RELIABLE IDENTIFICATION OF COMPTON-THICK QUASARS AT $z \approx 2$: SPITZER MID-INFRARED SPECTROSCOPY OF HDF-oMD49


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ABSTRACT

Many models that seek to explain the origin of the unresolved X-ray background predict that Compton-thick active galactic nuclei (AGNs) are ubiquitous at high redshift. However, few distant Compton-thick AGNs have been reliably identified to date. Here we present Spitzer IRS spectroscopy and 3.6–70 μm photometry of a $z = 2.211$ optically identified AGN (HDF-oMD49) that is formally undetected in the 2 Ms Chandra Deep Field–North (CDF-N) survey. The Spitzer IRS spectrum and spectral energy distribution of this object is AGN dominated, and a comparison of the energetics at X-ray wavelengths to those derived from mid-infrared (mid-IR) and optical spectroscopy shows that the AGN is intrinsically luminous ($L_{2.1-10keV} \approx 3 \times 10^{44}$ ergs s$^{-1}$) but heavily absorbed by Compton-thick material ($N_H \gg 10^{24}$ cm$^{-2}$); i.e., this object is a Compton-thick quasar. Adopting the same approach that we applied to HDF-oMD49, we found a further six objects at $z \approx 2–2.5$ in the literature that are also X-ray weak/undetected but have evidence for AGN activity from optical and/or mid-IR spectroscopy, and show that all of these sources are likely to be Compton-thick quasars with $L_{2.1-10keV} > 10^{44}$ ergs s$^{-1}$. On the basis of the definition of Daddi et al., these Compton-thick quasars would be classified as mid-IR excess galaxies, and our study provides the first spectroscopic confirmation of Compton-thick AGN activity in a subsample of these $z \approx 2$ mid-IR-bright galaxies. Using the four objects that lie in the CDF-N field, we estimate the space density of reliably identified Compton-thick quasars [$\Phi \approx (0.7–2.5) \times 10^{-5}$ Mpc$^{-3}$ for $L_{2.1-10keV} > 10^{44}$ ergs s$^{-1}$ objects at $z \approx 2–2.5$] and show that Compton-thick accretion was probably as ubiquitous as unobscured accretion in the distant universe.

Subject headings: galaxies: active — galaxies: high-redshift — infrared: galaxies — ultraviolet: galaxies — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

There is a growing need for a complete census of active galactic nuclei (AGNs). The seminal discovery that every massive galaxy in the local universe harbors a supermassive black hole ($M_H \sim 10^9 M_\odot$) implies that all massive galaxies must have hosted AGN activity at some time during the past ~13 Gyr (e.g., Rees 1984; Kormendy & Richstone 1995). To trace accurately how and when these black holes grew requires a detailed census of nuclear obscuration on AGN luminosity, redshift, and host galaxy type (e.g., Marconi et al. 2004; La Franca et al. 2005; Shankar et al. 2008).

The exceptional sensitivity of the Chandra Deep Field observations (e.g., Brandt et al. 2001; Giacconi et al. 2002; Alexander et al. 2003b) has helped to unveil a >10 times larger population of AGNs than found at most other wavelengths (≈7200 deg$^{-2}$; e.g., Bauer et al. 2004). Optical spectroscopic follow-up observations have shown that these AGNs are detected out to $z \approx 5$, and detailed X-ray spectral analyses have revealed that the majority of the sources are obscured by gas and dust (e.g., Barger et al. 2003; Szokoly et al. 2004; Tozzi et al. 2006; see Brandt & Hasinger [2005] for a review). However, although clearly effective at identifying even heavily obscured AGNs out to high redshift, there is compelling evidence that a large fraction of the AGN population remains undetected at the <10 keV observed-frame energies probed by these surveys: (1) about half of the X-ray background (XRB) is unresolved at >6 keV (Worsley et al. 2005); (2) the observed obscured: unobscured AGN ratio is lower than that found for comparably luminous AGNs in the local universe (e.g., Treister & Urry 2005); (3) the 5–10 keV blank-field number counts are steeply rising at the faintest X-ray fluxes (Rosati et al. 2002); and (4) few Compton-thick AGNs ($N_H \sim 1.5 \times 10^{24}$ cm$^{-2}$) have been identified, even though they comprise ≈50% of the AGN population in the local universe (e.g., Risaliti et al. 1999; Guainazzi et al. 2005; Tozzi et al. 2006).

Many of the X-ray-undetected AGNs are expected to be intrinsically luminous sources that are heavily obscured by Compton-thick material (i.e., $N_H > 1.5 \times 10^{24}$ cm$^{-2}$; see Comastri [2004] for a review). The most robust identification of a Compton-thick AGN is made from high signal-to-noise ratio (S/N) X-ray spectroscopy, where the detection of a high equivalent width Fe K emission line ($W_1 > 1$ keV at rest-frame energies 6.4–6.9 keV) and a steeply rising reflection component at >10 keV reveals that little or no X-ray emission is being seen directly, implying that the central source is very heavily absorbed (e.g., George & Fabian 1991; Matt et al. 1996, 2000; Maiolino et al. 1998). However, since the extreme obscuration toward the nucleus of a Compton-thick
AGN renders the observed <10 keV emission \( \approx 30-1000 \) times fainter than the intrinsic (i.e., unabsorbed) emission, it is often challenging to identify robustly these sources on the basis of their X-ray data alone; the range of absorption correction factors is based on the observed-to-intrinsic X-ray luminosity ratio for the AGN in Table 8.1 of Comastri (2004), with the observed X-ray fluxes from Bassani et al. (1999). For example, despite Compton-thick AGNs comprising half of the AGN population in the local universe, only \( \approx 50 \) sources have been reliably identified from X-ray data to date (e.g., Comastri 2004). Fortunately, although not as conclusive as high S/N X-ray spectroscopy, the presence of Compton-thick absorption can also be identified in X-ray-weak AGNs when a reliable measurement of the intrinsic power of the AGNs is available at other wavelengths; we stress here the necessity for X-ray constraints in order to identify a Compton-thick AGN, since it is only in the X-ray band that an absorbing column density can be measured or inferred.

Two of the most reliable measurements of the intrinsic power of an obscured AGN are the luminosity of the mid-infrared (mid-IR; rest frame \( >3 \mu \)m; e.g., Efstathiou & Rowan-Robinson 1995; Granato et al. 1997; Lutz et al. 2004) continuum and high-excitation lines (e.g., [O iii] \( \lambda 5007 \); e.g., Allen 1973; Kwan & Krolik 1981; Bassani et al. 1999), both of which are believed to be directly illuminated by the central source. These emission regions provide a good proxy for the intrinsic AGN luminosity, even in the presence of extreme Compton-thick absorption, since they are more extended than the X-ray-absorbing material (i.e., larger than the broad-line region; e.g., Lamer et al. 2003; Risaliti et al. 2007). As the luminosities of both the mid-IR continuum and the high-excitation emission-line region are dependent on many factors, including the location and geometry of the region with respect to the central source, more robust constraints are placed if both measurements are available.

