XMM-NEWTON OBSERVATIONS OF A COMPLETE SAMPLE OF OPTICALLY SELECTED TYPE 2 SEYFERT GALAXIES

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ABSTRACT

The majority of active galactic nuclei (AGNs) suffer from significant obscuration by surrounding dust and gas. The penetrating power and sensitivity of hard X-ray observations allow obscured AGNs to be probed out to high redshifts. However, X-ray surveys in the 2–10 keV band will miss the most heavily obscured AGNs in which the absorbing column density exceeds \( \sim 10^{24} \text{ cm}^{-2} \) (the Compton-thick AGN). It is, therefore, vital to know the fraction of AGNs that are missed in such X-ray surveys and to determine if these AGNs represent some distinct population in terms of the fundamental properties of AGNs and/or their host galaxies. In this paper, we present the analysis of XMM-Newton X-ray data for a complete sample of 17 low-redshift Type 2 Seyfert galaxies chosen from the Sloan Digital Sky Survey based solely on the high observed flux of the [O\text{iii}]/\lambda 5007 emission line. This line is formed in the narrow-line region hundreds of parsecs away from the central engine. Thus, unlike the X-ray emission, it is not affected by obscuration due to the torus surrounding the black hole. It therefore provides a useful isotropic indicator of the AGN luminosity. As additional indicators of the intrinsic AGN luminosity, we use the \textit{Spitzer Space Telescope} to measure the luminosities of the mid-infrared continuum and the [O\text{iv}] 25.89 \textmu m narrow emission line. We then use the ratio of the 2–10 keV X-ray luminosity to the [O\text{iii}] and mid-infrared luminosities to assess the amount of X-ray obscuration and to distinguish between Compton-thick and Compton-thin objects. The various diagnostics of AGN luminosity with heavily obscured hard X-ray emission are in broad agreement. We find that the majority of the sources suffer significant amounts of obscuration: the observed 2–10 keV emission is depressed by more than an order of magnitude in 11 of the 17 cases (as expected for Compton-thick sources). Thus, surveys in the rest-frame 2–10 keV band will be significantly incomplete for obscured AGNs. We find a strong inverse correlation between the ratio of the 2–10 keV X-ray and [O\text{iii}] or [O\text{iv}] or mid-IR fluxes and the equivalent width of the 6.4 keV Fe K\alpha line. This demonstrates that the weak hard X-ray continuum emission is due to obscuration (rather than due to intrinsically weak emission). In several cases, the large amount of obscuration is not consistent with the values of absorbing column density derived from simple spectral fits to the data. We run simulations of a more physically realistic model with partial covering of the X-ray source plus Compton scattering, and show that such models are consistent with the data. We show that the distribution of obscuration in the 2–10 keV band in our sample is similar to what is seen in samples selected in the \textit{Swift} BAT energy band (14–195 keV). This implies that the BAT surveys do recover a significant fraction of the local population of Compton-thick AGNs. Finally, we find no relationship between the amount of X-ray obscuration and the other properties of the AGN and its host galaxy. Hence, Compton-thick and Compton-thin sources do not seem to trace distinct populations.

