AGN Unification and the X-ray Background

Ezequiel Treister$^{1,2,3}$ and C. Megan Urry$^{2,4}$

treister@astro.yale.edu

ABSTRACT

Active Galactic Nuclei (AGN) unification, which implies a large number of obscured AGN, can explain the optical, infrared and X-ray content of deep multi-wavelength surveys. Here, we show that the same model also successfully explains the spectral shape and intensity of the X-ray background. The simplest possible unified model assumes a constant ratio of obscured to unobscured AGN, independent of redshift or luminosity. With almost no free parameters, the predicted X-ray background agrees remarkably well with observations. Both the observed properties of deep AGN samples and the X-ray background can be explained by the same model without invoking different evolution for obscured and unobscured AGN. Recent observational evidence shows that the ratio of obscured to unobscured AGN may depend on luminosity. An AGN unification model that allows for such a dependence also fits the X-ray background spectrum, and the predicted numbers counts in the 2-10 keV X-ray band are in good agreement with observations. We present predictions for the source counts in hard X-rays (10-100 keV), which indicate that future missions like the Black Hole Finder will observe thousands of heavily obscured AGN.

Subject headings: galaxies: active — X-rays: diffuse background

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1Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520.
2Yale Center for Astronomy & Astrophysics, Yale University, P.O. Box 208121, New Haven, CT 06520
3Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile.
4Department of Physics, Yale University, P.O. Box 208120, New Haven, CT 06520.
1. Introduction

More than forty years after its discovery, the nature of the X-ray background emission is still debated. About 80% of the background at low energies ($\lesssim 4$ keV) has been resolved into point sources (Mushotzky et al. 2000). Above 4 keV the situation is less clear, especially above 10 keV, where only a small fraction of the X-ray background has been resolved (Worsley et al. 2004). Since obscured AGN have a hard X-ray spectrum — harder than the typical unobscured AGN — they can be used to explain the observed spectrum of the X-ray background at energies from a few to $\sim 30$ keV (Setti & Woltjer 1989).

Early attempts to explain the X-ray background emission using AGN population synthesis models (Madau et al. 1994; Comastri et al. 1995; Gilli et al. 1999; Pompilio et al. 2000) needed to assume a changing ratio of obscured to unobscured AGN with redshift and/or luminosity. However, recent observational evidence (Gilli 2004) suggests that this ratio is constant with redshift. More recent calculations (Ueda et al. 2003; Gandhi & Fabian 2003) also assumed a constant obscured-to-unobscured AGN ratio with redshift; however, Ueda et al. (2003) assumed that this ratio changes with luminosity, while Gandhi & Fabian (2003) assumed different luminosity functions for obscured and unobscured AGN. Treister et al. (2005) pointed out that the previously reported dependence of this ratio with luminosity, more obscured AGN at lower luminosities, can arise naturally from selection effects, for samples extending to high redshift. More recently, Barger et al. (2005) presented a much larger and highly complete sample of X-ray selected AGN in which this dependence is still observed at low redshifts.

A general problem for these population synthesis models is the low redshift peak observed in X-ray selected AGN samples in deep surveys (e.g. Hasinger 2002; Szokoly et al. 2004; Barger et al. 2003), at $z \sim 0.7$, whereas the models predict a peak at $z \sim 2$, similar to optical quasar surveys (Boyle et al. 2000). Another problem is the discrepancy between the observed and predicted ratios of obscured to unobscured AGN. While most models need a ratio of 4:1 or higher to make up the hard X-ray peak in the X-ray background spectrum, the observed ratio in the deep X-ray surveys based on spectroscopic identifications is closer to $\sim 2:1$ (e.g. Barger et al. 2003; Szokoly et al. 2004). Both problems were addressed by Treister et al. (2004), who showed that a simple AGN unification model with constant ratio of 3:1 could account for the multiwavelength observations of hard X-ray selected AGN sample in the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) fields.

