Supermassive Black Holes in Deep Multiwavelength Surveys

By C. MEGAN URRY\(^1\) AND EZEQUIEL TREISTER\(^2\)

\(^1\)Department of Physics, Yale University, P.O. Box 208121, New Haven, CT 06520-8121, USA
\(^2\)European Southern Observatory, Casilla 19001, Santiago 19 Chile

In recent years deep X-ray and infrared surveys have provided an efficient way to find accreting supermassive black holes, otherwise known as active galactic nuclei (AGN), in the young universe. Such surveys can, unlike optical surveys, find AGN obscured by high column densities of gas and dust. In those cases, deep optical data show only the host galaxy, which can then be studied in greater detail than in unobscured AGN. Some years ago the hard spectrum of the X-ray “background” suggested that most AGN were obscured. Now GOODS, MUSYC, COSMOS and other surveys have confirmed this picture and given important quantitative constraints on AGN demographics. Specifically, we show that most AGN are obscured at all redshifts and the amount of obscuration depends on both luminosity and redshift, at least out to redshift \(z \sim 2\), the epoch of substantial black holes and galaxy growth. Larger-area deep infrared and hard X-ray surveys will be needed to reach higher redshifts and to probe fully the co-evolution of galaxies and black holes.

1. Cosmic Growth of Black Holes and Galaxies

Abundant evidence indicates that the growth of a supermassive black hole is closely tied to the formation and evolution of the surrounding galaxy. The energy released from accretion onto the black hole affects star formation in the galaxy, probably limiting growth at the high- and low-mass ends, and of course the distribution and angular momentum of matter in the galaxy governs the amount of matter accumulated by the black hole (Silk & Rees 1998; King 2005; Rovilos et al. 2007). Emergent energy from accretion is also a factor in understanding ionization and radiation backgrounds (Hasinger 2001; Lawrence 2001). Understanding the growth history of these black holes is therefore critical to understanding the global evolution of structure in the Universe.

Yet the demographics of supermassive black holes remain elusive. The largest samples of quasars and Active Galactic Nuclei (AGN), by which we mean supermassive black holes in a high accretion-rate phase \(^\dagger\), have been found through optical selection (e.g., the Sloan Digital Sky Survey quasar sample; Schneider et al. 2002, 2007), but, at least locally, these are not representative of the larger AGN population. Instead we need surveys less biased against obscured AGN.

There are three reasons to suspect that most AGN are obscured by large column densities of gas and dust. First, a large body of evidence suggests that local AGN have geometries that are not spherically symmetric, and that different aspect angles present markedly different observed characteristics; this is referred to as AGN unification (Antonucci 1993; Urry & Padovani 1993). Second, AGN are more common at high redshift \((z \sim 2 - 3)\), where the average star formation rate is higher and thus it is even more likely that gas and dust surround the galaxy nucleus than at \(z \sim 0\). Third, and most important, obscured AGN are required to explain the shape of the X-ray “background” radiation.

The X-ray “background” is actually the superposition of individual AGN that were

\(^\dagger\) Some make a distinction between AGN and quasars, with the latter being above an arbitrary luminosity, typically \(M_B = -23\) mag. Here we use the term AGN to refer to an actively accreting supermassive black hole above or below this luminosity.
Figure 1. (Left) The X-ray background spectrum (shown in units of energy per logarithmic band) is very hard, peaking near 30 keV, in contrast to the spectra of unobscured AGN which are roughly horizontal in these units. (Figure from Gilli 2004.) (Right) Large column densities of gas absorb low-energy photons via the photoelectric effect, such that emission from an obscured AGN peaks at an energy that increases with column density. Each line represents a factor of 10 increase in equivalent $N_H$ (lines are marked with log $N_H$ in atoms/cm$^2$; assumes solar abundances and the cross sections of Morrison & McCammon 1983).

not resolved in early X-ray experiments (hence the designation “background”). As shown in Figure 1a, its spectrum peaks at $\sim 30$ keV (i.e., this is where most of the energy is produced), much harder than the typical spectrum (roughly flat in these units) of an unobscured AGN. In obscured AGN, however, the softest X-ray photons have been absorbed via the photoelectric effect, and Compton-thick AGN (those with $N_H \geq 10^{24}$ cm$^{-2}$) actually peak at roughly 30 keV (Fig. 1b). Thus X-ray observations have long indicated there is a large population of heavily obscured AGN (Setti & Woltjer 1989; Comastri et al. 1995; Gilli et al. 2001). While much of the X-ray background has been resolved at low energies, recent work on X-ray deep fields suggests the hardest (most obscured) X-ray sources have yet to be detected (e.g., Worsley et al. 2005).

Relatively unbiased AGN samples require joint hard X-ray and infrared surveys. Hard X-rays ($E > 2$ keV) penetrate all but the thickest column densities and efficiently locate black hole accretion. The absorbed optical through soft X-ray emission heats the surrounding dust and is re-radiated in the infrared, at wavelengths that depend on the dust temperature. Meanwhile, high-resolution optical surveys (e.g., with HST) allow separation of nuclear (AGN) and host galaxy light. Today, NASA’s three operating Great Observatories — the Chandra X-ray Observatory, the Spitzer Space Telescope, and the Hubble Space Telescope — enable matched X-ray, infrared, and optical surveys at unprecedented depth and resolution.

