection band (4.5–7.5 keV) and the count rate limit of the HBSS survey in the same energy band ( $=2 \times 10^{-3}$  cts/s). The intrinsic (2–10 keV) luminosities (as derived from the X-ray spectral analysis of each source) have been thus used to divide the sources into luminosity bins and to derive the luminosity function. A similar procedure was recently used by Shinozaki et al. (2006) in computing the local luminosity function of the absorbed and unabsorbed AGN in the HEAO1 surveys; however, Shinozaki et al. (2006) did not prove the correctness of this approach and, in particular, if this approach may recover the *true* space density of the absorbed AGN population.

To investigate this aspect we have simulated a source sample assuming:

- a 2–10 keV local luminosity function described by a smoothly connected two power-law function (see Sect. 3.2) having the following parameters  $\gamma_1 = 1.55$ ,  $\gamma_2 = 2.61$ ,  $\text{Log } L^* = 44$ . These parameters are those describing the intrinsic 2–10 keV XLF of the absorbed AGN population in the HBSS survey;
- a LDDE cosmological evolution model (see Sect. 3.1) having best fit parameters as follows:  $p_1 = 6.5$ ,  $p_2 = -1.15$ ,  $z_c^* = 2.49$ ,  $\alpha = 0.20$ ,  $\text{Log } L_a = 45.80$ ; and
- a flat intrinsic  $\text{Log } N_H$  distribution from  $10^{20}$  to  $10^{25} \text{ cm}^{-2}$ .

Folding all this information together, we have produced a simulated sample of  $\sim 40\,000$  sources that would be visible at the count rate threshold of the HBSS survey. For each source we have computed the observed count rate in the 4.5–7.5 keV, the redshift, the absorbing column density  $N_H$  and the intrinsic luminosity in the 2–10 keV band. For simplicity we have assumed the same intrinsic photon index ( $\Gamma = 1.9$ ) for all the sources. This simulated sample has been thus analyzed with the same procedure used for the real HBSS source sample, namely, using the observed 4.5–7.5 count rate (and the count rate limit of the HBSS survey), combined with the input LDDE model, to evaluate space densities and the intrinsic (2–10 keV) luminosities to split the sources into luminosity bins.

The results obtained for one extreme example (the sources having an absorbing column density in the range between  $10^{23}$  and  $10^{24} \text{ cm}^{-2}$ ) are shown in Fig. A.1; we have reported the input XLF, the output XLF and the ratio between the derived XLF at  $z = 0$  from the simulated sample and the input local XLF. It is worth noting the very good agreement between the input and



**Fig. A.1.** The results reported in this figure are those relative to the sources filtered by an absorbing column density  $N_H$  between  $10^{23}$  and  $10^{24} \text{ cm}^{-2}$ . *Upper panel:* comparison between the input XLF (solid line) and the XLF computed (dots) using the method discussed here. *Lower panel:* ratio between the input and output XLF. The solid lines enclose  $1\sigma$  error bars on this ratio.

output XLF. Similar results have been obtained for less extreme values of the  $N_H$ . For the purpose of this paper the main conclusion we reached using these simulations is that for the HBSS selection band (4.5–7.5 keV) our approach to compute space densities can recover the *true* space density of the AGN population as a function of the intrinsic  $N_H$  up to  $N_H \sim 10^{24} \text{ cm}^{-2}$ , even if in the  $N_H$  bin between  $10^{23}$  and  $10^{24}$  about 50% of the AGN are lost (i.e. the observed count rate is below the survey threshold) because of the intrinsic absorption. Our simulations also show that the above statement is not true for  $N_H$  above  $10^{24}$  where a dramatic number of objects ( $\sim 95\%$  between  $10^{24}$  and  $10^{25}$ ) are lost because of absorption (note that for these high  $N_H$  values the situation could be even worse if Compton scattering is considered). In summary using the HBSS survey and our computation method we can recover the true space density of absorbed AGN up to  $N_H \sim 10^{24} \text{ cm}^{-2}$ , while we are quite inefficient in selecting AGN with an intrinsic  $N_H$  above this value. The shape of the intrinsic XLF, at least for AGN with  $N_H$  up to  $\sim 10^{24} \text{ cm}^{-2}$ , is therefore recovered allowing us to compare the XLF of absorbed and unabsorbed AGN consistently. We have repeated these simulations using different values of the parameters for the XLF and/or for the cosmological evolution, obtaining the same results thus giving us confidence in the overall procedure.