Key words: galaxies: Seyfert — X-rays: galaxies

Online-only material: color figure

1. INTRODUCTION

In the standard model (e.g., Urry & Padovani 1995), active galactic nuclei (AGNs) consist of an accretion disk around a supermassive black hole (SMBH) surrounded by a torus of dust and gas. The accretion disk is a source of ultraviolet and optical continuum emission, while X-rays are believed to originate through inverse Compton scattering of soft seed photons from the disk by hot electrons in a surrounding corona. Dust in the torus absorbs the emission from the accretion disk and re-emits it in the mid-infrared. Type 1 (unobscured) and Type 2 (obscured) AGNs are intrinsically the same, but they display different characteristics because of their orientation. In Type 2 AGN, the torus is viewed nearer edge-on, obscuring the central source; whereas in Type 1 AGN, the torus is viewed nearer face-on, providing an unobscured view of the central source (Antonucci 1993). Obscured AGNs have long been identified by their narrow high-ionization emission lines in the optical band, produced by photoionized gas far above and below the plane of the torus. Obscured AGNs can also be recognized by the mid-infrared emission from the torus. Optical and infrared surveys show that obscured AGNs constitute the majority of the population (e.g., Risaliti et al. 1999; Hao et al. 2005). Hard X-rays (\( E > 2 \text{ keV} \)) also offer a potentially powerful way to find obscured AGNs. So long as the obscuring column density (\( N_{\text{H}} \)) is \(< 10^{24} \text{ cm}^{-2} \) (the Compton-thin regime), hard X-rays will suffer little absorption. However, observations of a local (<0.035) sample of 49 Type 2 AGNs show that, in fact, many of these are very weak in the 2–10 keV X-ray band (Guainazzi et al. 2005). In the Chandra Deep Field South, only
82 out of over 300 AGNs with optical spectroscopy were “X-ray bright” (>80 counts in the 2–10 keV band). Though this sample includes AGNs up to much higher redshifts (up to z ~ 3), the subsamples of X-ray bright and X-ray faint targets have similar redshift distributions, indicating that the X-ray faint nature of the sample is not due to selection effects but rather that the majority of targets are weak X-ray emitters (Tozzi et al. 2006). The cases where the X-ray emission is severely attenuated are the Compton-thick targets where the X-ray emission is due to obscuration rather than an intrinsic property (e.g., Brightman & Nandra 2008)? Fortunately, there are signatures of obscuration in the X-ray spectra themselves. The weak X-ray emission that is seen in such cases often has a relatively flat X-ray spectrum and a strong Fe Kα emission line. These features are indicative of heavily reprocessed emission such as from reflection of hard X-rays off the torus wall. This is as expected for a highly obscured X-ray source.

The weakness of the hard X-ray emission in many Type 2 AGNs (regardless of its origin) implies that hard X-ray surveys do not fully probe the AGN population. This is important from several perspectives. First, phenomenological models often invoke a significant population of obscured AGNs in order to successfully match the spectral energy distribution of the cosmic X-ray background at energies above 10 keV (Comastri 2004). Are such models consistent with the observed properties of obscured AGN? Second, deep X-ray surveys can detect AGN out to high redshift. They then allow us to probe the cosmic evolution of the AGN population down to luminosities and SMBH masses well below the levels reached in optical surveys of quasars. Are the implications drawn from such surveys affected by a bias against Compton-thick AGNs?

To address these issues, it is important to study a complete sample of AGNs selected without regard to their hard X-ray properties. Optical spectroscopic surveys can, in principle, provide such a sample. Type 2 AGNs in these surveys are identified by the high-excitation narrow emission from photoionized gas in the narrow-line region (NLR), material located hundreds of parsecs out along the polar axis of the torus. This emission is therefore unaffected by the obscuration of the torus itself and is isotropically radiated up to first order. Comparison of the luminosity of the gas in the NLR to that in hard X-rays can then be used to estimate the amount of X-ray obscuration. The most commonly used optical emission line is [O II]λ5007 (e.g., Bassani et al. 1999; Heckman et al. 2005). Several indicators of the intrinsic AGN luminosity also exist in the mid-infrared band where the effects of obscuration will be minimal. A close analog to the [O II]λ5007 line is the luminosity of the [O IV] 25.89 μm line from the NLR (e.g., Meléndez et al. 2008; Diamond-Stanic et al. 2009; Rigby et al. 2009). The luminosity of the mid-infrared continuum from the torus is also a useful indicator, although the torus is not believed to emit in a fully isotropic fashion (e.g., Pier & Krolik 1993; Nenkova et al. 2008).

In this paper, we present X-ray analysis of a nearly complete sample of 17 Type 2 Seyfert galaxies (Sy2) selected from the Sloan Digital Sky Survey (SDSS) based on their high [O III]λ5007 flux. Using pointed XMM-Newton observations of these sources, we derive their X-ray spectral characteristics and calculate their hard X-ray luminosities. We then use the SDSS data to measure the luminosities of [O II]λ5007 lines and Spitzer Space Telescope Infrared Spectrograph (IRS) data to measure the luminosities of the mid-infrared continuum and of the [O IV] 25.89 μm line. We use these data to assess the amount of X-ray obscuration. We also use the measurements of the Fe Kα line as an additional tool for probing highly obscured X-ray emission. Finally, we use the SDSS and Spitzer data to derive the basic intrinsic properties of the AGNs and their host galaxies. This allows us to determine whether the Compton-thick and Compton-thin populations differ in any systematic way.