Comprehensive evidence for a large X-ray-undetected AGN population has been found from a variety of X-ray-based analyses using sources detected in deep Spitzer surveys at mid-IR wavelengths, suggesting that Compton-thick AGNs may be ubiquitous in the distant universe (e.g., Donley et al. 2005, 2007; Alonso-Herrero et al. 2006; Polletta et al. 2006; Daddi et al. 2007b; Steffen et al. 2007; Martínez-Sansigre et al. 2007; Fiore et al. 2008). However, all of these studies have relied on photometric observations for the identification of candidate Compton-thick AGNs, leading to significant uncertainties in measurements of the intrinsic AGN luminosity, the absorbing column density, the degree of contamination from star formation activity, and by implication, the space density of distant Compton-thick AGNs. In this paper we present Spitzer Infrared Spectrograph (IRS) spectroscopy and 3.6–70 \( \mu \)m observations of an optically identified narrow emission-line AGN at \( z = 2.211 \) (HDF-oMD49; Steidel et al. 2002) that is undetected in the published catalogs of the deepest X-ray observation currently available (the 2 Ms Chandra Deep Field–North [CDF-N]; Alexander et al. 2003b). From a comparison of the AGN energetics at X-ray wavelengths to those determined from optical and mid-IR spectroscopy, we robustly show that HDF-oMD49 hosts an intrinsically luminous \( L_{2-10 \text{keV}} \approx 3 \times 10^{44} \text{ ergs s}^{-1} \), Compton-thick AGN; i.e., this source is a Compton-thick quasar. We then use these X-ray–optical–mid-IR diagnostics to identify a further six distant Compton-thick quasars in the literature and place limits on the space density of Compton-thick quasars at \( z \approx 2 \). We adopted \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.27 \), and \( \Omega_{\Lambda} = 0.73 \) throughout.

2. Observations

HDF-oMD49 (optical position \( \alpha_{2000} = 12^h 37^m 04.34^s, \delta_{2000} = +62^\circ 14' 46.2'' \); Steidel et al. 2002) was originally identified in the Lyman break galaxy (LBG) searches of Steidel et al. (2002, 2003). With a redshift of \( z = 2.211 \), HDF-oMD49 lies at the low-redshift end of the LBG population (median redshift \( z \approx 3 \)). HDF-oMD49 is also identified as a BX/BM galaxy, based on the criteria of Steidel et al. (2004), and it is dubbed BM 1156 in the BX/BM study of Reddy et al. (2006). The apparent contradiction in HDF-oMD49 being selected as both an LBG and BX/BM is due to small differences in the photometric data used in these studies.

2.1. Spitzer Data

HDF-oMD49 is detected by the Infrared Array Camera (IRAC) at 3.6–8.0 \( \mu \)m and the Multiband Imaging Photometer for Spitzer (MIPS) at 24 \( \mu \)m in the Spitzer observations obtained as part of the Great Observatories Origins Deep Survey (GOODS) legacy project (PI: M. Dickinson; R. Chary et al. 2008, in preparation); the 3.6, 4.5, 5.8, 8.0, and 24 \( \mu \)m fluxes are 6.1, 7.0, 14.8, 40.1, and 380 \( \mu \)Jy, respectively. Although HDF-oMD49 is bright at 24 \( \mu \)m, it is undetected in the ultradeep 70 \( \mu \)m observations of Frayer et al. (2006); 3 \( \sigma \) upper limit of \( f_{70 \mu m} < 2.0 \) mJy, indicating that it has a “warm” mid-IR spectral energy distribution (SED; e.g., Papovich et al. 2007). HDF-oMD49 is also detected at 16 \( \mu \m \) with \( f_{16 \mu m} = 222 \mu \)Jy using the “peak-up” imaging capability of Spitzer IRS (H. Teplitz et al. 2008, in preparation).

The Spitzer IRS spectroscopy of HDF-oMD49 was obtained in spectral staring mode as part of program GO2-20456 (PI: R. Chary) using the Low-Low (LL) modules (\( R \approx 64-128 \); Houck et al. 2004). HDF-oMD49 was observed with LL1 (20.5–37.9 \( \mu \)m) for 3 hr, and additional observations with LL1 (0.93 hr) and LL2 (1.33 hr; 14.3–21.2 \( \mu \m \)) were obtained when HDF-oMD49 fell serendipitously into the slit of another target from the same program. We analyzed the two-dimensional basic calibrated data files from the S14.0.0 Spitzer IRS pipeline data; data reduction includes cleaning rogue pixels, fitting and removing the latent charge buildup, subtracting the sky, and averaging the two-dimensional files together. Spectral extraction was performed using a 2 pixel wide window in SPICE, and the data were calibrated using the same extraction window on a standard–star spectrum.\(^9\) The average rms of the LL1 and LL2 spectra are 97 and 120 \( \mu \)Jy, respectively. The Spitzer IRS fluxes measured through the 16 and 24 \( \mu \)m filter spectral response curves are 180 \( \pm 120 \) and 370 \( \pm 100 \) \( \mu \)Jy, respectively, consistent with the observed fluxes in these bands.\(^{10}\) For more details on the observations and data reduction, see Pope et al. (2008).

2.2. Chandra Data

HDF-oMD49 is undetected in the published 2 Ms Chandra catalogs of Alexander et al. (2003b). However, these catalogs were produced using a conservative source detection algorithm to minimize the number of spurious detections, and it is possible to identify robustly fainter sources when searching for X-ray emission...
associated with a known source (e.g., see § 3.4.2 of Alexander et al. [2003b] and § 5 of Alexander et al. [2001]). Indeed, adopting a WAVDETECT (Freeman et al. 2002) false-positive probability threshold of 10^{-5} we detected significant X-ray emission (X-ray position $\alpha_{2000.0} = 12^{h}37^{m}04.3^{s}$, $\delta_{2000.0} = +62^\circ 14'46.4''$) within 0.25'' of the optical position of HDF-oMD49 in the 0.5–8, 0.5–2, and 4–8 keV bands with 8.1 ± 3.5, 6.7 ± 2.8, and 4.9 ± 2.6 counts, respectively (see also Laird et al. 2006). HDF-oMD49 remains undetected in all of the other four X-ray bands explored by Alexander et al. (2003b), and we calculated 3 $\sigma$ upper limits following § 3.4.1 of Alexander et al. (2003b). Although the S/N of the X-ray data is low, the low background of Chandra allows sources with very low count rates to be reliably detected. For example, with a measured background in the detection aperture of HDF-oMD49 ($\sim$2 pixel radius) of only $\approx$1 counts in the 0.5–2 keV band, the probability of detecting $\approx$7 counts by chance is $\approx$10^{-5}; furthermore, HDF-oMD49 is detected in two independent bands, increasing the overall probability that the detection is real.

The X-ray counts correspond to fluxes of $7.1 \times 10^{-17}$ ergs s^{-1} cm^{-2} (0.5–8 keV), $2.6 \times 10^{-17}$ ergs s^{-1} cm^{-2} (0.5–2 keV), and $1.5 \times 10^{-16}$ ergs s^{-1} cm^{-2} (4–8 keV), for $\Gamma = 1.4$ (i.e., the spectral slope of the XRB). The detection in the 4–8 keV band is particularly notable, since Chandra is significantly less sensitive to 4–8 keV than at <4 keV energies, suggesting that HDF-oMD49 has a flat X-ray spectral slope; the nondetection in the wider 2–8 keV band provides support for this hypothesis. The X-ray band ratio (the 2–8 keV/0.5–2 keV count rate ratio) is $<1.9$, which corresponds to $\Gamma > 2.0$ and is consistent with the X-ray spectral slope derived from the 4–8 keV/0.5–2 keV count rate ratio ($\Gamma \approx 0.4$); the difference in the X-ray fluxes estimated using $\Gamma = 0.4$ instead of $\Gamma = 1.4$ is negligible given the low S/N of the X-ray data ($\leq$15%). The corresponding rest-frame 1.6–6.4, 6.4–12.8, and 12.8–25.7 keV luminosities (or 3 $\sigma$ upper limit) of HDF-oMD49 are $10^{42}$, $<4 \times 10^{42}$, and $6 \times 10^{42}$ ergs s^{-1}, respectively.