2. Deep Multiwavelength Surveys

The announcement in spring 2000 of the first Spitzer Legacy opportunity led to the Great Observatories Origins Deep Survey (GOODS), to date the deepest wide-area multiwavelength survey carried out with Spitzer, Hubble, and Chandra (Dickinson et al. 2003; Giavalisco et al. 2004). By targeting the Spitzer Legacy, and later the Hubble Treasury, observations on the pre-existing Chandra deep fields, we leveraged substantial investments of observing time, probed AGN demographics at the peak of quasar activity
(\(z \sim 1 - 2\)), and enabled a wide range of other science, described in the *Astrophysical Journal Letters* special edition of January 10, 2004.[1]

The GOODS data are deep enough to detect AGN to very high redshift (\(z \gtrsim 6\)), and the volume sampled ensures sizable AGN samples out to \(z \sim 3\). To sample larger volumes and to search effectively for rare objects like AGN or massive galaxies at high redshift, in 2002 we designed the MUSYC survey (Multiwavelength Survey by Yale and Chile), covering one square degree in two equatorial and two southern fields. Three of the four regions had already been observed extensively, including the Extended Chandra Deep Field South (ECDF-S) and the Extended Hubble Deep Field South (EHDF-S), thus leveraging substantial investments with Chandra, XMM-Newton, HST, and the largest ground-based telescopes.[2]

Soon after starting MUSYC we helped start the COSMOS survey (Scoville et al. 2007), a 2-square degree field centered at 1000+02 that has now been imaged extensively with HST, Spitzer, XMM, and Chandra.[3] The unprecedented combination of area and depth allow a wide variety of science, described in the September 2007 special edition of the *Astrophysical Journal Supplement*. Other relevant multiwavelength surveys include the Lockman Hole (Hasinger et al. 2001), CLASXS (Yang et al. 2004), the Extended Groth Strip (Davis et al. 2007), SWIRE (Lonsdale et al. 2003), XBOOTES (Hickox et al. 2006), HELAS2XMM (Baldi et al. 2002), SEXSI (Harrison et al. 2003), CYDER (Treister et al. 2003), CHAMP (Kim et al. 2004), and AMSS (Akiyama et al. 2003).

### 3. Finding Obscured AGN

The question we set out to answer with GOODS, MUSYC, and COSMOS was, “Is there a substantial population of obscured AGN that is missed by traditional optical surveys?” To answer this question we need to sample the AGN population at \(z \sim 1 - 2\), at the peak of the number density. The GOODS survey, and the Chandra Deep Field South (CDF-S) X-ray survey on which GOODS piggy-backed (Giacconi et al. 2002), were designed to sample the AGN population at \(z \sim 0.5 - 2\), which includes the AGN that make up the X-ray background. Luminous AGN at higher redshifts could certainly be detected but the volume surveyed is too small to expect to see a reasonable number of them.

Early results in the CDFS and other deep X-ray fields showed there was a population of optically faint hard X-ray sources (Alexander et al. 2001; Franceschini et al. 2002a; Mainieri et al. 2005), which collectively comprised a large fraction of the integrated X-ray background intensity. However, as optical counterparts were identified and spectra obtained, several apparent problems emerged. First, the redshift distribution peaked at relatively low values, \(z \lesssim 1\), lower than expected from the early population synthesis.
models for the X-ray background. Second, the fraction of X-ray sources that were identified as obscured, either because of high $N_H$ or absence of broad lines, was less than the canonical $3/4$ seen at low redshift, and appeared to decline with redshift rather than increase, as specified by the best population synthesis model at that time (Gilli et al. 2001).

A number of authors pointed out these problems (e.g., Mainieri et al. 2005; Rosati et al. 2002; Brandt & Hasinger 2005), and Franceschini et al. (2002a) suggested that “the unification scheme based on a simple orientation effect fails at high redshifts” and that the production of the X-ray background by a collection of obscured AGN “requires major revision.”

At the same time, these faint red X-ray AGN were copious emitters of infrared radiation (Treister et al. 2004, 2006), fully consistent with the unification paradigm. It also became apparent early on that, as for optically-selected quasars, the evolution of X-ray selected AGN is luminosity dependent, with high-luminosity AGN evolving earlier and more rapidly than low-luminosity AGN (Ueda et al. 2003; Cowie et al. 2003); this luminosity-dependent density evolution had not been incorporated in earlier population synthesis models for the X-ray background. Finally, we suspected that selection effects could play a significant role in affecting the redshifts and optical identifications of survey sources.

Accordingly, we developed a comprehensive quantitative approach, based on the unification scenario and incorporating the most recent, best luminosity function and evolution, to predict the number counts and redshift distributions at any wavelength (for the moment, infrared through X-ray, though it could be generalized) for surveys of arbitrary area, depth, and wavelength. Here we describe the quantitative interpretation of the multiwavelength data from GOODS, MUSYC, COSMOS and other deep multiwavelength surveys, including the dependence of the obscured fraction of AGN on luminosity and redshift. Specifically, we show that most AGN are obscured at all redshifts; that the fraction of obscured AGN decreases with luminosity; and that it increases with redshift, at least out to redshift $z \sim 2.5$, an epoch of substantial black hole and galaxy growth. Deep infrared and hard X-ray surveys over larger areas will be needed to reach higher redshifts and to probe fully the co-evolution of galaxies and black holes.

3.1. Connecting X-Ray, Optical, and Infrared Surveys

Our approach was to connect surveys at different wavelengths by assuming something sensible about AGN spectral energy distributions (SEDs), then combining those with well-measured luminosity functions and evolution to understand the source counts and redshift distributions of AGN selected at a given flux limit at any wavelength (Treister et al. 2004, 2006; Treister & Urry 2005). Analogous approaches have been taken by Ballantyne et al. 2007 and Dwelly & Page 2006. Simultaneously, we constrain the same AGN population to fit the X-ray background (Treister & Urry 2005). An alternative approach is to model only the X-ray spectra of AGN and to fit the X-ray background alone with a mixture of obscured and unobscured AGN (Comastri et al. 1995; Gilli et al. 2001, 2007); this constrains the demographics but does not connect the X-ray sources to those detected at optical and infrared wavelengths — and thus does not use those additional constraints on the AGN demographics, nor does it allow a quantitative estimate of the important effect of optical or infrared flux limits on the survey content or spectroscopic identifications.

Briefly, our procedure was as follows: We started with the underlying AGN demographics, described by an AGN luminosity function that incorporates dependence on absorbing column density, and the luminosity-dependent evolution of this function (Ueda et al. 2003). Because this luminosity function is based on hard X-ray observations, it is relatively free of bias against obscured AGN.
Figure 2. The infrared spectra of AGN were modeled by dust emission \cite{Nenkova2002} from a clumpy torus geometry (left) that, assuming random orientations and adjusting the torus geometry to give a 3:1 ratio of column densities above:below $N_H = 10^{22}$ cm$^{-2}$, yields an $N_H$ distribution consistent with various observational estimates (see text for details). (Right) Two examples of model SEDs (lines), which are fully determined from $L_X$ and $N_H$. These fit very well the observed SEDs of local unobscured (datapoints, top) and obscured (bottom) AGN, with no free parameters. The composite model SEDs include infrared dust emission, reddened quasar spectra (keyed to $N_H$ value), and an $L_*$ host galaxy, linked to the X-rays by the known optical-to-X-ray ratio (which depends on $L_X$).