2. XMM-NEWTON OBSERVATIONS AND DATA REDUCTION

2.1. Sample Selection

Our Type 2 AGNs are drawn from a parent sample of the spectra of roughly 480,000 galaxies in the SDSS Data Release 4 = DR4 (Adelman-McCarthy et al. 2006). This parent sample of “SDSS Main Galaxies” (Strauss et al. 2002) is complete over the SDSS DR4 footprint and is selected solely on the basis of the galaxy r-band apparent magnitude (14.5 < r < 17.77). The diagnostic line ratio plot of [N II]/Hα versus [O III]/Hβ in Kauffmann et al. (2003a, hereafter K03) and Kewley et al. (2006) was used to identify Type 2 AGNs based on the SDSS spectra. Our sample was then defined as the 20 such objects having an observed [O III]λ5007 flux above 4 × 10^{-14} erg cm^{-2} s^{-1}, corresponding to a luminosity of ~10^{-9} erg s^{-1} at the median distance for our sample (~150 Mpc). XMM-Newton data exist for 17 of the 20 objects in our sample, so the present sample is nearly complete.

We note that our sample is highly complementary to the sample of “Type II Quasars” investigated by Zakamska et al. (2003, 2008) and Ptak et al. (2006). These objects were selected on the basis of a high [O III]λ5007 luminosity (rather than on the basis of a flux limit as we have done). The Type II Quasars were drawn from the full set of SDSS spectra, rather than from the homogeneous SDSS Main Galaxy sample. These objects define the extreme high luminosity end of the Type 2 AGN population, while our sample deals with typical Type 2 AGN.

2.2. Data Analysis

We were awarded XMM-Newton time to observe 15 of the 20 members from this sample for a nominal 23 ks per target before filtering. Two additional targets from this sample were previously observed with XMM-Newton and were added: 0325−0608 (Mrk 609, PI: Aschenbach) and 1218+4706 (PI: Page), bringing the sample total to 17. Table 1 lists the targets along with their observation ID (ObsID) number. The luminosity distances listed in Table 1 are based on the optical spectroscopic redshift, adopting a cosmology of H_0 = 71 km s^{-1} Mpc^{-1}, Ω_M = 0.27, and Ω_{Λ} = 0.73.

The XMM-Newton data were reduced using XAssist (Ptak & Griffiths 2003), which runs the Science Analysis System (SAS) tasks to filter the raw data, generate light curves, clean the data for flaring, and extract spectra and associated response files (rmfs and arfs) for user-defined sources. Table 1 lists the good exposure time for each detector. For three sources, 1018+3722, 1111+0228, and 1437+3634, flaring was significant, so
we applied minimal background filtering. The soft counts (0.5–2 keV) and hard counts (2–10 keV) are listed in Table 2.

For most of the sources, there were sufficient counts to group the PN, MOS1, and MOS2 data by >5 counts bin$^{-1}$ and in a majority of these cases, >10 counts bin$^{-1}$; and we used the $\chi^2$ statistic for the spectral analysis. The following targets were grouped by 2–3 counts bin$^{-1}$ and were therefore analyzed using the C-statistic (XSpec handles spectral fitting via C-stat better when the data are slightly binned rather than unbinned, e.g., Teng et al. 2003): 0053–0846, 1123+4703, and 1346+6423. One target, 1218+4706, fell on the chip gap in the pn detector, so we analyzed only the MOS1 and MOS2 data for this source.

The PN, MOS1, and MOS2 data were fit simultaneously for each source in XSpec, with all parameters tied together except for a constant multiplicative factor, which was frozen at 1 for the PN spectra and allowed to vary between 0.8 and 1.2 for MOS1 and MOS2, as the responses among detectors should generally not vary by greater than ~20% (http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0052.ps.gz); though in some cases, these limits were extended slightly to better fit the data when necessary (i.e., when the error on the statistical count rate is >20%). We first fit all targets with a simple absorbed power law. The parameters derived from these fits are given in Table 3.

In many cases, a second power-law component at higher energies was needed to accommodate the data, evident by both the shape of the spectrum and the inability of a single absorbed power law to accurately model the data as reflected by the high $\chi^2$ value for a single power-law fit. The targets best fit by a single absorbed power law are 0325–0608, 0959+1259, 1018+3722, 1123+4703, 1346+6423, and 1437+3634. The remaining 11 targets were fit by a double absorbed power law, where the photon indices for the two power-law components were tied together. In some cases (0325–0608, 0800+2636, 0824+2959, 1111+0228, 1123+4703, and 1218+4706), the best-fit absorption was the same as the Galactic absorption, so we froze this parameter to the Galactic value for these spectral fits; for 1346+6423, the spectral fit was best constrained by freezing absorption to the Galactic value and the photon index to 1.8. The best-fit parameters from these fits are listed in Table 3, along with their corresponding $\chi^2$ values. As shown in Table 4, the double power-law fit passes the F-test at almost or better than the 3$\sigma$ confidence level for all 11 targets to which it was applied, indicating that this model more accurately represents the data. Though applying the F-test to certain astrophysical