3. RESULTS

3.1. The Spitzer SED

In Figure 1a we show the Spitzer IRS spectrum of HDF-oMD49. The spectrum is noisy, particularly in the LL2 order. However, there is no significant emission from the dominant rest-frame 7.7 $\mu$m polycyclic aromatic hydrocarbon (PAH) feature found in star-forming galaxies, indicating that the mid-IR spectrum does not have a strong contribution from star formation activity. By contrast, the Spitzer IRS spectrum of HDF-oMD49 is similar to the nearby Compton-thick AGN NGC 1068 and even shows weak evidence for Si absorption at 9.7 $\mu$m, a feature often seen in obscured AGNs (e.g., Shi et al. 2006; Hao et al. 2007; Spoon et al. 2007). The Spitzer IRS spectrum of HDF-oMD49 is also qualitatively similar to the composite mid-IR spectrum of the X-ray-obscured quasars ($L_X > 10^{44}$ ergs s^{-1}; $N_H > 10^{22}$ cm^{-2}) investigated by Sturm et al. (2006); see Figure 1b.

We can quantify the contributions from AGN and star formation activity to the mid-IR luminosity of HDF-oMD49 by fitting the Spitzer IRS spectrum with AGN and star formation templates. Adopting the approach of Pope et al. (2008), we fit the Spitzer IRS spectrum with an M82 starburst component and include an AGN component using the nuclear spectrum of NGC 1068, performing a $\chi^2$ minimization to obtain the best-fitting normalization. On the basis of this approach, we find that the mid-IR spectrum of HDF-oMD49 is dominated by AGN activity, with a limit of a 10% contribution from star formation in the Spitzer IRS band; there is no clear signature for star formation, and this limit effectively corresponds to the noise per pixel in the spectra. We get consistent results if we fit the mid-IR spectrum with an M82 starburst component and an absorbed power-law component (to represent the AGN), leaving the slope of the power law and the extinction as free parameters. The best-fitting results with this second approach give a spectral slope of $\alpha = 2$ (consistent with that found for AGN-dominated sources; e.g., Alonso-Herrero et al. [2003], where
color were taken from Rigopoulou et al. (1999), Chary & Elbaz (2001), Galliano et al. shows the combined model results. The data for the NGC 1068 and M82 SEDs blackbody component of very hot 1000 K dust (see normalized based on the results from fitting the mid-IR spectrum of HDF-oMD49 x-axis direction indicates the width that corresponds to >50% of the maximum transmission in each of the photometric bands; see footnote 3. The data are compared to the SEDs of the Compton-thick AGN NGC 1068 (dashed curve) and the starburst galaxy M82 (long-dashed curve), which are shifted to z = 2.21 and normalized based on the results from fitting the mid-IR spectrum of HDF-oMD49 (see § 3.1). In order to fit the data in the IRAC bands, it was necessary to also add a blackbody component of very hot 1000 K dust (dotted curve). The thin solid curve shows the combined model results. The data for the NGC 1068 and M82 SEDs were taken from Rigopoulou et al. (1999), Chary & Elbaz (2001), Galliano et al. (2003), and Magnelli et al. (2008). [See the electronic edition of the Journal for a color version of this figure.]

In Figure 2 we show the 3.6–70 \( \mu \text{m} \) SED of HDF-oMD49 and the strong observed-frame 3.6–8 \( \mu \text{m} \) emission and the power-law-like, featureless SED extends the interest from the mid-IR spectral fitting, showing that the IR SED of HDF-oMD49 is dominated by AGN activity. The strongly rising continuum at >4.5 \( \mu \text{m} \) (rest frame >1.4 \( \mu \text{m} \)) also indicates that the contribution from starlight (which typically peaks at rest frame 1.6 \( \mu \text{m} \)) is weak at these wavelengths. The combination of the NGC 1068 and M82 templates gives a respectible fit to the overall SED of HDF-oMD49, even though the wavelength coverage of the SED data is 3 times broader than that used when fitting the mid-IR spectrum (rest frame 1.1–21.8 \( \mu \text{m} \) vs. rest frame 4.4–106.6 \( \mu \text{m} \)). However, the combination of the NGC 1068 and M82 components lies below the observed emission in the IRAC bands (rest frame <3 \( \mu \text{m} \)). This excess emission can be fitted by adding a blackbody component of very hot dust (≈1000 K), as often found in obscured AGNs (e.g., Alonso-Herrero et al. 2001). On the basis of the fitted NGC 1068 component, the rest-frame 6 \( \mu \text{m} \) luminosity from HDF-oMD49 is \( \nu L_{6 \mu \text{m}} \approx 1.3 \times 10^{45} \text{ ergs s}^{-1} \) (\( f_{6 \mu \text{m}} = 210 \mu\text{Jy} \)), indicating that the AGN is powerful (e.g., compare to the nearby AGNs explored by Lutz et al. [2004]).

Our analyses show that the IR SED of HDF-oMD49 is dominated by AGN activity and allows for just a small contribution from star formation. Using the best-fitting star formation component normalizations and the relationship between PAH luminosity and star formation rate (SFR) given by Pope et al. (2008; see their eq. [7]), we predict SFR of \( \approx 60–120 M_\odot \text{ yr}^{-1} \), with the range representing the two different star formation contributions we estimated from the mid-IR spectral fitting. The radio detection of HDF-oMD49 with \( f_{4.8\text{GHz}} \approx 32 \mu\text{Jy} \) (G. Morrison et al. 2008, in preparation) implies a SFR of \( \approx 500 M_\odot \text{ yr}^{-1} \) (calculated following Bauer et al. [2002]). This is clearly inconsistent with the mid-IR data, suggesting that either the radio emission is dominated by the AGN or the radio-SFR relationship is not applicable for high-redshift objects such as HDF-oMD49.

3.2. The Chandra SED

The contrast between the weak X-ray SED (see § 2.2) and the bright, AGN-dominated IR SED implies that the AGN in HDF-oMD49 is heavily absorbed at X-ray energies. The signature of absorption should be evident in the X-ray spectrum of HDF-oMD49. However, before examining the X-ray data it is necessary to consider the contribution to the X-ray emission from star formation. Assuming a SFR of 120 \( M_\odot \text{ yr}^{-1} \) (see § 3.1) and the empirically determined \( L_X \text{-SFR} \) relationship found by Bauer et al. (2002), we predict a rest-frame 0.5–8 keV flux of \( 2 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2} \), which corresponds to an observed-frame 0.5–2 keV flux of \( 1.1 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2} \) (\( L_X \approx 4 \times 10^{41} \text{ ergs s}^{-1} \)), for a typical X-ray spectral slope for star-forming galaxies of \( \Gamma = 1.8 \). Consistent X-ray luminosities are obtained from the empirically derived Ranalli et al. (2003) relationship, although the Persic et al. (2004) relationship would predict an ≈4 times lower X-ray luminosity but only takes into account the contribution from high-mass X-ray binaries. These analyses show that the contribution from star formation could be significant to the observed-frame 0.5–2 keV flux (≈40%). However, the contribution will be negligible in the other X-ray band in which HDF-oMD49 is detected (observed frame 4–8 keV).