We then developed a set of SEDs, based on the unification paradigm, that represent AGN with a wide range in intrinsic luminosity and absorbing column density (parameterized in terms of the neutral hydrogen column density, $N_H$, along the line of sight). Specifically, at optical wavelengths ($\lambda=0.1$-1 microns), we used a Sloan Digital Sky Survey composite quasar spectrum \cite{VandenBerk2001} plus Milky-Way-type reddening laws and a standard dust-to-gas ratio to convert $N_H$ to $A_V$; we also added an $L_*$ elliptical host galaxy, which is the dominant component for heavily obscured AGN. In the X-ray ($E > 0.5$ keV), we assumed a power-law spectrum with photon index $\Gamma = 1.9$, typical of unobscured AGN, absorbed by column densities in the range $\log N_H = 20$-24 cm$^{-2}$. To describe the infrared part of the SEDs ($\lambda > 1$ micron), which in the unification paradigm includes radiation from dust heated by absorbed ultraviolet through soft X-ray photons, we used dust emission models by \cite{Nenkova2002} in a clumpy torus geometry (Fig. 2a), converting to $N_H$ from viewing angle assuming random orientations. The resulting $N_H$ distribution is completely consistent with various observational estimates \cite{Ueda2003, Dwelly2006, Risaliti1999, Comastri1995, Tozzi2006, Gilli2007}. AGN models with the same intrinsic X-ray luminosities were normalized at 100 microns. To connect the ultraviolet and X-ray parts of the SED we used the standard dependence of X-ray to optical luminosity ratio on luminosity \cite[e.g.,][]{Steffen2006}.

The SED models, parameterized in terms of $L_X$ (as a proxy for intrinsic luminosity) and $N_H$ (which depends only on viewing angle and torus geometry), describe extremely well the local population of AGN. There is some freedom in the choice of torus geometry, of course; we selected an aspect ratio that would produce three times as many AGN with $N_H$ greater than $10^{22}$ cm$^{-2}$ compared to smaller column densities (Fig. 2a), which is roughly the observed local ratio \cite{Risaliti1999}. Figure 2b shows the observed SEDs of two local AGN, one unobscured (top) and one heavily obscured (bottom), compared...
In a series of papers we showed that this straightforward model matches very well the observed properties of AGN samples. The first paper, Treister et al. (2004), assumed for the sake of simplicity that the torus geometry (and hence the $N_H$ distribution) did not depend on luminosity or redshift. Even this simplest population synthesis model fits beautifully the observed X-ray and optical counts in the deep GOODS survey (Fig. 3). The source population at faint optical magnitudes, particularly the AGN too faint for identification with optical spectroscopy, is dominated by obscured AGN.

The unification-inspired model described above, like other population synthesis models (e.g., Gilli et al. 2001), predicts a large population of obscured AGN out to high redshift. The predicted peak of the redshift distribution (dashed histogram, Fig. 3b) is near $z \sim 1$, not much higher than that observed in the GOODS data (shaded/open histogram,
Fig. 4. (Left) Observed spectroscopic redshift distribution (hatched histogram) and photometric redshift distribution (open histogram) for the GOODS-North field, compared to that expected from the unification model (dashed line). There is poor agreement at high redshifts. (Right) Imposing an optical flux limit on the model leads to an expected distribution (dashed line) that agrees very well with the observed distribution.

Fig. 4a), but there discrepancy at $z > 1$. Many of these high-redshift obscured AGN, because they are optically faint, are not identified in follow-up optical spectra of X-ray sources. This can be clearly seen imposing the spectroscopic limit, $R \sim 24$ mag, on the expected redshift distribution (dashed histogram, Fig. 4b); in this case, the observed and expected distributions agree well because the higher-redshift AGN remain largely unidentified. Equivalently, AGN without spectroscopic identifications will preferentially be faint, obscured sources.

The advent of multiple large AGN samples with high spectroscopic completeness allowed Barger et al. (2005) to deduce a dependence of obscured fraction on optical luminosity. We incorporated a simple functional form of that dependence in our model — namely, a linear transition between 100% of AGN with $L_X = 10^{42}$ ergs/s being obscured and no AGN with $L_X = 10^{46}$ ergs/s being obscured. Taking into account the selection effects due to flux limits, the model then matches the observed dependence very well (Fig. 11). The resulting number counts and redshift distributions for GOODS do not change, since only a restricted luminosity range (primarily $10^{43-44}$ ergs/s) is probed by that survey. In all work subsequent to Treister et al. (2004) — on infrared counts, X-ray background, and evolution of obscuration (see below) — we incorporated this luminosity dependence.

Our population synthesis model predicts, with very little freedom, the spectrum of the X-ray background. We simply sum the X-ray emission from all the AGN. There is some freedom in that we (like everyone else who does this kind of calculation) have to model the X-ray spectrum. We used an absorbed power law plus an iron line and a Compton-reflection hump, consistent with the AGN spectra that are well measured locally; we also assumed solar abundances and used the $N_H$ distribution described above for log $N_H = 20-24$ cm$^{-2}$. The $N_H$ distribution for higher column densities ($N_H > 10^{24}$ cm$^{-2}$) is poorly constrained at present, so we extrapolated from $N_H < 10^{24}$ cm$^{-2}$ with a flat slope (again, much like what others have assumed). Beyond this, one can adjust the metallicity (this increases the hard X-rays, holding everything else constant) or the include a small range of power-law slopes (ditto; Gilli et al. 2007), but we did not feel the data could constrain those parameters and so left them fixed. In any case, the integral constraint of the X-ray
background is an excellent check on whether the demographics of AGN assumed here is realistic. Figure 5 shows that, with almost no free parameters, the data are very well fit indeed. (The normalization of the background at $E > 10$ keV is discussed below in §3.3.)