### Table 1

Sample and XMM-Newton Observation Log

| Target | Distance (Mpc) | Alternate Name | ObsID | Observation Start Date | Exposure Time MOS1/MOS2/PN (ks) |
|--------|----------------|----------------|-------|-------------------------|---------------------------------|
| 0053–0846 | 81.4 | NGC 0291 | 0504100301 | 2007 Jun 24 | 6.4/6.2/2.2 |
| 0325–0608 | 147.4 | Mrk 609 | 0103861001 | 2002 Aug 13 | 9.1/9.1/7.5 |
| 0800+2636 | 116.4 | IC 0486 | 0504101201 | 2007 Oct 28 | 21.6/21.6/20.1 |
| 0804+2345 | 125.3 | 2MASX J0804+2345 | 0504101201 | 2007 Nov 09 | 22.6/22.6/20.4 |
| 0824+2959 | 107.6 | IRAS F08216+3009 | 0504102001 | 2007 Nov 03 | 23.4/23.4/21.8 |
| 0959+1259 | 147.4 | CGCG 064–017 | 0504100201 | 2007 Nov 25 | 21.6/21.6/20.0 |
| 1018+3722 | 214.9 | 2MASX J1018+3722 | 0504101701 | 2007 May 18 | 23.2/23.2/18.8 |
| 1111+0228 | 151.9 | 2MASX J1111+0228 | 0504101801 | 2007 Jun 10 | 24.0/24.0/22.6 |
| 1123+4703 | 107.6 | CGCG 242–028 | 0504101301 | 2007 Jun 11 | 19.5/19.8/4.0 |
| 1136+5657 | 224.0 | MCG +10-17-021 | 0504101001 | 2007 Dec 15 | 21.6/21.6/19.8 |
| 1147+5226 | 214.9 | Mrk 1457 | 0504101401 | 2008 Apr 21 | 26.4/26.4/14.5 |
| 1157+5249 | 156.3 | 2MASX J1157+5249 | 0504100901 | 2007 Jun 21 | 25.0/25.2/22.1 |
| 1218+4706 | 425.8 | 2MASX J1218+4706 | 0203270201 | 2004 Jun 01 | 43.7/43.9/36.6 |
| 1238+0927 | 373.0 | 2MASX J1238+0927 | 0504100601 | 2007 Dec 09 | 21.6/21.6/20.1 |
| 1323+4318 | 116.4 | CGCG 218–007 | 0504101601 | 2007 Nov 21 | 8.3/8.3/5.7 |
| 1346+6423 | 103.3 | 2MASX J1346+6423 | 0504101501 | 2007 Jun 13 | 10.5/10.0/1.3 |
| 1437+3634 | 59.8 | NGC 5695 | 0504100401 | 2007 Dec 16 | 20.4/20.2/11.2 |

**Notes.**

1. Distances based on optical spectroscopic redshift using $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$.

2. Net exposure time after filtering.

### Table 2

X-ray Counts

| Target | Soft (0.5–2 keV) | Hard (2–10 keV) |
|--------|----------------|----------------|
| 0053–0846 | 62 | 18 |
| 0325–0608 | 5392 | 1898 |
| 0800+2636 | 5327 | 11,477 |
| 0804+2345 | 163 | 67 |
| 0824+2959 | 816 | 2188 |
| 0959+1259 | 2858 | 3327 |
| 1018+3722 | 233 | 19.2/34/38 |
| 1111+0228 | 304 | 416 |
| 1123+4703 | 63 | 59 |
| 1126+5657 | 474 | 81 |
| 1147+5226 | 261 | 316 |
| 1157+5249 | 530 | 179 |
| 1218+4706 | 76 | 83 |
| 1238+0927 | 658 | 1934 |
| 1323+4318 | 100 | 506 |
| 1346+6423 | 16 | 24 |
| 1437+3634 | 299 | 71/40/15 |

**Notes.**

1. About half the total counts are from the pn detector with the remainder roughly equally split between the MOS1 and MOS2 detectors.