Here we verify that population synthesis using AGN unification models with co-evolving populations of obscured and unobscured AGN can reproduce the X-ray background spectral shape and intensity in the 1–100 keV energy range. This is true for both the simplest AGN unification model, in which the obscured-to-unobscured ratio is constant with luminosity and
redshift, and for a modified unification model in which this ratio changes with luminosity. We also predict the AGN number counts in the hard X-ray 10-100 keV band, which will be observed by future missions like the “Black Hole Finder” Einstein Probe. Specifically, EXIST (Grindlay et al. 2003) will see as many as 20,000 AGN in all-sky observations, while pointed missions like NuStar (Harrison & NuSTAR Science Team 2004) will see several hundred AGN per square degree, depending on the final spatial resolution ($\sim 1000$ sources deg$^{-2}$ at $f_{10-100} = 2 \times 10^{-14}$ erg cm$^{-2}$s$^{-1}$). These hard X-ray missions will have the sensitivity to detect all the active supermassive black holes out to high redshifts, and the most luminous AGN at any redshift, allowing for the determination of black hole demographics throughout the Universe.

Throughout this paper we assume $H_0 = 70$ kms$^{-1}$Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. Population Synthesis Using a Unified AGN Model

The simplest AGN unification model assumes that dust and gas surrounds the central engine in a toroidal geometry, which dictates the distribution of $N_H$ column density along the line of sight. Treister et al. (2004) developed a family of self-consistent AGN spectra for this model, as a function of orientation and intrinsic hard X-ray luminosity, from which they calculated the expected AGN number counts in optical and X-ray bands. Here we sum the X-ray spectra of AGN, modified appropriately by absorption, and compare to the observed X-ray background. Although the distribution of $N_H$ is actually continuous, we define “obscured” and “unobscured” AGN as those with $N_H$ greater than and less than $10^{22}$ cm$^{-2}$, respectively. Extensive details of the model assumptions are given by Treister et al. (2004) and the parameters used are discussed below.

2.1. X-ray Spectra

AGN X-ray emission above 2 keV can be well represented by an attenuated power law of the form:

$$\frac{dN(E)}{dE} \propto E^{-\Gamma} e^{-\sigma(E)N_H} e^{-E/E_c},$$

where $N(E)$ is the number of photons with energy $E$; $\Gamma$ is the power-law photon index; $\sigma(E)$ represents the cross section for photoelectric absorption of soft X-rays, given by Morrison & McCammon (1983) assuming solar abundance of metals; $N_H$ is the neutral hydrogen column
density along the line of sight; and $E_c$ is the cutoff energy. In this work we assume typical values for the intrinsic power law slope, $\Gamma = 1.9$ (e.g., Nandra & Pounds 1994; Nandra et al. 1997; Mainieri et al. 2002), and the cutoff energy, $E_c = 300$ keV (Matt et al. 1999). Later we explore the effects of changing these parameters (§2.3).

At hard X-ray energies ($E \gtrsim 10$ keV), the contribution to AGN spectra from emission reprocessed by the accretion disk is significant. To account for this emission we used the Compton reflection models of Magdziarz & Zdziarski (1995) assuming solar abundance of metals, a 2 times solar iron abundance and an average inclination angle with respect to the line of sight of $\cos i = 0.45$; we verified that this angle gives a spectrum very similar to the average spectrum over all angles. The assumed iron abundance is consistent with observations of local AGN, where values of 1-2 times solar are commonly found (Nandra & Pounds 1994), and values as high as $\sim 3 \times$ solar have been measured (Boller et al. 2002). We note that for energies below the peak of the X-ray background, $E \lesssim 30$ keV, a power law spectrum with $\Gamma = 1.7$ is very similar to a spectrum with $\Gamma = 1.9$ plus a reflection component (Ueda et al. 2003).

### 2.2. AGN Luminosity function and the $N_{HI}$ Function

For this work we use the hard X-ray (2-10 keV) AGN luminosity function and evolution of Ueda et al. (2003), which is based on a compilation of ASCA, HEAO-1 and Chandra observations. Recently, a new hard X-ray luminosity function was presented by Barger et al. (2005), based on a much larger sample; however, because an analytical fit of the luminosity function is given only for low redshifts ($z < 1.2$), we use the Ueda et al. (2003) in this work. (In any case, high-redshift luminosity functions at $z > 1.2$ are not that well-determined, so the analytic fit is necessarily uncertain.) We note that in the redshift range over which AGN contribute significantly to the X-ray background, $z \sim 0.5 - 1$, the luminosity functions of Ueda et al. (2003) and Barger et al. (2005) are very similar, so the choice of luminosity function should not affect our results for the synthesized X-ray background.