Another strong prediction of the Treister model concerns the infrared data, which at the time the model was developed had not yet been taken. We calculated the expected Spitzer counts in IRAC and MIPS 24-micron bands; Figure 6 shows the excellent agreement with observations (Treister et al. 2006). Small discrepancies at the faint end are due to the overly simple assumption of a single host galaxy magnitude (which dominates at low fluxes), rather than a distribution.

From the Spitzer observations, we calculate the minimum AGN contribution to the extragalactic infrared background, obtaining a lower value than previously estimated, ranging from 2% to 10% in the 3-24 micron range (Treister et al. 2006). Accounting for heavily obscured AGN that, according to our population synthesis model, are not detected in X-rays, the AGN contribution to the infrared background increases by $\sim 45\%$, to $\sim 3$-$15\%$. Figure 7a shows the AGN contributions deduced from GOODS data (Treister et al. 2006) compared to other estimates and to the (uncertain) total extragalactic background light, as a function of infrared wavelength. The GOODS measurements place the strongest constraints to date on the AGN contribution to the extragalactic background light, indicating that stars dominate completely over AGN at infrared wavelengths.

The fraction of sources that are AGN rises sharply with 24 $\mu$m infrared flux (Fig. 7b). Thus in deep surveys like GOODS or COSMOS, AGN are a small fraction of the total infrared source population, while in high flux limit surveys like SWIRE (Lonsdale et al. 2003), they constitute a much higher fraction. AGN detected in large-area, shallow surveys are on average closer and/or more luminous than AGN found in deep pencil-beam surveys. We show in Figure 7b that this very strong dependence of AGN fraction on infrared flux is not an artifact of the X-ray flux limit. Specifically, using our AGN population synthesis model, we plot the number of AGN as a function of infrared flux including those too faint to be detected in X-rays in the Chandra Deep Fields (open circles). Clearly the trend is independent of X-ray flux limit.
3.3. Integral and Swift Hard X-Ray Surveys

If the population synthesis model presented here is correct, ∼50% of AGN are currently missed even in deep X-ray surveys with *Chandra* or *XMM*. These are very obscured AGN, many of them Compton thick (i.e., \( N_H > 10^{24} \text{ cm}^{-2} \)), so all but the hardest X-ray surveys are biased against them. Fortunately, hard X-ray instruments on the INTEGRAL and Swift satellites can now reach fluxes below \( \sim 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \) at energies above 20 keV. Serendipitous AGN surveys at these energies covering almost the full sky have been carried out using Swift/BAT (Markwardt et al. 2005) and INTEGRAL/IBIS (Beckmann et al. 2006; Sazonov et al. 2007), yielding samples of \( \sim 100 \) AGN each. These surveys provide an unbiased view of the AGN population, independent of the amount of obscuration, although at present the sensitivity is sufficient to reach only local populations.

Figure 8a shows the logN-logS distribution from the INTEGRAL catalog (Sazonov et al. 2007) of AGN confirmed as Compton thick with \( N_H \) measurements from X-ray data. Clearly the original population synthesis model of Treister & Urry (2005) overpredicted the density of Compton-thick AGN by a factor of \( \sim 4 \). This is not too surprising, as the model included assumptions that, at the time of the publication of that work, were
Figure 7. (Left) Extragalactic infrared background intensity as a function of wavelength. (Shaded region) Allowed values for the total intensity compiled by Hauser & Dwek (2001). 1–4 µm: Measurements reported by Matsumoto et al. (2005). 4.8 µm: Lower limits from Fazio et al. (2004), upper limits from Kashlinsky et al. (1998) at 4.5 µm and Stanev & Franceschini (1998) at 5.8 and 8 µm. Measurement at 24 µm from Papovich et al. (2004). (Solid circles) Integrated infrared emission from X-ray-detected AGN in the GOODS fields, with 1σ error bars from source number statistics (which dominate over measured flux errors) calculated as in Gehrels (1986). (Triangles) Integrated AGN emission from the models of Treister & Urry (2005) if only X-ray-detected AGN are considered (lower) or including all AGN (upper). (Dotted lines) Expected AGN integrated emission from the AGN models of Silva et al. (2004; upper line) and Xu et al. (2001; lower line). (Open squares) Expected AGN integrated emission at 15 µm from the extrapolation to fainter fluxes of IRAS and ISO (Matute et al. 2002 [M02]; corrected by a factor of 5 to include the contribution from obscured AGN) and ISO only (Fadda et al. 2002 [F02]) observations. (Right) The fraction of sources that are AGN rises sharply with 24 µm infrared flux (filled circles). Vertical error bars show the 1σ Poissonian errors on the number of sources (Gehrels 1986). Also shown is the contribution corrected by the AGN expected to be missed by X-ray selection (open circles), as estimated using our AGN population synthesis model; this shows the same strong dependence on infrared flux, indicating that that dependence is not a selection effect induced by the X-ray flux limit.

unconstrained — for example, the reflection fraction† was assumed to be unity, and the number of Compton-thick AGN was simply extrapolated with a flat slope from the \(N_H\) distribution at lower column densities.

Now we explore the constraints on these quantities that come from the new Swift and INTEGRAL surveys. First, we define a “Compton-thick AGN correction factor,” which simply multiplies the original flat-extrapolation assumption to match the observed number density of AGN with \(N_H > 10^{24}\) cm\(^{-2}\). According to a \(\chi^2\) minimization, the best-fit value for the Compton-thick AGN factor is 0.25; this produces a good agreement between model and observations, with a reduced \(\chi^2\) of 0.3.