2. In the 2–10 keV band, there are 3$\sigma$ upper limits count rate for one or both of the MOS detectors. Counts are therefore listed separately for each detector: PN/MOS1/MOS2.
The lower error range for No. 1, 2009 XMM-NEWTON indicates that we are observing scattered and probabilities derived indicate that the more complex models are accommodated by fitting a starburst is commonly found in Seyfert galaxies. We will discuss the evidence for starbursts in our sample based on the SDSS and Spitzer IRS spectra in a future paper. Here, we simply accommodate the possible presence of a starburst by fitting each of the targets with a thermal component (APEC in XSpec) added to the aforementioned absorbed single or double power-law model. The metal abundances were initially fixed to solar, allowing only the plasma temperature and normalization to be fit. We were able to fit the metal abundances for two of the sources: 0053−0846 and 1123−4703. The fit parameters from the power law plus thermal model are listed in Table 5. For four of the targets (0325−0608, 1018+3722, 1123+4703, and 1147+5226), addition of the thermal component significantly improved the results at greater than the 3σ level according to the F-test (see Table 6). We note that inclusion of this model component causes the power-law index to decrease and to fall within the more commonly observed range for 1147+5226 and 1157+5249; though Γ increases for 1018+3722, the lower end of the 90% confidence level for this parameter now falls within the typical range observed in Seyferts. However, the power-law indices remained too steep for 0804+2345 and 1136+5657 (4.94±0.36 and 3.11±0.43, respectively) and allowing the two photon indices to be fit independently caused more unphysical results: a negative Γ for 0804+2345 and a much steeper Γ for 1136+5657. Hence, we froze Γ at 1.8 for these sources.

Using the APEC model, we calculated the thermal X-ray luminosity (L_{\text{APEC}}) for all sources. We also fit these sources with the abundance of the thermal component frozen to 0.3 since though solar abundances would be expected in spiral galaxies, lower abundances are observed in practice when X-ray binaries are not resolved out, “diluting” the observed abundances (e.g., Ptak et al. 1999). We find the fit parameters to be consistent with those where the abundance is frozen to solar and find the thermal luminosity to be consistent between both cases, with at most a factor of 2 difference. In a future paper, we will examine the relationship between thermal X-ray emission and star formation rate (SFR).

We detected the Fe Kα emission line in nine cases. For five cases with the highest signal-to-noise ratio (S/N; 0800+2636,
Parameters for Thermal + Power-law Fits

| Target      | \( N_H \) (10\(^22\) cm\(^{-2}\)) | \( kT \) (keV) | Abundance | \( \Gamma_1 \) | \( \Gamma_2 \) | \( N_H \) (10\(^22\) cm\(^{-2}\)) | \( \chi^2 \) (dof) |
|-------------|----------------------------------|---------------|------------|-------------|-------------|----------------------------------|-------------------|
| 0325−0608\(^a\) | 0.04 | 0.27±0.05 | 0.04 | 1 | 0.77±0.05 | 159.7 ± (203) |
| 0800+2636 | 0.06±0.06 | 0.04 | 0.17 | 1 | 1.22±0.08 | 489.2 ± (445) |
| 0804+2345 | 0.53±0.15 | 0.12 | 1 | 5.16±0.97 | 197.9±0.03 | 1.8 | 23.9 ± (40) |
| 0824+2959\(^b\) | 0.03 | 0.18±0.04 | 0.05 | 1 | 2.49±0.18 | 22.1±2.3 | 1 = \( \Gamma_1 \) | 214.9 ± (163) |
| 0959+1259 | 0.80±0.07 | 0.07 | 1 | 1.90±0.07 | 51.1 ± (60) |
| 1018+3722 | 0.13±0.06 | 0.20 | 1 | 3.41±2.35 | 204.4 ± (265) |
| 1111+0228 | 0.06±0.06 | 0.02 | 0.11 | 1 | 1.72±0.06 | 54.3 ± (37) |
| 1136+5657 | 0.03±0.08 | 0.02 | 0.19 | 1 | 3.06±0.30 | 36.6 ± (48) |
| 1147+5226 | 0.52±0.14 | 0.10 | 1 | 1.64±0.68 | 11.8 ± (13) |
| 1157+5249 | 0.05±0.07 | 0.03 | 0.20±0.05 | 1 | 2.69±0.51 | 75.8 ± (63) |
| 1218+4706\(^b\) | 0.02 | 0.24 | 0.22 | 1 | 1.96±0.26 | 176.7 ± (122) |
| 1238+0927 | 0.03±0.06 | 0.02 | 0.22 | 1 | 2.37±0.46 | 56.0 ± (62) |
| 1323+4318 | 0.02±0.01 | - | - | 1 | 2.55±0.74 | 75.8 ± (63) |
| 1347+3634\(^b\) | 0.01 | 0.26±0.04 | 0.13 | 1 | 2.41±0.08 | 75.8 ± (63) |

Notes. \(^a\) Best-fit absorption is same as Galactic absorption. \(^b\) \( \Gamma \) frozen to 1.8 to constrain spectral fit.