In Figure 3 we show the X-ray data of HDF-oMD49 and compare them to the AGN model SEDs adopted by Gilli et al. (2007) to interpret the XRB. The X-ray data of HDF-oMD49 clearly indicate that the AGN is absorbed at X-ray energies; on the basis of the X-ray band ratio (see § 2.2), the X-ray data are consistent with \( N_{\text{H}} > 10^{23} \text{ cm}^{-2} \) (e.g., see Fig. 4 of Alexander et al. [2003a]). However, with our low S/N X-ray data we cannot unambiguously distinguish between Compton-thick and Compton-thin absorption. Furthermore, the X-ray spectrum of a Compton-thick AGN is source specific and depends on the strength of the reflected and scattered X-ray components, in addition to the underlying power-law continuum and any additional absorption; for example, see Appendix A of Guainazzi et al. (2005) for information on the difficulty of identifying Compton-thick AGNs on the basis of X-ray colors alone. Therefore, without detailed X-ray spectral signatures that clearly indicate the presence of Compton-thick absorption (e.g., the identification of a prominent Fe K emission line or a strong reflection component), it is not possible to argue solely on the basis of low S/N X-ray data that an AGN is absorbed by Compton-thick material. In order to confirm whether such an X-ray weak source is Compton thick, it is necessary to estimate the intrinsic AGN luminosity.

3.3. Quantifying the Intrinsic Properties of the AGN in HDF-oMD49

A good proxy for the intrinsic luminosity of AGN activity is the rest-frame mid-IR emission, which can provide an absorption-independent measure of the intrinsic luminosity even in the presence of Compton-thick absorption (e.g., Krabbe et al. 2001; Lutz et al. 2004; Maiolino et al. 2007; Horst et al. 2008). When
combined with the observed X-ray emission, the rest-frame mid-IR luminosity can therefore provide a diagnostic for the presence of heavy absorption. In this study we adopt the X-ray–6 μm luminosity relationship found by Lutz et al. (2004), which was determined by constraining the AGN continuum component in large-aperture mid-IR spectra for a sample of nearby AGNs. We favor the Lutz et al. (2004) X-ray–mid-IR luminosity relationship over the small-aperture mid-IR imaging studies of Krabbe et al. (2001) and Horst et al. (2008), since HDF-oMD49 is unresolved by Spitzer. Furthermore, the Lutz et al. (2004) study also covers a broader range in luminosity, and includes AGNs as luminous as those explored here. Indeed, we note that the X-ray–mid-IR luminosity ratio found for X-ray-obscured but Compton-thin quasars (Sturm et al. 2006) is consistent with the Lutz et al. (2004) relationship, indicating that it is applicable for the objects explored in our study; see Figure 4. However, the differences in the X-ray–mid-IR luminosity of these studies are small (the Lutz et al. [2004] luminosity ratio is within a factor of 2–3 of that found by Krabbe et al. [2001] and Horst et al. [2008], assuming typical SEDs [i.e., NGC 1068; Mrk 231; M82] when converting to a common rest-frame wavelength of 6 μm).

Since it is now well established that the X-ray–to–optical luminosity ratio of optically selected AGNs is luminosity dependent (e.g., Vignali et al. 2003; Steffen et al. 2006), it is also interesting to explore whether the X-ray–mid-IR luminosity ratio is luminosity dependent. Krabbe et al. (2001), Lutz et al. (2004), and Horst et al. (2008) did not find evidence for a luminosity-dependent X-ray–mid-IR luminosity ratio for local AGNs over 3–5 orders of magnitude in luminosity. By comparison, the inference from the study of distant optically selected quasars by Maiolino et al. (2007) is that the X-ray–mid-IR luminosity ratio may be luminosity dependent. For example, solving equations (1) and (5) in Maiolino et al. (2007) gives an X-ray–mid-IR luminosity relationship of $L_X \propto L_{6.7 \mu m}$. However, there is considerable uncertainty in this result, and the derived X-ray–mid-IR luminosity relationship would be linear if a different X-ray–optical luminosity ratio from Steffen et al. (2006) is used (i.e., if their eq. [1b] is adopted instead of eq. [1c]). In any case, the differences between the Lutz et al. (2004) and Maiolino et al. (2007) relationships are small (factor of 2–3) for the luminosities of the majority of the AGNs explored here ($L_X < 3 \times 10^{44}$ erg s$^{-1}$; see Fig. 4); however, we indicate the cases where our results would significantly change if the luminosity-dependent version of the Maiolino et al. (2007) X-ray–mid-IR luminosity relationship is used.

In Figure 4 we show the rest-frame 2–10 keV luminosity versus 6 μm continuum luminosity of HDF-oMD49 and compare it to those found for AGNs in the local universe; we converted the rest-frame 6.7 μm data used by Maiolino et al. (2007) to rest frame 6 μm assuming the SED of NGC 1068, which results in small corrections (≈10%). The rest-frame 2–10 keV luminosity of HDF-oMD49 ($L_X = 1.4 \times 10^{44}$ ergs s$^{-1}$) is estimated from the observed-frame 0.5–2 keV luminosity (rest frame 1.6–6.4 keV), for a spectral slope of $\Gamma = 1.4$. Assuming both the X-ray–mid-IR luminosity relationship found for local AGNs (Lutz et al. 2004), and the relationship derived from Maiolino et al. (2007), the intrinsic rest-frame 2–10 keV luminosity of HDF-oMD49 is $>10^{44}$ ergs s$^{-1}$, suggesting that the X-ray absorption toward the AGN in HDF-oMD49 is Compton thick; see Figure 4 and Table 1. However, to reduce further uncertainties on the X-ray–IR luminosity relationship due to, for example, the geometry and covering factor of the gas and dust surrounding the X-ray-emitting region, it is useful to have other measurements of the intrinsic AGN luminosity.

The rest-frame UV spectrum of HDF-oMD49 shows strong AGN emission lines (C iv, C ii, He II, Lyα; see Fig. 2 of Steidel et al. [2002]), which can be used to provide additional estimates of the intrinsic AGN luminosity. We calculated the emission-line fluxes using the Steidel et al. (2002) optical spectrum and integrating the flux over the emission-line profiles; see Reddy et al. (2006) for more details. Adopting the average emission-line ratios of Netzer et al. (2006), to calculate the expected [O iii]λ5007 luminosity, and the [O iii]λ5007–X-ray flux ratio found by Mulchaey et al. (1994), the range of predicted intrinsic rest-frame 2–10 keV luminosity from the different emission lines is $(1.8–4.8) \times 10^{44}$ erg s$^{-1}$. We get similar intrinsic X-ray luminosities if we use the [O iii]λ5007–X-ray flux ratio found by Alonso-Herrero et al. (1997), and we get higher intrinsic X-ray luminosities (up to an order of magnitude higher for the most luminous AGNs) if we use the Netzer et al. (2006) [O iii]λ5007–X-ray flux ratio. We have not corrected these emission-line fluxes for extinction or contaminations from star formation, which are poorly constrained at rest-frame UV wavelengths. However, we note that the Mulchaey et al. (1994), Alonso-Herrero et al. (1997), and Netzer et al. (2006) correlations were also derived using uncorrected emission-line fluxes. The uncertainties in both the emission-line ratios and the [O iii]λ5007–X-ray flux ratio are ≈2 (see Table 1 of Netzer et al. [2006] and Table 2 of Mulchaey et al. [1994]), giving a combined uncertainty of a factor of 3, comparable to the uncertainty in the intrinsic X-ray luminosity based on the rest-frame 6 μm luminosity. The intrinsic rest-frame 2–10 keV luminosities predicted from both the optical and the mid-IR spectroscopy are in good agreement, providing compelling
evidence for Compton-thick absorption of an intrinsically luminous quasar in HDF-oMD49 ($L_{2-10\text{ keV}} \approx 3 \times 10^{44} \text{ ergs s}^{-1}$; $N_{\text{H}} \gg 10^{24} \text{ cm}^{-2}$).