A key new feature of the Ueda et al. (2003) luminosity function is the luminosity-dependent density evolution, in which low luminosity AGN peak at lower redshift than high luminosity sources. Similar evolution has been seen in optical quasar surveys (e.g. Boyle et al. 2000); in that case, the observed redshift distribution actually peaks at high redshift, $z \sim 2$, because those surveys are sensitive only to high luminosity AGN. In contrast, deep X-ray selected samples include low luminosity AGN, and those with small area, such as the Chandra Deep Fields, actually exclude high luminosity AGN because of the limited volume sampled.
To calculate the number of AGN as a function of $N_H$ we assume a simple dust torus in which the geometrical parameters give an obscured to unobscured AGN ratio of $\sim 3:1$ (Treister et al. 2004), consistent with observations of AGN in the local Universe (Risaliti et al. 1999). In order to account for the presence of Compton-thick sources we increased the equatorial column density of Treister et al. (2004) from $N_H = 10^{24}$ cm$^{-2}$ to $N_H = 10^{25}$ cm$^{-2}$. This does not affect observations at energies lower than 10 keV so it has no effect on the results presented by Treister et al. (2004). The Ueda et al. (2003) luminosity function is based on Compton-thin AGN, and so the normalization applies to AGN with $N_H < 10^{24}$ cm$^{-2}$; the number of additional Compton-thick AGN is then given by the $N_H$ distribution. This adds $\sim 47\%$ more AGN to the original sample of Treister et al. (2004), none of which would be detected in even the deepest Chandra observations. Fig. 1 shows that the $N_H$ distribution observed for the X-ray sources in the GOODS fields (Treister et al. 2004) agrees well with the predictions of the dusty torus model for the GOODS flux limit ($f_X > 2 \times 10^{-16}$ erg cm$^{-2}$s$^{-1}$), particularly considering the uncertainties in the $N_H$ determination for the observed sample and the fact that none of the parameters in the model were adjusted to obtain a better fit to the observations. The only exception is that the number of observed sources in the $10^{20}$ cm$^{-2}$ $N_H$ bin is significantly higher than the predicted value. This is because some sources will have soft X-ray excesses, in which case our conversion of observed hardness ratio into $N_H$ using a simple power law will significantly underestimate the amount of absorption present in the X-ray spectrum.

### 2.3. Free Parameters

Although in this calculation there are many parameters, the vast majority are fixed by observations. Eight (fixed) parameters describe the luminosity function and evolution. The ratio of obscured to unobscured AGN is fixed by the locally observed value; when modified as a function of luminosity, two more parameters are added (the luminosity range over which the percentage of obscured AGN is allowed to vary from 0 to 100%). The distribution of $N_H$ is constrained so that the equatorial value is $10^{25}$ cm$^{-2}$, since Compton-thick AGN are observed locally. The remaining parameters describe the X-ray spectrum, and only two of these were adjusted to fit the observed X-ray background, namely the universal cutoff energy, $E_c$, and the iron abundance. The choice of cutoff energy is relevant for $E \gtrsim 80$ keV, while the iron abundance affects the emission in the $E \sim 10−20$ region, so the two parameters can be determined independently. We chose the highest cutoff energy that does not overproduce the observed X-ray background at $E \simeq 100$ keV, namely, $E_c = 300$ keV, and we chose the minimum iron abundance needed to produce the absorption edge at $E \simeq 10$ keV while not overproducing the total emission around that energy. In both cases, the assumed values
are in good agreement with observations of individual AGN, and so cannot be adjusted arbitrarily. Roughly speaking, acceptable fits can be obtained for $200 \text{ keV} \lesssim E_c \lesssim 400 \text{ keV}$ and iron abundances in the range $\sim 1.5 - 3$ solar.