Table 6

| Target      | \( F_{calc} \) | Probability |
|-------------|---------------|-------------|
| 0325−0608 | 8.83 | >0.9973 |
| 1018+3722 | 8.53 | >0.9973 |
| 1123+4703 | 7.59 | >0.9973 |
| 1147+5226 | 8.63 | >0.9973 |

0824+2959, 0959+1259, 1238+0927, and 1323+4318), we were able to measure the energy and, for four of these, the width of the \( \kappa \) line while the other four detected sources were fit with a Gaussian component frozen at the expected Fe K\( \alpha \) line energy (i.e., 6.4/(1 + \( z \)) keV) and a \( \sigma \) of 0.01 keV.\(^7\) To assess the significance of the Fe K\( \alpha \) detection, we simulated 1000 spectra for each of the 9 sources based on the best-fit high energy (i.e., 4–8 keV) power-law model. These simulated spectra were then fit with a power-law and Gaussian component to assess the probability that the Fe K\( \alpha \) feature is detected due to random noise (we performed rigorous error analysis on a subset of these simulated spectra and found no statistically significant change in the Fe K\( \alpha \) detection when new global minimizations were found). The simulation results indicate that the chance of detecting the Fe K\( \alpha \) line at or above the observed value due to random variations is less than 1\% for 0800+2636, 0824+2959, 0959+1259, 1147+5226, 1157+5249, 1238+0927, and 1323+4318; less than 6\% for 0325−0608, and less than 14\% for 1218+4706. Data-to-model ratio plots for the five cases with the highest S/N are shown in Figure 1, where the spectra were fit without the line component; the presence of residuals at the Fe K\( \alpha \) energy indicate that this line is present. For the eight undetected targets, we were only able to obtain \( 3 \sigma \) upper limits on the flux. The measurements for all 17 sources are listed in Table 7, where the Fe K\( \alpha \) luminosities and EWs are the observed values.

The five targets for which we were able to measure the energy of the Fe K\( \alpha \) line were also fit with a diskline model (Fabian et al. 1989), as this model applies to Fe K\( \alpha \) emission resulting from reflection of photons off the accretion disk. The results are listed in Table 8. The inclination angle was constrained for three targets (0800+2636, 0824+2959, and 1238+0927), indicating that these lines are likely Doppler broadened. The EWs derived from the diskline model are listed in Table 7. However, this model does not provide an improved fit over the use of a Gaussian component to model the Fe K\( \alpha \) line.

The spectra with the best-fit models are shown in Figures 2–4. The observed APEC and hard X-ray luminosities derived from the fits above are listed in Table 9.\(^8\) The APEC luminosity in some cases may reflect the luminosity due to scattered soft X-ray flux rather than thermal emission from star formation processes. Both the APEC and hard X-ray luminosities have not been corrected for absorption.

3. ANCILLARY DATA

3.1. SDSS

The methodology we used to derive the properties of the AGNs and their host galaxies are described in detail in K03, Heckman et al. (2004), and Kauffmann & Heckman (2009). It is important to note that the SDSS spectra are obtained through fibers with angular diameters of 3″. This corresponds to typical projected dimensions of \( \sim 2 \) to 3 kpc for our targets. This is

\(^7\) For the five cases with fitted Fe K\( \alpha \) line energy, the fitted energy is consistent with the rest-frame Fe K\( \alpha \) energy, 6.4 keV.

\(^8\) The hard X-ray luminosities for 0325−0608, 0804+2345, 1018+3722, 1123+4703, 1136+5657, 1147+5226, and 1157+5249 are based on the power-law component of the APEC + power-law fits as the addition of the APEC component improved the fit statistically and/or resulted in more physically reasonable fits for \( \Gamma \) for these targets; the hard X-ray luminosities for the remaining targets are derived from the single/double power-law fits. We note, however, that the differences between the luminosity derived using the APEC + power-law model vs. just the power-law model are minor.
Figure 1. Data-to-model ratio plots of sources where the Fe Kα line was detected at high significance for the five targets with the highest signal-to-noise ratio. In these plots, the spectra were fitted with the best-fit model (double absorbed power law for 0800+2636, 0824+2959, 1238+0927, and 1323+4318; and single absorbed power law for 0959+1259) without adding the Gaussian component. The residuals at the Fe Kα energy indicate that this line is present. (a) 0800+2636, (b) 0824+2959, (c) 0959+1259, (d) 1238+0927, and (e) 1323+4318.