An alternative scenario for the weak X-ray emission from HDF-oMD49 is that the AGN has recently faded (e.g., Guainazzi et al. 1998). However, since the light crossing time of the mid-IR-emitting region is likely to be short (i.e., on the basis of the dust sublimation radius it will be $\approx 1-2$ yr, e.g., see Table 1 of Granato et al. [1997] and Fig. 30 of Suganuma et al. [2006]), this scenario is only tenable for HDF-oMD49 if we have caught the AGN during a very brief transitional stage where the X-ray emission has faded but the mid-IR emission is still strong. The good agreement between the fluxes measured from the Spitzer MIPS photometry and the Spitzer IRS spectroscopy, taken 2 years apart, suggests that this scenario is unlikely.

4. DISCUSSION

We have used Spitzer IRS spectroscopy, 3.6–70 $\mu$m photometry, optical spectroscopy, and ultradeep 2 Ms Chandra data to show that HDF-oMD49 hosts an intrinsically luminous AGN that is heavily obscured by Compton-thick material ($L_{2-10\text{ keV}} \approx 3 \times 10^{44} \text{ ergs s}^{-1}$; $N_{\text{H}} \gg 10^{24} \text{ cm}^{-2}$); i.e., it is a Compton-thick quasar. The S/N of the X-ray data alone was too poor to show conclusively that the AGN is obscured by Compton-thick material. However, when combined with rest-frame 6 $\mu$m and optical emission-line luminosity constraints, the evidence for Compton-thick absorption...
### TABLE 1
**ROBUSTLY IDENTIFIED $z \approx 2$ COMPTON-THICK QUASARS**

<table>
<thead>
<tr>
<th>Name</th>
<th>$z$</th>
<th>$d_L$ (Mpc)</th>
<th>$L_{X, \text{obs}}$ (ergs s$^{-1}$)</th>
<th>$\nu L_{6\mu m}$ (ergs s$^{-1}$)</th>
<th>$L_{\text{Ly}\alpha}$ (ergs s$^{-1}$)</th>
<th>$L_{\text{He}\text{II}}$ (ergs s$^{-1}$)</th>
<th>$L_{\text{C}\text{IV}}$ (ergs s$^{-1}$)</th>
<th>$L_{[\text{O}\text{III}]}$ (ergs s$^{-1}$)</th>
<th>$L_{X, 6\mu m}$ (ergs s$^{-1}$)</th>
<th>$L_{X, \text{lines}}$ (ergs s$^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMM J123600+621047$^a$</td>
<td>2.002</td>
<td>15,750</td>
<td>$&lt;42.4$</td>
<td>45.3$^b$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>44.7</td>
<td>...</td>
<td>...</td>
<td>1, 2</td>
</tr>
<tr>
<td>HDF-oMD49$^a$</td>
<td>2.211</td>
<td>17,800</td>
<td>42.1</td>
<td>45.2$^b$</td>
<td>42.5</td>
<td>42.4</td>
<td>41.9</td>
<td>41.7</td>
<td>44.6</td>
<td>44.4</td>
<td>3, 4</td>
</tr>
<tr>
<td>FSC 10214+4724$^a$</td>
<td>2.285</td>
<td>18,550</td>
<td>42.3</td>
<td>44.9$^b$</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>42.6</td>
<td>44.3</td>
<td>44.4</td>
<td>5, 6, 7</td>
</tr>
<tr>
<td>SW J104406+583954$^\ldots$</td>
<td>2.430</td>
<td>19,990</td>
<td>$&lt;43.4$</td>
<td>45.8$^b$</td>
<td>43.9</td>
<td>43.5</td>
<td>42.9</td>
<td>...</td>
<td>45.2</td>
<td>45.6</td>
<td>8, 9</td>
</tr>
<tr>
<td>BX 160$^a$</td>
<td>2.462</td>
<td>20,290</td>
<td>$&lt;42.3$</td>
<td>44.9$^d$</td>
<td>42.3</td>
<td>41.8</td>
<td>...</td>
<td>...</td>
<td>44.3</td>
<td>44.1</td>
<td>3, 4</td>
</tr>
<tr>
<td>SW J104409+585224$^\ldots$</td>
<td>2.540</td>
<td>21,100</td>
<td>$&lt;43.4$</td>
<td>46.4$^b$</td>
<td>43.8</td>
<td>43.1</td>
<td>...</td>
<td>...</td>
<td>44.3</td>
<td>44.1</td>
<td>3, 4</td>
</tr>
</tbody>
</table>

**Notes.**—The luminosities are given in logarithmic units of ergs s$^{-1}$. The X-ray luminosities are given in the rest-frame 2–10 keV band: $L_{X, \text{obs}}$ is the observed X-ray luminosity calculated from the observed-frame $0.5–2$ keV luminosity assuming $\Gamma = 1.4$, $L_{X, 6\mu m}$ is the X-ray luminosity implied from the rest-frame $6\mu m$ AGN continuum, and $L_{X, \text{lines}}$ is the average X-ray luminosity implied from the emission-line luminosities; see §3.3 and 4.1 for more details. The references correspond to the X-ray, mid-IR, and optical emission-line data.

$^a$ Object lies in the GOODS-N field.

$^b$ Rest-frame 6 $\mu m$ luminosity is calculated from the best-fitting AGN component to the Spitzer IRS data.

$^c$ Data have been corrected for an assumed lensing boost of 50.

$^d$ Rest-frame 6 $\mu m$ luminosity is calculated from the Spitzer SED.

in this X-ray-faint source is compelling. Additional support for this interpretation comes from the similarity to the mid-IR spectrum of HDF-oMD49 and the composite mid-IR spectrum of X-ray-obscured but Compton-thin quasars; see Figure 1b.

On the basis of the comparatively weak ultrahard 4–8 keV emission from HDF-oMD49, even the rest-frame 12.8–25.7 keV emission appears to be heavily suppressed. For example, assuming an X-ray spectral slope of $\Gamma = 2.0$, the predicted 12.8–25.7 keV luminosity based on the intrinsic rest-frame 2–10 keV luminosity is a factor of $\approx 20$ higher than the observed 12.8–25.7 keV luminosity ($\approx 1.3 \times 10^{44}$ vs. $\approx 6 \times 10^{42}$ ergs s$^{-1}$; see § 2.2). It is difficult to relate this factor of $\approx 20$ suppression to an accurate estimate of the absorbing column density, since the observed X-ray emission in the 12.8–25.7 keV band could be dominated by reflected and scattered components (e.g., NGC 1068; Matt et al. 1997; see Fig. 8.1 in Comastri [2004]). However, on the basis of the PLCABS model (Yaqoob 1997) in XSPEC, which considers the effects of electron scattering and photoelectric absorption through an absorbing medium, this amount of suppression in the 12.8–25.7 keV band would correspond to an absorbing column density of $N_H \approx 4 \times 10^{24}$ cm$^{-2}$. Due to the absence of a reflection component in this model, and the simplifying assumption of a spherical geometry, this absorbing column density should only be considered representative (e.g., see Fig. 8.1 in Comastri [2004] for an alternative model).