Second, we consider the ratio of direct and reflected X-rays. The spectrum of Compton-thick AGN at high energies is dominated by the Compton reflection component (e.g., Matt et al. 2000), which has a strong peak at \(E \sim 30\) keV (Magdziarz & Zdziarski 1995). The observed spectrum of the X-ray background, which we now understand as the integrated emission from previously unresolved AGN, also has peak at about the same energy (Gruber et al. 1999). The normalization of the reflection component relative to the direct

† The reflection fraction is the geometrical factor describing the solid angle, relative to 2\(\pi\), subtended by cold reflecting material as seen from the primary X-ray source.
Figure 8. (Left) Log$N$-log$S$ relation for Compton-thick AGN only. The dashed line shows the original prediction of Treister & Urry (2005), which assumed a reflection component normalization of 1 and a Compton-thick AGN factor of 1 (i.e., as many Compton-thick AGN as Compton-thin AGN in the next lowest decade of the $N_{\text{H}}$ distribution). Data points are from the INTEGRAL survey of Sazonov et al. (2007). The population synthesis model can be brought to agreement with the observations if there are a factor of 4 fewer Compton-thick AGN (i.e., the Compton-thick AGN factor is 0.25). (Right) Compton-thick AGN factor versus normalization of the Compton reflection component. The gray region shows the values of these parameters that produce a space density of Compton-thick AGN consistent with the observed value in the Sazonov et al. (2007) sample, considering 1-$\sigma$ statistical fluctuations. The allowed values of the parameters needed to fit the intensity of the X-ray background at 20-40 keV, assuming a 5% uncertainty in each case, are shown by the blue region for the original Gruber et al. (1999) measurements, the red region for the INTEGRAL values and by the green region for the Gruber et al. (1999) points increased by 40% (which was the assumption in Treister & Urry 2005). A large value of the reflection component is required to obtain values consistent with the latter X-ray background intensity, inconsistent with observations of the reflection component in individual AGN. Both the reflection value and the renormalization of the X-ray background intensity must be lower.

emission is known only for a few nearby AGN, mostly from BeppoSAX observations (e.g., Perola et al. 2002), and therefore this parameter is usually taken as an assumption in AGN population synthesis models that can explain the spectral shape and intensity of the X-ray background. The resulting peak X-ray background intensity depends on both the assumed space density of Compton-thick AGN and the normalization of the reflection component, $R$; while satisfying the overall intensity constraint, one can trade increased reflection for fewer Compton-thick AGN, or vice versa. Figure 8 shows the allowed regions in terms of the Compton-thick AGN factor versus reflection parameter. That is, the shaded regions show the values of these two parameters that produce an integrated X-ray background intensity in the 20-40 keV range, the region most affected by both the number of Compton-thick AGN and $R$, consistent with: (green region) the Gruber et al. (1999) data increased by 40% (the maximum suggested renormalization to match higher estimates with imaging instruments at lower energies; Treister & Urry 2005); (red region) the recent INTEGRAL X-ray background intensity measured using Earth occultation by Churazov et al. (2006); (blue region) the original Gruber et al. (1999) measurements, not renormalized. In each case uncertainties in the X-ray background intensity were assumed to be 5%. The gray shaded region shows the parameter space that produces a density of Compton-thick AGN consistent with the observations in Fig. 8.

Previously, Treister & Urry (2005) assumed an X-ray background intensity consistent
with the value increased by 40%, which was well fit by a Compton-thick AGN factor of 1 (flat extrapolation of the \(N_H\) distribution; Fig. 5). However, such a high value of the Compton-thick AGN factor is clearly inconsistent with the new observational constraints on the density of Compton-thick AGN. So, either the intensity of the X-ray background is lower, as suggested by recent INTEGRAL measurements (Churazov et al. 2006), or the average value of the reflection parameter is high, \(R \sim 2\), or some combination of the two. Observations of individual sources seem to indicate that such a high value for the reflection component is unlikely. From a sample of 22 Seyfert galaxies, excluding Compton-thick sources, Malizia et al. (2003) concluded that both obscured and unobscured sources have similar reflections with normalization values in the 0.6-1 range. A similar value of \(R \approx 1\) was reported by Perola et al. (2002) based on BeppoSAX observations of a sample of nine Seyfert 1 galaxies. Although with large scatter, normalizations for the average reflection component of 0.9 for Seyfert 1 and 1.5 for Seyfert 2 were measured from BeppoSAX observations of a sample of 36 sources (Deluit & Courvoisier 2003). Therefore, a value of \(R \sim 1\) for the normalization of the reflection component, required by both the observed Compton-thick AGN space density and the X-ray background intensity reported by INTEGRAL and HEAO-1, is in good agreement with the observed values in nearby Seyfert galaxies.

4. Evolution of the Obscured Fraction of AGN

The X-ray background, being an integral constraint, is not a strong probe of the fraction of AGN that is obscured (as we showed in the previous section), much less of the evolution of that fraction with cosmic epoch. As shown in Figure 5, a simple population synthesis model in which obscured and unobscured AGN have the same evolution (or equivalently, the fraction of AGN that is obscured does not evolve) is fully consistent with the spectrum of the X-ray background. Now, however, the large X-ray samples that have become available in the past few years, spanning a range of depths and with
Figure 10. Fraction of optically identified AGN as a function of optical magnitude (data points), for four of the seven surveys comprising our super-sample. All seven are well described by a simple linear increase to a constant fraction at bright magnitudes (lines). This allows us to derive the effective survey area as a function of both X-ray flux and optical magnitude.

high spectroscopic completeness, allow us to determine whether and how the fraction of obscured AGN depends on redshift (Treister & Urry 2006).

To study the evolution of the obscured AGN fraction, one needs to distinguish between the effects of redshift and luminosity, which are correlated in any flux-limited sample. Wide area, shallow X-ray surveys (e.g., XBOOTES; Hickox et al. 2006) sample moderate luminosity AGN at low redshifts and only high luminosity sources up to high redshifts, while deep pencil-beam surveys (e.g., CDFS; Giacconi et al. 2002) find moderate luminosity AGN out to high redshifts but lack rare, high-luminosity sources because of the small volume sampled. Combining the two extremes covers the luminosity-redshift plane effectively.

We generate an AGN super-sample comprising seven large surveys with high identification fractions: AMSS (Akiyama et al. 2003), SEXSI (Harrison et al. 2003), HEL-LAS2XMM (Baldi et al. 2002), CLASXS (Yang et al. 2004), CYDER (Treister et al. 2006).
This super-sample contains a total of 2341 hard X-ray-selected AGN (X-ray sources with $L_X > 10^{42}$ ergs/s), the largest such sample to date by a factor of $\sim 4$ (Treister & Urry 2006). It spans a range of luminosities at each redshift, over a broad redshift range. The total area of this super-sample as a function of X-ray flux is shown in Figure 9a.