(A color version of this figure is available in the online journal.)

large enough to encompass the AGN NLR (e.g., Schmitt & Kinney 1996; Schmitt et al. 2003). However, since the galaxies in our sample have typical optical diameters of 15–20 kpc (e.g., Kauffmann et al. 2003b), the fiber only covers the inner region of the host galaxy (bulge and inner disk).

For the AGN, we first compute an apparent [O iii]λ5007 luminosity using the observed emission-line flux. We then compute an extinction-corrected [O iii] luminosity using the measured flux ratio of the narrow Hα and Hβ emission lines and assuming an intrinsic ratio of 3.1 and the standard R = 3.16 extinction curve for galactic dust (Osterbrock & Ferland 2006). The median [O iii] extinction correction for our sample is 1.0 mag (with a range from 0.5 to 2.3 mag).

To estimate a bolometric correction, we used the ratio of the mid-IR continuum luminosity from the Spitzer IRS data (see below) to the extinction-corrected [O iii] luminosities from SDSS for the present sample and then used the models of IR emission from obscuring tori in Type 2 AGN in Nenkova et al. (2008) to estimate the ratio of mid-IR and bolometric luminosity. The implied bolometric corrections to the extinction-corrected [O iii] luminosity was 3500. Typical measured values for the Balmer decrement in Type 2 Seyferts imply extinction corrections of ~0.8–2.0 mag (e.g., Kewley et al. 2006), so we would expect the typical bolometric correction to the extinction-corrected [O iii] luminosity for such AGNs to be in the range ~ 550–1700. This range is consistent with what we infer for our sample based on the mid-IR data. We adopt a bolometric correction of 700 for our sample.

We use the observed correlation between black hole mass $M_{BH}$ and bulge velocity dispersion $\sigma_*$ (Tremaine et al. 2002) to derive an estimated black hole mass for each galaxy. We then use the ratio of the extinction-corrected [O iii]λ5007 emission-line luminosity and the black hole mass as a proxy for the Eddington ratio ($L_{AGN}/L_{Edd}$). For reference, a ratio of $L_{[O\text{ iii}]}/M_{BH}$ ~50 corresponds roughly to $L_{AGN}/L_{Edd}$ = 1 (Heckman et al. 2004; Kauffmann & Heckman 2009).

For ordinary star-forming galaxies, SFRs can be derived for the region sampled by the spectroscopic fiber by using the extinction-corrected luminosity of the Hα emission line, together with the additional information about nebular conditions provided by the [O iii]5007, [N ii]6584, and [S ii]6717,6731 lines (Brinchmann et al. 2004). However, in our objects these lines will be strongly contaminated by the contribution of the
AGN. Since we can not directly calculate SFRs using these nebular emission lines, we instead use the amplitude of the 4000 Å break ($D_0(4000)$), and the strong inverse correlation between $D_0(4000)$ and specific star formation rate (SFR/$M_\ast$) found for galaxies without AGN (Brinchmann et al. 2004). Brinchmann et al. show that typical uncertainties in log(SFR/$M_\ast$) estimated this way are about ± 0.5 dex (1σ) for any individual object. We have verified these estimates using the positive correlation between the strength of the high-order stellar Balmer absorption lines and SFR/$M_\ast$ (Chen et al. 2009).

In one object (1218+4706), the small value for both $D_0(4000)$ and the equivalent widths of the Balmer absorption lines imply that the spectrum is significantly contaminated by scattered continuum from the hidden Type 1 AGN. We are thus not able to estimate a SFR for this galaxy from the SDSS spectrum.

The parameters derived from the SDSS spectra are listed in Table 10.