In this final section we adopt the approach that we used in § 3 to identify other distant Compton-thick AGNs using data obtained from the literature. Utilizing these constraints we then directly estimate the space density of Compton-thick quasars at $z \approx 2$ and compare our results to current observational and theoretical constraints.

4.1. The Identification of Other Distant Compton-thick AGNs

From a search of the published Spitzer IRS spectroscopic data, there are four good candidate $z \approx 2$ Compton-thick AGNs that have mid-IR spectroscopy and the essential sensitive X-ray constraints required to identify Compton-thick AGN activity: FSC 10214+4714, SW J104406+583954, SW J104409+585224, and SMM J123600+621047. FSC 10214+4714 is a strongly lensed Seyfert 2 galaxy at $z = 2.285$ which produces luminous 6 $\mu$m AGN continuum emission (Teplitz et al. 2006) but is only weakly detected at X-ray energies, despite an effective lensing-corrected Chandra exposure of $\approx 2$ Ms (Alexander et al. 2005b). In Figure 4 we plot FSC 10214 and provide secondary support for the intrinsic luminosity of the AGN using the [O iii] $\lambda 5007$ luminosity from Alexander et al. (2005b) and the [O iii] $\lambda 5007$–X-ray flux ratio of Mulchaey et al. (1994); see Table 1. The combination of the X-ray data and optical–mid-IR spectroscopy confirms that FSC 10214 hosts a Compton-thick quasar ($L_{2-10 \text{keV}} \approx 2 \times 10^{44}$ ergs s$^{-1}$), even given the considerable scatter in the relationships.

SW J104406+583954 and SW J104409+585224 are X-ray-weak candidate Compton-thick AGNs identified in the Chandra/SPWIRE (Spitzer Wide-Area Infrared Extragalactic) survey (Polletta et al. 2006) that lie at $z = 2.430$ and $z = 2.540$, respectively. The optical and mid-IR spectra of both sources show clear signatures of AGN activity (Polletta et al. 2006, 2008; Weedman et al. 2006), which we use to determine the intrinsic luminosities of the central sources; see Table 1. In Figure 4 we plot their X-ray–6 $\mu$m luminosities, showing that the properties of both objects are consistent with those expected for a luminous Compton-thick quasar ($L_{2-10 \text{keV}} > 10^{45}$ ergs s$^{-1}$); however, we note that the evidence is weaker for SW 104406 if the luminosity-dependent X-ray–mid-IR luminosity relationship inferred from Maiolino et al. (2007) is used.

SMM J123600+621047 is a $z = 2.002$ submillimeter-emitting galaxy (SMG) with a mid-IR-bright AGN (Pope et al. 2008) that is undetected in the 2 Ms CDF-N data (Alexander et al. 2003b); we ran WAVDETECT using a false-positive probability threshold of $10^{-5}$ but did not detect X-ray emission from this source (see Table 1 of Alexander et al. [2005a]). The X-ray–6 $\mu$m luminosity ratio indicates that it hosts a Compton-thick AGN (see Fig. 4), although optical and near-IR spectroscopic observations do not reveal the signatures of AGN activity (e.g., Swinbank et al. 2004; Chapman et al. 2005), leaving some uncertainty on the intrinsic luminosity of the AGN. However, since the mid-IR luminosity of the AGN in SMMJ 123600 is about an order of magnitude larger than that found in typical SMGs (e.g., Lutz et al. 2005; Menéndez-Delmestre et al. 2007; Valiante et al. 2007; Pope et al. 2008), the $\approx 10$ times larger intrinsic X-ray luminosity derived here seems plausible ($L_{X,6 \mu m} \approx 5 \times 10^{44}$ ergs s$^{-1}$; i.e., compare to Alexander et al. [2005a]); see our Table 1. In Alexander et al. (2005c), it was argued that SMGs represent a rapid black hole growth phase before the onset of optically luminous quasar activity. The discovery of this one mid-IR luminous X-ray-undetected SMG in the CDF-N field increases current constraints on the integrated black hole growth density in SMGs by a factor of $\approx 2$ (see Fig. 2 of Alexander et al. [2005c]).

Other studies have used optical spectroscopy to identify AGNs that are mid-IR bright and X-ray weak/undetected but lack Spitzer IRS spectroscopy. Reddy et al. (2006) found two $z \approx 2.4–2.5$ optically identified AGNs (BX 160; BX 1637) that are X-ray undetected in the 2 Ms CDF-N survey and have power-law-like IR SEDs [the $24 \mu$m fluxes of these sources ($f_{24 \mu m} \approx 100–140 \mu Jy$) are too faint for good S/N Spitzer IRS spectroscopy]; see Table 1. Following our approach for HDF-oMD49 (see § 2.2), we ran WAVDETECT using a false-positive probability threshold of $10^{-5}$ but did not detect X-ray emission from either source; $3 \sigma$ X-ray upper limits are calculated following § 3.4.1 in Alexander et al. (2003b). We plot the X-ray–to–6 $\mu$m luminosity ratios of these objects in Figure 4. The mid-IR data, when combined with the optical emission-line luminosities, indicate that these sources are likely to be Compton-thick quasars; we determined their emission-line properties using the same procedure as for HDF-oMD49 (see § 3.3). The evidence would be weaker for BX 1637 if the luminosity-dependent X-ray–mid-IR luminosity ratio inferred from Maiolino et al. (2007) is used, although we note that the X-ray–6 $\mu$m luminosity ratio for this source is an upper limit.

We also note that other studies have selected candidate Compton-thick AGNs using a combination of multiwavelength data with sensitive X-ray constraints (e.g., Donley et al. 2005, 2007; Alonso-Herrero et al. 2006; Daddi et al. 2007b; Martínez-Sansigre et al. 2007; Fiore et al. 2008); many other studies have identified obscured AGNs using mid-IR spectroscopy but lack the essential X-ray data to provide a case for Compton-thick absorption. However, none of these studies have optical or mid-IR spectroscopy to provide accurate measurements of the intrinsic AGN luminosities.

4.2. The Properties of Distant Compton-thick AGNs

The intrinsic X-ray–mid-IR continuum ratios, inferred using the rest-frame UV emission-line luminosities of the six Compton-thick quasars with optical AGN signatures, are consistent with those found for AGNs in the local universe; see Figure 4. This is in agreement with the results of Sturm et al. (2006), who found that the average intrinsic X-ray–6 $\mu$m luminosities of distant X-ray-obscured quasars are similar to those found for local AGNs,
suggestion that the objects explored here are the extreme Compton-thick end of the X-ray-obsured quasar population. We also showed in §3.1 and Figure 1b that the Spitzer IRS spectrum of HDF-oMD49 is similar to the composite mid-IR spectrum produced by Sturm et al. (2006), providing a particularly strong case for a quasar that is absorbed in the X-ray band by Compton-thick material in this source. These pieces of evidence also suggest that the accretion properties of distant, optically identifiable AGNs are similar to those observed in local AGNs, in agreement with previous studies that have explored the X-ray—optical and X-ray—infrared properties of optically selected AGNs (e.g., Steffen et al. 2006; Jiang et al. 2006).