More than half the super-sample is optically identified. We define an AGN as unobscured when there is evidence for broad emission lines in their spectra, and as obscured AGN otherwise. The “obscured fraction” is then the number of obscured AGN divided by the total number of AGN. For obvious reasons, the identified fraction of any survey depends on the brightness of the optical counterparts. We parameterized the identified fraction of each of the seven surveys with a simple function that is constant at bright magnitudes and falls linearly to faint magnitudes (Fig. 10; see Treister & Urry 2006 for details). We then weight the area versus X-ray flux curve (Fig. 9a) by the completeness at each optical magnitude, for each survey, and sum those to get the effective area of the super-sample as a function of both X-ray flux and optical magnitude (Fig. 9b). This allows us to calculate the expected numbers of optically identified AGN for the super-sample, i.e., we can now correct for both X-ray and optical spectroscopic limits.

As discussed earlier (§ 3.2), the fraction of obscured AGN depends on luminosity (Barger et al. 2005). Our population synthesis model assumed a linear transition between 100% obscured fraction at $L_X = 10^{42}$ ergs/s and 0 obscured fraction at $L_X = 10^{46}$ ergs/s. Taking into account the selection effects due to flux limits (Fig. 9b), this assumption (black line, Fig. 11) matches the observed dependence very well in the present super-sample (black line, Fig. 11). The somewhat shallower luminosity dependence adopted by (Gilli et al. 2007; blue dashed line is their assumed dependence, red dotted line incorporates flux limits), in contrast, does not describe the obscured fraction well for high-luminosity AGN, probably because their model was constrained by the X-ray background, which is dominated by moderate luminosity AGN.

Our population synthesis model fits the X-ray, optical, and infrared counts of AGN; the X-ray background (modulo the trade-off between the number of Compton-thick AGN and the reflection fraction of each); the hard X-ray counts measured with Swift and INTEGRAL (ditto); and the observed luminosity dependence of the obscured fraction of AGN in the largest AGN sample to date. What can it tell us about the evolution of this obscured fraction?

Figure 12a shows the observed fraction as a function of redshift (black data points). As many have noted previously, the observed fraction declines with redshift, from roughly 3/4 locally to $\sim 1/3$ at $z \sim 4$. This has been interpreted to mean that obscured AGN are rare at high redshift. However, the lines in Figure 12b show the expected decline for an underlying population whose obscured fraction is actually constant with redshift, calculated for our super-sample using the appropriate corrections for X-ray and optical flux limits and spectroscopic completeness. That is, an even steeper decline is expected in the observed samples even when the underlying population does not change at all with redshift.

Three significant selection effects cause this strong decline. First, obscured AGN have smaller X-ray fluxes, so there is a bias against their detection in the X-ray sample in the first place. This is a small effect, particularly because it becomes relatively less important with increasing redshift (for which rest-frame emission is in an increasingly harder X-ray band affected only by higher and higher column densities). Second, obscured AGN are fainter in the optical, so there is a bias against spectroscopic identifications for $z \gtrsim 1$ (Treister et al. 2004); this is not important for samples with highly complete spectroscopic identifications. Third and quite important, the obscured fraction depends...
Figure 11. Fraction of obscured AGN in the super-sample as a function of hard X-ray luminosity. (Black data points) Observed distribution for the super-sample described in this work. (Red data points) Compilation of G. Hasinger (2007, in prep.) used in the work reported by Gilli et al. (2007). (Black solid line) Expected luminosity dependence for the Treister population synthesis models, taking into account the X-ray flux limit and spectroscopic completeness of the super-sample described here (Treister & Urry 2006). (Blue dashed and red dotted lines) Intrinsic and bias-corrected (i.e., expected) luminosity dependences for the population synthesis model of Gilli et al. (2007). This assumed luminosity dependence is not a good description of AGN demographics at higher luminosities; the Gilli et al. (2007) model is constrained primarily by the X-ray background intensity, which is dominated by moderate luminosity AGN.

strongly on luminosity (Fig. 11). Given the luminosity-redshift correlation inherent in flux-limited samples, the mean AGN luminosity increases with redshift and therefore the obscured fraction that is observed decreases — even if the same population of obscured lower-luminosity AGN is present. Our analysis shows that this is the dominant selection effect. It is an important effect even in AGN samples with 100% complete spectroscopic identifications, as indicated by the blue line in Figure 12. Simply put, high redshift AGN samples are biased to higher luminosity, and thus contain lower obscured fractions, even if there is no underlying evolution of the ratio between obscured and unobscured AGN at all.

The observed more gradual decline in obscured fraction of AGN actually implies an increase in obscured fraction with redshift. Figure 12b shows the data relative to (i.e., divided by) the expectation for a non-evolving population, for the super-sample and the two sub-samples with higher identification fractions. The effect is largely independent of the completeness of the optical identifications. Fitting the increasing fraction with a simple power-law dependence on redshift, $\propto (1 + z)^\alpha$, gives a good fit for $\alpha = 0.4 \pm 0.1$. This means that the fraction of AGN at redshift $z \sim 4$ that are obscured is observed to be twice as high as would be the case were the intrinsic fraction constant. AGN obscuration is substantially greater in the young Universe.
5. Summary

GOODS, MUSYC, and other deep multiwavelength surveys provide overwhelming evidence for a large population of obscured AGN that dominate AGN demographics out to high redshifts. Optical surveys are biased against detecting these objects, and even hard X-ray surveys, which are considerably less biased, suffer strong selection effects, primarily due to the luminosity-dependence of obscuration.

Taking these effects into account quantitatively, with a realistic, well-constrained population synthesis model that uses AGN spectral energy distributions based on a unification paradigm, we deduce that the ratio of obscured ($N_H > 10^{22}$ cm$^{-2}$) to unobscured ($N_H < 10^{22}$ cm$^{-2}$) AGN is roughly 3:1 locally (integrated over all luminosities), and increases with redshift. Low-luminosity AGN ($10^{42}$ ergs/s < $L_X$ < $10^{44}$ ergs/s) are much more likely to be obscured than high-luminosity AGN ($L_X > 10^{44}$ ergs/s).