3. Discussion

3.1. The X-ray Background Fit with the Simple Unified Model

The simplest unified AGN model we consider has a fixed 3:1 ratio of obscured to unobscured AGN, independent of redshift or luminosity. We calculate the total X-ray emission from the AGN population, integrating over luminosities $10^{41.5} \text{ erg s}^{-1} < L_X < 10^{48} \text{ erg s}^{-1}$, redshifts $0 < z < 5$, and column densities $10^{20} \text{ cm}^{-2} < N_H < 10^{25} \text{ cm}^{-2}$. Sources with $L_X < 10^{41.5} \text{ erg s}^{-1}$ or $z > 5$ do not contribute significantly to the X-ray background (Ueda et al. 2003). For sources with $N_H > 10^{25} \text{ cm}^{-2}$, the large amount of obscuration blocks almost all the primary emission and makes their total contribution to the X-ray background negligible (Gilli et al. 1999). The contribution of galaxy clusters in the soft X-ray region ($E \sim 1 \text{ keV}$) was added following the prescription of Gilli et al. (1999); this component is relevant only for very low energies, $E \sim 1 \text{ keV}$, and even then is only $\sim 10\%$ of the total X-ray background emission. The predicted X-ray background spectrum using this model is presented in Fig. 2.

We compare these predictions with HEAO-1 observations of the X-ray background compiled by Gruber et al. (1999). More recent observations at 2-10 keV using XMM (De Luca & Molendi 2004) agree in shape but have 40% higher normalization than the HEAO-1 data (Marshall et al. 1980). This higher value of the X-ray background intensity was observed also in other missions like BeppoSAX (Vecchi et al. 1999) and ASCA (Kushino et al. 2003). While a full reanalysis of the Marshall et al. (1980) HEAO-1 data is beyond the scope of this paper, we adopt a value of the normalization that is 40% higher than the original HEAO-1 data in order to match the XMM data, a procedure followed by other authors previously (e.g., Ueda et al. 2003; Worsley et al. 2005). Consequences of this assumption have been discussed by other authors. For example, Barger (2003) concluded that if the higher normalization is assumed there is very good agreement between the XRB intensity and the number of resolved sources in deep Chandra observations. If instead the XRB intensity at high energies is lower, this will reduce the number of obscured and/or Compton-thick AGN needed to explain the observations.

In Figure 2 our simple population synthesis model is compared to the observed data points and an analytic fit from Gruber et al. (1999). The agreement between predictions and
observations is remarkably good especially given the low number of free parameters in the calculation; the $\chi^2$ per degree of freedom for $E < 100$ keV is 0.794. The residuals are very small below $E > 100$ keV; at higher energies, unresolved blazars (not included here) become dominant (see Gruber et al. 1999 and references therein). There is a small discrepancy at $E \sim 40$ keV, $\lesssim 5\sigma$, which can be greatly reduced by adding a few ($\sim 5 - 10\%$) obscured AGN with super-solar iron abundances (which makes the reflection component peak at higher energies; Wilman & Fabian 1999). However, given the low significance of this discrepancy and the ad hoc nature of the solution, we did not add these sources to our model.

This is the first time the X-ray background has been well fitted by a model fully consistent with the simplest AGN unification paradigm, i.e., with a constant ratio of obscured to unobscured AGN, independent of intrinsic luminosity or redshift. As shown by the thin solid lines on Fig. 2, unobscured AGN dominate the energy budget in the soft X-ray regime ($E \lesssim 3$ keV) while obscured AGN clearly dominate at higher energies. A similar conclusion was presented by Bauer et al. (2004) using a detailed analysis of the AGN number counts in the Chandra Deep Fields.

### 3.2. The Modified Unified Model

An apparent dependence of the obscured to unobscured AGN ratio with luminosity has been reported (Hasinger 2004; Ueda et al. 2003; Steffen et al. 2003). One interpretation is that the torus is evaporated by radiation (Lawrence 1987). Indeed, the Ueda et al. (2003) population synthesis model for the X-ray background differs from the calculation above because it assumes that there are relatively more obscured AGN at lower luminosities. Treister et al. (2005) showed that this observed trend with luminosity could be explained as a selection effect, whereby high-redshift obscured AGN are too faint for optical spectroscopy and thus do not have known redshifts or luminosities. This also can explain the low peak in the redshift distribution in deep surveys (e.g., Hasinger 2004). Barger et al. (2005) have recently reported this dependence of ratio on luminosity still pertains at low redshift, where selection effects are not important (Steffen et al. 2003). (This is the first time a sample has been large enough to determine obscured-to-unobscured ratio as a function of luminosity at low redshift.) The simple unified model predicts that the effects of incompleteness are only important at $z > 1$, therefore at lower redshifts this ratio is predicted to be constant. In Fig. 3, we compare the predictions of the simple unification model to the Barger et al. (2005) observations, with which they clearly disagree.