In Figure 5 we show the observed and intrinsic X-ray luminosities versus redshift of the seven Compton-thick quasars identified here. Four of the Compton-thick quasars lie in the GOODS-N region (≈160 arcmin$^2$) of the CDF-N and, despite being X-ray weak/undetected, they are among the most intrinsically luminous AGNs identified in this field. This shows that even in the deepest X-ray survey currently available, we are only able to directly probe the peak of the Compton-thick AGN population at $z \approx 2$. The two luminous Compton-thick quasars were identified in the wider area SWIRE survey (≈0.6 deg$^2$) and are among the most luminous obscured AGNs known.

Four of the seven Compton-thick quasars are detected in the X-ray band, most typically at $>2$ keV. Three of these objects have hard X-ray spectra ($\Gamma < 1$; HDF-oMD49; SW 104406; SW 104409; Polletta et al. 2006), and one object has a comparatively soft X-ray spectrum ($\Gamma \approx 1.6$; FSC 10214; Alexander et al. 2005c). The comparatively soft X-ray spectrum of FSC 10214 might be dominated by scattered emission and star formation from the host galaxy, as often found in Compton-thick AGNs (e.g., Bassani et al. 1999; Comastri 2004; Guainazzi et al. 2005). We can also place basic X-ray spectral constraints on the three X-ray-undetected Compton-thick quasars by stacking their X-ray data; all of these objects lie in the GOODS-N field, where the X-ray data are particularly sensitive. Using the X-ray stacking code adopted by Worsley et al. (2005), we obtain $\approx 3 \sigma$ detections in the 0.5–8 and 2–8 keV bands, and have a $\approx 2 \sigma$ constraint in the 0.5–2 keV band; the significance of these stacking results were calculated using 10,000 Monte Carlo trials. The stacked data correspond to fluxes (and a $3 \sigma$ upper limit) of $2.8 \times 10^{-16}$ ergs cm$^{-2}$ (0.5–8 keV), $<2.3 \times 10^{-17}$ ergs cm$^{-2}$ (0.5–2 keV), and $2.7 \times 10^{-15}$ ergs cm$^{-2}$ (2–8 keV). The average rest-frame 2–10 keV luminosity constraint for these three objects derived from the observed-frame 0.5–2 keV flux is $<10^{42}$ ergs s$^{-1}$. The derived X-ray spectral slope of $\Gamma < 0.3$ unambiguously confirms that heavily obscured AGNs are present in these sources (e.g., see Fig. 2a in Alexander et al. [2005a]).

4.3. The Selection of Distant Compton-thick AGNs

The seven Compton-thick quasars investigated here were selected on the basis of unambiguous evidence for AGN activity from optical and/or mid-IR spectroscopy. The advantage with this approach is that we have been able to estimate the intrinsic AGN properties of these objects using the optical—mid-IR spectroscopy. However, the requirement for spectroscopic evidence of AGN activity has led to a comparatively small sample of objects. Nevertheless, we can provide some insight into the completeness of Compton-thick AGN selection by comparing the properties of our reliably identified Compton-thick quasars to the larger samples of candidate Compton-thick AGNs that have been photometrically identified in other studies. Arguably, the most complete identification studies of distant Compton-thick AGNs to date are Daddi et al. (2007a, 2007b) and Fiore et al. (2008). Daddi et al. (2007a, 2007b) identified a large population of X-ray-undetected $z \approx 2$ galaxies with an excess of mid-IR emission over that expected from star formation (as predicted using the dust-extinction-corrected UV luminosity). X-ray stacking analyses revealed a hard X-ray spectral slope from these objects ($\Gamma = 0.8$), comparable to that of the Compton-thick quasars and unambiguously identifying the presence of heavily obscured AGNs; see §4.2. In Figure 6a we plot the ratio of mid-IR-based to UV-based SFR versus $8 \mu$m luminosity of the Compton-thick quasars and compare them to Daddi et al. (2007a, 2007b); we have not calculated the properties of FSC 10214 due to the significant uncertainties in the lensing magnification of the star-forming regions. The Compton-thick quasars lie significantly above the mid-IR excess threshold defined by Daddi et al. (2007b), indicating that they are extreme examples of the mid-IR excess galaxy population. This analysis shows reliably that at least a subsample of the mid-IR excess galaxy population host Compton-thick AGNs.

Fiore et al. (2008) took a complementary approach to that of Daddi et al. (2007a, 2007b) and selected X-ray-undetected objects with extreme mid-IR—optical flux ratios ($f_{8\mu m}/f_R > 1000$) and red optical colors ($R - K > 4.5$). X-ray stacking analyses of these objects revealed a hard X-ray spectrum with a slope similar to that found for the mid-IR excess galaxies ($\Gamma \approx 1.0$, calculated from their stacked X-ray count rates). In Figure 6b we plot the mid-IR—optical flux ratio versus $R - K$ color of the Compton-thick quasars and compare them to the candidate Compton-thick AGNs studied by Fiore et al. (2008) and Daddi et al. (2007b); as before, we did not calculate the properties of FSC 10214. Formally,
none of the Compton-thick quasars match the candidate Compton-thick AGN selection criteria of Fiore et al. (2008), although two of the objects lie close. Furthermore, only ≈10% of the mid-IR excess galaxies of Daddi et al. (2007b) match the Fiore et al. (2008) criteria. These analyses show that the candidate Compton-thick AGN criteria of Daddi et al. (2007b) and Fiore et al. (2008) are mutually exclusive, suggesting that the distant X-ray-undetected AGN population may be larger than either study has suggested. The requirements in our study for optical spectroscopic redshifts and the optical identification of AGN activity (with the exception of SMM J123600) probably causes a bias against selecting objects with red R − K colors, which by definition will be optically faint.

4.4. The Ubiquity of Distant Compton-thick AGNs

Our seven Compton-thick quasars do not comprise a complete sample. However, four of the objects lie in the GOODS-N field, providing basic constraints on the space density of Compton-thick quasars at z ≈ 2–2.5. On the basis of the comoving volume at z = 2–2.5 in a region the size of the GOODS-N field, we estimate a comoving space density for Compton-thick quasars with $L_{\text{rest-frame} \ 8\mu m} \approx 10^{44} - 10^{45}$ ergs s$^{-1}$ of $\Phi \approx (0.7-2.5) \times 10^{-5}$ Mpc$^{-3}$, where the range only reflects the uncertainty due to small number statistics (e.g., Gehrels 1986).

In Figure 7 we plot the Compton-thick quasar space density and compare it to that found in other studies. Our results suggest that the space density of Compton-thick quasars is $\approx 1$–5 times higher than that of comparably luminous unobscured quasars at $z \approx 2–2.5$ ($\Phi \approx 5 \times 10^{-6}$ Mpc$^{-3}$; e.g., Hasinger et al. 2005). Since the Gilli et al. (2007) model of the XRB constrains the number of Compton-thick quasars to be the same as the number of unobscured quasars, our Compton-thick quasar space density is also $\approx 1$–5 times higher than the Compton-thick quasar predictions of Gilli et al. (2007). As we mention in § 4.1 and show in Figure 4, the evidence for a Compton-thick quasar in BX 1637 is weaker if the X-ray–mid-IR luminosity ratio inferred by Maiolino et al. (2007) is used. However, we note that a significantly more important issue is likely to be the effect of cosmic variance, since we have only identified Compton-thick quasars in a small region over a narrow redshift range. For example, within the GOODS-N field, there are also four X-ray-unobserved quasars that lie at $z \approx 2–2.5$, indicating that the true Compton-thick–unobscured quasar ratio may be toward the lower end of the value given above. Nevertheless, our results clearly indicate that a large fraction of the growth of black holes was obscured by Compton-thick material, in general agreement with results based on less reliable photometrically identified objects (e.g., Daddi et al. 2007b; Martínez-Sansigre et al. 2007; Fiore et al. 2008), the predictions made by theoretical models (e.g., Marconi et al. 2004; Treister et al. 2006), and the Compton-thick AGN fraction inferred by the study of Maiolino et al. (2007; their Fig. 7a).