To the extent that our assumed infrared through X-ray spectral energy distributions are reasonable, and our assumed $N_H$ distribution is reasonable (it is essentially the same as that used by others in the field; see Gilli et al. 2007 for a comparison of the different distributions), these results are completely robust.

How might one avoid the biases inherent in optical and X-ray surveys? In principle, far-infrared surveys are unbiased because the absorbed energy is re-radiated thermally; however, infrared surveys are very inefficient for AGN selection since the infrared sky is strongly dominated by starlight (Fig. 7). In addition, AGN signatures (such as broad emission lines, strong power-law continua, and rapid variability) may well be hidden in obscured objects. Thus, identifying complete samples of AGN from far-infrared surveys will never be a simple matter, although it can potentially put useful limits on the fraction of galaxies with buried AGN.

Selection effects are very important to take into account for any survey, even those
that are 100% identified. For example, consider a deep hard X-ray survey for which all sources have optical and/or infrared counterparts with known redshifts and classification. Many would assume the survey itself is not strongly biased and that the identifications yield the underlying demographics, since no X-ray sources remain unidentified. However, missing from the X-ray sample are the most heavily obscured AGN; even more important, unobscured AGN are over-represented (relative to their fraction of the underlying population), especially at high redshift, because of the dependence of obscuration on luminosity. This in fact is the dominant effect for existing surveys.

Therefore, to understand the distribution of black holes in the universe and to estimate cosmic accretion rates, the selection effects must be modeled using reasonable assumptions about the underlying population. That in turns yields a picture of the universe that matches well our picture of nascent accreting black holes at the centers of dusty, star-forming, young galaxies in the early Universe.

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REFERENCES

Akiyama, M., Ueda, Y., Ohta, K., Takahashi, T. & Yamada, T. 2003 Optical Identification of the ASCA Medium Sensitivity Survey in the Northern Sky: Nature of Hard X-Ray-Selected Luminous Active Galactic Nuclei. *ApJ* **148**, 275–315.

Alexander, D. M., Bauer, F. E., Brandt, W. N., Schneider, D. P., Hornschemeier, A. E., Vignali, C., Barger, A. J., Broos, P. S., Cowie, L. L., Garmire, G. P., Townsley, L. K., Bautz, M. W., Chartas, G. & Sargent, W. L. W. 2003 The Chandra Deep Field North Survey. XIII. 2 Ms Point-Source Catalogs. *AJ* **126**, 539–574.

Alexander, D. M., Brandt, W. N., Hornschemeier, A. E., Garmire, G. P., Schneider, D. P., Bauer, F. E. & Griffiths, R. E. 2001 The Chandra Deep Field North Survey. VI. The Nature of the Optically Faint X-Ray Source Population. *AJ* **122**, 2156–2176.

Antonucci, R. 1993 Unified models for active galactic nuclei and quasars. *ARA&A* **31**, 473–521.

Baldi, A., Molendi, S., Comastri, A., Fiore, F., Matt, G. & Vignali, C. 2002 The HELLAS2XMM Survey. I. The X-Ray Data and the logN-logS Relation. *ApJ* **564**, 190–195.

Ballantyne, D. R., Everett, J. E. & Murray, N. 2006 Connecting Galaxy Evolution, Star Formation, and the Cosmic X-Ray Background. *ApJ* **639**, 740–752.

Barger, A. J., Cowie, L. L., Mushotzky, R. F., Yang, Y., Wang, W.-H., Steffen, A. T. & Capak, P. 2005 The Cosmic Evolution of Hard X-Ray-selected Active Galactic Nuclei. *AJ* **129**, 578–609.

Beckmann, V., Gehrels, N., Shrader, C. R. & Soldi, S. 2006 The First INTEGRAL AGN Catalog. *ApJ* **638**, 642–652.

Brandt, W. N. & Hasinger, G. 2005 Deep Extragalactic X-Ray Surveys. *ARA&A* **43**, 827–859.

Capak, P., Aussel, H., Ajiki, M., McCracken, H. J., Mobasher, B., Scoville, N., Shopbell, P., Taniguchi, Y., Thompson, D., Tribiano, S., Sasaki, S., Blain, A. W., Brusa, M., Carilli, C., Comastri, A., Carollo, C. M., Cassata, P., Colbert, J., Ellis, R. S., Elvis, M., Giavalisco, M., Green, W., Guzzo, L., Hasinger, G., Ilbert, O., Impey, C., Jahreis, K., Kartaltepe, J., Kneib, J.-P., Koda, J., Koekemoer, A., Komiyama, Y., Leauthaud, A., Lefevre, O., Lilly, S., Liu, C., Massey, R., Miyazaki, S., Murayama, T., Nagao, T., Peacock, J. A., Pickles, A., Porciani, C., Renzini, A., Rhodes, J., Rich, M., Salvato, M., Sanders, D. B., Scarlata, C., Schiminovich, D., Schinnerer, E., Scovell, M., Sheth, K., Shioya, Y., Tasca,
Gilli, R., Comastri, A. & Hasinger, G. 2007 The synthesis of the cosmic X-ray background in the Chandra and XMM-Newton era. A&A 463, 79–96.

Gilli, R., Salvati, M. & Hasinger, G. 2001 Testing current synthesis models of the X-ray background. A&A 366, 407–417.

Gruber, D. E., Matteson, J. L., Peterson, L. E. & Jung, G. V. 1999 The Spectrum of Diffuse Cosmic Hard X-Rays Measured with HEAO 1. ApJ 520, 124–129.

Harrison, F. A., Eckart, M. E., Mao, P. H., Helfand, D. J. & Stern, D. 2003 The Serendipitous Extragalactic X-Ray Source Identification Program. I. Characteristics of the Hard X-Ray Sample. ApJ 596, 944–956.

Hasinger, G. 2000 X-ray Surveys of the Obscured Universe. In ISO Survey of a Dusty Universe (ed. D. Lemke, M. Stickel & K. Wilke), Lecture Notes in Physics, Berlin Springer Verlag, vol. 548, pp. 423+.