In order to account for this effect, we modify the simple unification model so that the percentage of obscured AGN varies linearly from 100% at $L_X = 10^{42}$ erg s$^{-1}$ to 0% at
\[ L_X = 3 \times 10^{46} \text{ erg s}^{-1}. \] This new modified unification model agrees very well with the Barger et al. (2005) data, as shown in Fig. 3, and is also consistent with the observed optical and X-ray number counts in the GOODS fields. (The model distributions are very similar to the simple unification case, Figs. 6 and 7 in Treister et al. (2004), and so are not reproduced here.)

This modified unified model can also explain the spectral shape and normalization of the X-ray background, as shown in Fig. 4; the agreement is good, with a reduced \( \chi^2 \) of 0.648. According to this model, the contribution of unobscured AGN is slightly more important than in the simple unified model since obscured AGN are found only at low luminosities. The maximum contribution to the X-ray background comes from moderate luminosity AGN, as shown in Fig. 4b, with luminosities in the \( 10^{43} - 10^{44} \text{ erg s}^{-1} \) range. A significant contribution also comes from sources with lower luminosities, while the contribution from high-luminosity AGN/quasars (\( L_X > 10^{45} \text{ erg s}^{-1} \)) is negligible.

The possible dependence on redshift is less clear. We combined existing data from the CDF-N, CDF-S and CLASXS (Steffen et al. 2004) surveys, which have the highest spectroscopic completeness levels, in order to obtain a large sample of 189 mostly identified X-ray sources with \( f_X > 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \). This sample is essentially the Barger et al. (2005) sample minus the 32 bright ASCA sources, which we excluded in order to have an uniform coverage down to the X-ray flux limit.

Fig. 5 shows the observed unobscured-to-total and obscured-to-unobscured AGN ratios versus redshift, for sources with hard X-ray flux greater than \( 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \). Excluding fainter X-ray sources means the spectroscopic completeness of this sample is very high (66%). The agreement between the modified model and observations is good up to \( z \sim 1 \). At higher redshifts an apparent increase in the unobscured-to-total ratio with redshift is observed, contrary to the predictions of both our simple and modified models. However, this may be due to the difficulty of obtaining spectroscopic redshifts for obscured AGN at \( z > 1 \) (e.g., Gandhi & Fabian 2003).

In particular, we considered whether the effects of incompleteness in this sample could explain the apparent discrepancy. The unidentified sources could be either obscured or unobscured AGN; we looked at the limits on the data obtained by assigning all the unidentified sources to either obscured or unobscured sources. Specifically, for the ratio-versus-redshift plots, we assigned unidentified sources (of unknown redshift) to redshift bins by weighting the volume in that bin relative to the total volume of the sample. If they are all unobscured AGN one gets the upper (lower) line in Figure 5a(b); if they are all obscured AGN one gets the lower (upper) line in Figure 5a(b).
As Figure 5 shows, the allowed region is consistent with the modified unification model, that is, with a unified scenario in which the obscured-to-unobscured AGN ratio does not change with redshift. A similar result was obtained previously using similar (but less complete) samples (e.g., see Gilli 2004), with somewhat larger error bars. Not until redshifts can be measured for obscured AGN at high redshift will this issue of a possible redshift dependence be resolved. Since spectroscopic redshifts are impossible at such faint flux levels, medium-band spectrophotometry is necessary in order to determine whether obscured and unobscured AGN evolve differently. If they do, AGN unification at higher redshift will be ruled out.

3.3. AGN Number Counts

Figure 6 shows the cumulative distribution of sources as a function of flux (the log $N$ − log $S$ plot), calculated using the modified unification model for three different X-ray bands: 0.5-2 keV, 2-10 keV and 10-100 keV. (The curves are not very different for the simple unified model.) The effects of absorption are most significant in the lowest energy band, where $\sim 60\%$ of the AGN are completely obscured and thus invisible in soft X-rays. The predicted number counts in the 2-10 keV bands agree well with the observed distribution compiled by Moretti et al. (2003). At the flux level of the deepest Chandra observations, this model suggests that only $\sim 50\%$ of the AGN are detected (Treister et al. 2004).