We can compare our estimated space density to those determined from the photometric selection of candidate Compton-thick AGNs by Daddi et al. (2007b) and Fiore et al. (2008). On the basis of the X-ray data and the X-ray–$6 \mu m$ luminosity, Daddi et al. (2007b) argued that their candidate Compton-thick AGNs have an average intrinsic luminosity of $L_{\text{rest-frame} \ 8\mu m} \approx (1–4) \times 10^{43}$ ergs s$^{-1}$. The intrinsic luminosities of these mid-IR excess galaxies are about an order of magnitude lower than the Compton-thick quasars identified here, and consequently their space density is higher ($\Phi \approx 2.6 \times 10^{-4}$ Mpc$^{-3}$; see Fig. 7). Fiore et al. (2008) estimated the intrinsic X-ray luminosities of their X-ray-undetected candidate Compton-thick AGNs using the $5.8 \mu m$ luminosities, finding $L_{\text{rest-frame} \ 8\mu m} > 10^{43}$ ergs s$^{-1}$. Taking into account the estimated redshift range of their objects ($z = 1.2–2.6$), we calculate a space density of $\Phi \approx 7 \times 10^{-5}$ Mpc$^{-3}$, as mentioned in Fiore et al.
the Compton-thick quasars robustly identified here is a factor of \( L_{\text{x}} \) lower limits from the Gilli et al. (2007) XRB model. The space density of Compton-thick accretion is ubiquitous at thick AGNs, and they are therefore upper limits (see (2007b) and Fiore et al. (2008) using photometrically identified objects and X-ray non-Compton-thick AGNs in their samples (i.e., either Compton-thick material). This suggests that either the intrinsic AGN luminosities of these quasars would be more modest (\( L_{\text{x}} \approx 3 \times 10^{44} \text{ ergs s}^{-1} \)), casting significant doubt on whether they are obscured by Compton-thick material; the rest-frame 6 \( \mu \text{m} \) fluxes are derived from the observed 24 \( \mu \text{m} \) fluxes using the NGC 1068 SED to apply small K-corrections. Direct spectroscopic identification of these photometrically classified Compton-thick quasars is required to place more direct constraints, which should be possible with current instrumentation.

Finally, we compare our results to the Compton-thick AGNs identified by Tozzi et al. (2006) using X-ray spectral analysis of X-ray-detected AGNs in the Chandra Deep Field—South survey. Fourteen of the objects investigated by Tozzi et al. (2006) had X-ray spectra that were better fitted by a pure reflection model than an absorbed power-law model, and were consequently classified as Compton-thick AGNs; derived space densities are \( L_{\text{x}} \approx 3 \times 10^{43} \text{ Mpc}^{-3} \) at \( z \approx 1 \) and \( L_{\text{x}} \approx 8 \times 10^{42} \text{ Mpc}^{-3} \) at \( z \approx 2 \). While the Tozzi et al. (2006) study provides the most quantitative X-ray identification of distant Compton-thick AGNs to date, it is also possible for Compton-thin AGNs to have a pure reflection component (i.e., if the power-law component has temporarily decreased), and other pieces of evidence are required to confirm that these are Compton-thick AGNs. Two of the seven objects with spectroscopic redshifts have strong Fe K\( \alpha \) emission lines, confirming that they are likely to be Compton thick, but supporting evidence for Compton-thick absorption is lacking in the other objects.

4.5. Prospects for Improved Observational Constraints

The current study provides diagnostics to identify distant Compton-thick AGNs but is limited in source statistics, covers a narrow redshift range, and is restricted to the brightest AGNs at \( z \approx 2 \). Future studies could focus on obtaining optical—mid-IR spectroscopy of lower luminosity \( z \approx 2 \) candidate Compton-thick AGNs, as well as identifying objects at lower and higher redshifts. Assuming the NGC 1068 template used here and the average X-ray—mid-IR relationship shown in Figure 4, an AGN with \( L_{\text{x}} \approx 10^{43} \text{ ergs s}^{-1} \) will have 24 \( \mu \text{m} \) fluxes of \( \approx 2 \mu \text{Jy}, \approx 15 \mu \text{Jy}, \approx 0.3 \text{ mJy} \), and \( \approx 5 \text{ mJy} \) at \( z \approx 4, z \approx 2, z \approx 0.7, \) and \( z \approx 0.2 \), respectively; these fluxes will typically scale linearly with luminosity (see § 3.3). Mid-IR-bright objects (\( f_{\text{24 \mu m}} > 0.2 \text{ mJy} \)) should be identifiable with Spitzer IRS, but mid-IR spectroscopic identification of fainter objects will need to wait until the launch of the James Webb Space Telescope. Optical and near-IR spectroscopy may be easier to obtain for many of the candidate Compton-thick AGNs, although only if the AGNs have identifiable emission lines, which could be weak in low-luminosity and dust-reddened AGNs (e.g., Caccianiga et al. 2007; see § 4.3).

Ultimately, deep X-ray data are required to search directly for the presence of Compton-thick absorption in individual objects using high S/N X-ray spectroscopy. For the majority of the objects investigated here, this will require >2 Ms exposures with current X-ray telescopes; see Figure 5. However, due to its large...
We have presented Spitzer IRS spectroscopy and 3.6–70 μm photometry of HDF-oMD49, a z = 2.211 optically identified AGN that is formally undetected in the 2 Ms CDF-N observation. From a combination of optical–mid-IR spectroscopy and X-ray data, we have shown that HDF-oMD49 hosts an intrinsically luminous quasar that is obscured by Compton-thick material (L_{2-10 keV} ≈ 3 × 10^{44} ergs s^{-1}; N_{Y} > 10^{24} cm^{-2}). We selected six further z ≈ 2 AGNs from the literature (four with Spitzer IRS spectroscopy) and used the same X-ray–optical–mid-IR diagnostics applied to HDF-oMD49 to show that these objects are also likely to be Compton-thick quasars with L_{2-10 keV} > 10^{44} ergs s^{-1}. We demonstrated that these Compton-thick quasars would be classified as mid-IR excess galaxies, on the basis of the Daddi et al. (2007b) definition, providing the first spectroscopic confirmation of Compton-thick AGN activity in a subsample of these z ≈ 2 mid-IR-bright galaxies. Four of these Compton-thick quasars lie in the GOODS-N field, and we used these objects to constrain the space density of distant Compton-thick quasars, finding Φ ≈ (0.7–2.5) × 10^{-5} Mpc^{-3} at z ≈ 2–2.5. On the basis of our results, Compton-thick quasars were as ubiquitous as unobscured quasars at z ≈ 2–2.5, implying that a large fraction of the growth of supermassive black holes must have been obscured by Compton-thick material.

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