Hasinger, G., Cappelluti, N., Brunner, H., Brusa, M., Comastri, A., Elvis, M., Finoguenov, A., Fiore, F., Franceschini, A., Gilli, R., Griffiths, R. E., Lehmann, I., Mainieri, V., Matt, G., Matute, I., Miyaji, T., Molendi, S., Paltani, S., Sanders, D. B., Scoville, N., Tresse, L., Urry, C. M., Vettolani, P. & Zamorani, G. 2007 The XMM-Newton Wide-Field Survey in the COSMOS Field. I. Survey Description. ApJ 172, 29–37.

Hasinger, G. et al. 2001 XMM-Newton observation of the Lockman Hole. I. The X-ray data. A&A 365, L45–L50.

Hauser, M. G. & Dwek, E. 2001 The Cosmic Infrared Background: Measurements and Implications. ARA&A 39, 249–307.

Hickox, R. C., Jones, C., Forman, W. R., Murray, S. S., Brodwin, M., XBOOTES, T. C., IRAC SHALLOW SURVEY, S., AGES & NOAO DWFS TEAMS 2006 X-ray and infrared properties of galaxies and AGNs in the 9 square degree Bootes field. ArXiv Astrophysics e-prints.

Kashlinsky, A., Mather, J. C. & Odenwald, S. 1996 Clustering of the Diffuse Infrared Light from the COBE DIRBE Maps: an All-Sky Survey of C(0). ApJ 473, L9+.

Kim, D.-W. et al. 2004 Chandra Multiwavelength Project. I. First X-Ray Source Catalog. ApJ 150, 19–41.

King, A. 2005 The AGN-Starburst Connection, Galactic Superwinds, and MBH-σ. ApJ 635, L121–L123.

Lawrence, A. 2001 Quasars, Starbursts, and the Cosmic Energy Budget. In The Promise of the Herschel Space Observatory (ed. G. L. Pilbratt, J. Cernicharo, A. M. Heras, T. Prusti & R. Harris), ESA Special Publication, vol. 460, pp. 95+.

Lehmer, B. D., Brandt, W. N., Alexander, D. M., Bauer, F. E., Schneider, D. P., Tozzi, P., Bergeron, J., Garmire, G. P., Giacconi, R., Gilli, R., Hasinger, G., Hornschemeier, A. E., Koekemoer, A. M., Mainieri, V., Miyaji, T., Nonino, M., Rosati, P., Silverman, J. D., Szokoly, G. & Vignali, C. 2005 The Extended Chandra Deep Field-South Survey: Chandra Point-Source Catalogs. ApJ 161, 21–40.

Lilly, S. J., Fèvre, O. L., Renzini, A., Zamorani, G., Scovelllo, M., Contini, T., Carollo, C. M., Hasinger, G., Kneib, J.-P., Iovino, A., Le Brun, V., Maior, C., Mainieri, V., Mignoli, M., Silverman, J., Tasca, L. A. M., Bolzonella, M., Bongiani, A., Bottini, D., Capak, P., Caputi, K., Cimatti, A., Cucciati, O., Daddi, E., Feldmann, R., Franzetti, P., Garilli, B., Guzzo, L., Ilbert, O., Kampczyk, P., Kovac, K., Lamareille, F., Leauthaud, A., Borgne, J.-F. L., McCracken, H. J., Marinoni, C., Pello, R., Ricciardelli, E., Scarlata, C., Vergani, D., Sanders, D. B., Schinnerer, E., Scoville, N., Taniguchi, Y., Arnouts, S., Aussel, H., Bardeni, S., Brusa, M., Cappi, A., Ciliegi, P., Finoguenov, A., Foucaud, S., Franceschini, R., Halliday, C., Impey, C., Knobel, C., Koekemoer, A., Kurk, J., Maccagni, D., Maddox, S., Marano, B., Marconi, G., Meneux, B., Mobasher, B., Moreau, C., Peacock, J. A., Porciani, C., Pozzetti, L., Scarlata, R., Schinnerer, E., Shopbell, P., Smail, I., Thompson, D., Tresse, L., Vettolani, G., Zanichelli, A. & Zucca, E. 2007 zCOSMOS: A Large VLT/VIMOS Redshift Survey Covering 0 < z < 3 in the COSMOS Field. ApJ 172, 70–85.

Lonsdale, C. J. et al. 2003 SWIRE: The SIRTF Wide-Area Infrared Extragalactic Survey. PASP 115, 897–927.
Infrared Number Counts of Active Galactic Nuclei in the GOODS Fields. ApJ 616, 123–135.

Ueda, Y., Akiyama, M., Ohta, K. & Miyaji, T. 2003 Cosmological Evolution of the Hard X-Ray Active Galactic Nucleus Luminosity Function and the Origin of the Hard X-Ray Background. ApJ 598, 886–908.

Urry, C. M. & Padovani, P. 1995 Unified Schemes for Radio-Loud Active Galactic Nuclei. PASP 107, 803–+.

van Dokkum, P. G., Quadri, R., Marchesini, D., Rudnick, G., Franx, M., Gawiser, E., Herrera, D., Wuyts, S., Lira, P., Labbé, I., Mazu, J., Illingworth, G. D., Förster Schreiber, N. M., Kriek, M., Rix, H.-W., Taylor, E. N., Toft, S., Webb, T. & Yi, S. K. 2006 The Space Density and Colors of Massive Galaxies at 2 < z < 3: The Predominance of Distant Red Galaxies. ApJ 638, L59–L62.

Vanden Berk, D. E. et al. 2001 Composite Quasar Spectra from the Sloan Digital Sky Survey. AJ 122, 549–564.

Virani, S. N., Treister, E., Urry, C. M. & Gawiser, E. 2006 The Extended Chandra Deep Field-South Survey: X-Ray Point-Source Catalog. AJ 131, 2373–2382.

Worsley, M. A., Fabian, A. C., Bauer, F. E., Alexander, D. M., Hasinger, G., Mateos, S., Brunner, H., Brandt, W. N. & Schneider, D. P. 2005 The unresolved hard X-ray background: the missing source population implied by the Chandra and XMM-Newton deep fields. MNRAS 357, 1281–1287.

Yang, Y., Mushotzky, R. F., Steffen, A. T., Barger, A. J. & Cowie, L. L. 2004 The Chandra Large Area Synoptic X-Ray Survey (CLASXS) of the Lockman Hole-Northwest: The X-Ray Catalog. AJ 128, 1501–1523.