The resolved fraction of the X-ray background in deep Chandra/XMM surveys goes from $\sim 95\%$ in the 0.5-2 keV band to $\sim 70 - 80\%$ in the 2-7 keV band, to $\lesssim 50\%$ at higher energies (Bauer et al. 2004; Worsley et al. 2004). The properties of the unresolved sources are not the same as those of already detected AGN. Unresolved sources must have a much harder X-ray spectrum (Worsley et al. 2004) and therefore are likely to be obscured AGN. These AGN should be detected easily in surveys at $E \gtrsim 10$ keV, which are unaffected by dust obscuration, and will be also detected in deep infrared surveys, where most of the dust re-emission occurs. In Fig. 6 (solid line) we show the predicted log $N$ − log $S$ distribution for 10-100 keV surveys, together with the expected flux limits for example hard X-ray missions like EXIST and NuStar. At the flux limit of a typical NuStar observation we expect to have $\sim 800$ AGN per deg$^2$, $\sim 60\%$ of them obscured AGN, including $\sim 10\%$ Compton-thick. For the EXIST flux limit, the expected source density is $\sim 1$ AGN per deg$^2$, about 50% of them obscured AGN ($\sim 6\%$ Compton-thick). EXIST covers a much larger area, so will detect a much larger sample of AGN, roughly 40,000 all-sky.
4. Conclusions

Using the simplest AGN unification model we have explained the spectral shape and intensity of the X-ray background. This is the first demonstration that a model assuming a constant ratio of obscured to unobscured AGN, independent of redshift or luminosity, can simultaneously explain the observed X-ray background and the optical and X-ray counts of AGN detected in deep X-ray surveys (Treister et al. 2004). At the same time, a model that incorporates a changing ratio with luminosity, as suggested by recently available observations, can also successfully explain the X-ray background properties. The integral constraint of the X-ray background clearly does not provide a sensitive probe of the fraction of the obscured AGN; other observations, in particular a high-flux X-ray sample (\(\gtrsim 10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\)) with a very high spectroscopic completeness level (>90%), is needed to test whether the ratio depends on redshift, i.e., whether the evolution of obscured and unobscured AGN is different. At present, unification by orientation — in which obscured and unobscured AGN have the same evolution — is consistent with the data. In order to obtain this highly complete sample, accurate redshifts for sources with optical magnitudes \(24 \lesssim R \lesssim 27\) are needed. This is impossible with current state-of-the-art 8m-class telescopes. However, good photometric redshifts using medium-band filters down to these magnitudes are possible and will allow to solve the redshift dependence problem.

The log \(N\) − log \(S\) distribution predicted by the modified AGN unification model is in very good agreement with existing observations in the 2-10 keV band. The resolved fraction of the X-ray background is \(\lesssim 50\%\) in the 7-10 keV band and decreases with increasing energy. If the unification model presented here is correct, \(\sim 50\%\) of AGN are currently missed by deep Chandra or XMM surveys. These are very obscured AGN that will be detected only by hard X-ray observatories, like the Black Hole Finder probe, at X-ray energies where the effects of dust obscuration are negligible. These surveys will detect a large fraction of the most obscured AGN, providing for the first time an unbiased census of the black hole activity in the Universe.

ET would like to thank the support of Fundación Andes, Centro de Astrofísica FONDAP and the Sigma-Xi foundation through a Grant in-aid of Research. This work was supported in part by NASA grant HST-GO-09425.13-A. We thank Duane Gruber for providing us his observational data in electronic format and the anonymous referee for a very detailed and critical review of this paper and for pointing our recently available observational results.
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Fig. 1.— Distribution of neutral hydrogen column density ($N_H$) along the line of sight calculated assuming the simple unified model described in the text (thick solid line). Dashed line: Observed $N_H$ distribution for sources in the GOODS fields as computed by Treister et al. (2004) assuming an intrinsic power-law with $\Gamma = 1.7$ and no reflection component. Only Poisson errors are shown. Dotted line: $N_H$ distribution predicted by the model for sources brighter than $2 \times 10^{-16}$ erg cm$^{-2}$s$^{-1}$ in the 2-10 keV band (roughly the flux limit for the GOODS fields). The agreement between the observed and predicted distributions is very good, particularly considering the uncertainties in determining the $N_H$ value for faint X-ray sources. Highly obscured sources ($N_H > 10^{23.5}$ cm$^{-2}$) are not detected in the Chandra Deep Fields. An apparent excess of observed sources at $N_H \sim 10^{20}$ cm$^{-2}$ is due to complex X-ray spectra not modeled in our analysis.
Fig. 2.— Upper panel: Observed X-ray background spectrum (points) as compiled by Gruber et al. (1999) based on HEAO-1 observations. Dashed line: Analytic fit to the observed data from Gruber et al. (1999). In both cases the overall normalization was increased by a factor of 1.4 in order to match the observations in the 2-10 keV band, as described in detail by De Luca & Molendi (2004) and Worsley et al. (2005). Thick solid line: Integrated AGN emission for the simple unified model described in Section 3.1. Separate contributions from obscured and unobscured AGN are shown by the thin solid lines. Bottom panel: Residuals (observed/fit). the quality of the fit below 100 keV is excellent ($\chi^2$/DOF=0.794). At $E > 100$ keV, unresolved blazars dominate the X-ray background (see Gruber et al. 1999 and references therein).
Fig. 3.— Unobscured (broad-line) AGN ratio as a function of hard X-rays luminosity in three redshift bins, $z=0.1-0.4$ (upper left panel), $z=0.4-0.8$ (upper right panel) and $z=0.8-1.2$ (lower panel). Filled circles: data from Barger et al. (2005). Solid lines: Unobscured AGN ratio as predicted by our simple unified model. The discrepancy between predictions and observations is very clear. In this redshift range, $z \lesssim 1.2$, the discrepancy cannot be attributed to selection effects since the observed sample is mostly complete both for obscured and unobscured AGN. Therefore, we also used a modified unified model (dashed lines) in which the obscured-to-unobscured AGN ratio decreases with luminosity but is still independent of redshift, i.e., all AGN have the same evolution, consistent with simple unification by orientation. The modified unification model agrees well with observations.
Fig. 4.— Left Panel: X-ray background population synthesis for the modified AGN unification model, with the fraction of obscured AGN decreasing with increasing luminosity (solid lines, as in Fig. 2). The agreement with observations (data points, dashed line, as in Fig. 2) is very good, with a reduced $\chi^2$ of 0.648. The contribution by unobscured AGN is more important here than in the simpler unification model shown in Fig. 2 since obscured AGN are found only at low luminosities. Right Panel: Same as left panel, but showing the contribution from sources in the log $L_X=41.5$-43, 43-44 and 44-45 bins. The maximum contribution to the X-ray background comes from sources with log $L_X=43$-44, that is, moderate luminosity AGN.
Fig. 5.—*Left Panel:* Ratio of unobscured-to-total AGN as a function of redshift. The classification is the same as in Fig. 19 of Barger et al. (2005). *Circles:* Observed data points for sources with hard X-ray flux higher than $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ for which the spectroscopic completeness level is 66%. *Thin solid lines:* Effects of adding the unidentified sources to each bin, weighting by the comoving volume on each redshift bin, assuming that all the unidentified sources are obscured (lower line) or unobscured (higher) AGN. *Thick lines:* Predicted ratio as a function of redshift for the simple (dotted) and modified (dashed) unified models. *Right Panel:* Same as left panel but for the obscured-to-unobscured AGN ratio versus redshift.
Fig. 6.— Predicted cumulative log $N - \log S$ distribution in the 0.5-2 keV (dotted line), 2-10 keV (dashed line) and 10-100 keV (solid line) X-ray bands. Shaded region: Observed log $N - \log S$ distribution (including 1σ uncertainties) in the 2-10 keV band (Moretti et al. 2003). The agreement between predictions and observations is very good. The predicted distribution implies that only $\sim 50\%$ of the AGN have been detected at the depth of the Chandra Deep Fields. Vertical dashed lines show the approximate flux limits in the 10-100 keV band for EXIST and NuStar assuming a typical integration time of 40 ks.