### 3.2. Spitzer Space Telescope

The data used in this paper are taken from the analysis reported in S. LaMassa et al. (2010, in preparation). In brief, the IRS on the Spitzer Space Telescope was used to obtain low-resolution ($64 < R < 128$) spectra with the Short-Low (3′′ × 57′′ aperture) and Long–Low modules (10′′.7 × 16′′ aperture), and high-resolution ($R \sim 650$) spectra with the Short–High (4′′.7 × 11′.3 aperture) and Long–High modules (11′.1 × 22′.3 aperture). Standard observing and data reduction procedures were followed (see S. LaMassa et al. 2010, in preparation for details).

For the purposes of this paper, we will utilize two diagnostics of the luminosity of the AGN. The first is the luminosity of the [Oiv] 25.89 μm emission line. Since the production of Oiv requires photons with energies above 54.9 eV (above the He H edge at 54.4 eV), it is weak in purely star-forming galaxies. Thus, it is a good tracer of the hard AGN-ionizing continuum (Meléndez et al. 2008). Since it is produced in the NLR, it should suffer minimal obscuration in our AGN. We use [Oiv] as opposed to the higher ionization [Ne v] 14.32, 24.32 μm lines in the mid-infrared as the [Oiv] line is stronger (has larger S/N).

The second diagnostic is the luminosity of the mid-infrared continuum. This is produced by the warm dust in the obscuring torus. As described in S. LaMassa et al. (2010, in preparation), we have defined two windows in the mid-infrared spectrum that are devoid of significant emission or absorption features: one is centered at 13.5 μm and the other at 30 μm. The mid-infrared continuum luminosity we use in this paper is the sum of the

### Table 7

| Target          | Energy* (keV) | $\sigma$ (keV) | EW (keV) | Flux $(10^{-14}$ ergs cm$^{-2}$ s$^{-1}$) | log $L_\text{Fe K} \alpha$ (ergs s$^{-1}$) |
|-----------------|---------------|---------------|---------|-----------------------------------|--------------------------------|
monochromatic luminosities ($\nu L_{\nu}$) at the midpoints of these two bands. In principle, dust emission associated with a starburst can also contribute to the mid-IR continuum. To assess this, we have used the correlations between the mid-IR continuum luminosity and the luminosities of the 6.2, 7.7, 11.3, and 17.3 $\mu$m polycyclic aromatic hydrocarbon (PAH) features seen in starbursts (Smith et al. 2007). Using the PAH luminosities in our Type 2 AGN, we then find that the estimated starburst contribution to the mid-IR continuum is typically only about 10%, with a range from a few percent to a few tens of percent. We will discuss this in detail in a future paper in this series.

The parameters derived from the Spitzer data are listed in Table 10.

4. RESULTS

4.1. The Relative Strength of the Hard X-ray Continuum: Comparison with Previous Samples

As discussed in the Introduction, it is well known that the hard X-ray emission is very weak in many obscured AGNs. This can be quantified by comparing the ratio of the hard X-ray luminosity to that of proxies for the bolometric luminosity of the AGN. In this section, we will consider four such proxies: (1) the observed luminosity of the $\lambda$5007 emission line ($L_{\lambda 5007}^{\text{obs}}$) as used in, e.g., Vignali et al. 2006; Ptak et al. 2006); (2) the luminosity of the $\lambda$5007 line, corrected for dust
extinction ($L_{\text{[OIII], corr}}$), listed in Table 9; (3) the luminosity of the [O IV] 25.89 μm line ($L_{\text{[OIV]}}$); and (4) the luminosity of the mid-infrared (13.5 plus 30 μm) continuum ($L_{\text{MIR}}$). In all cases, the hard X-ray luminosity is measured in the 2–10 keV band ($L_{2-10\text{keV}}$) based on the fits discussed in Section 2 above.

We begin with the left panel of Figure 5 with a plot of the distribution of the ratio of $L_{2-10\text{keV}}/L_{\text{[OIII], obs}}$ for our sample. There is a huge range in the luminosity ratio (roughly 4 orders of magnitude). In order to assess the effect of X-ray absorption, we compare this distribution to that for a sample of “[O III]-bright” Type 1 (dashed blue line) AGN taken from Heckman et al. (2005). This comparison shows that the distribution of hard X-ray luminosities for our sample of Type 2 AGN is significantly displaced below the peak of the narrow distribution of the Type 1 AGN. For completeness, we also show the distribution of $L_{2-10\text{keV}}/L_{\text{[OIII], obs}}$ for the sample of Type 2 AGN (dot-dashed red line) from Heckman et al. (2005). These objects were drawn from many different heterogeneous samples of AGNs rather than representing a complete and homogeneously selected sample like ours. Nevertheless, the distributions in the two samples of Type 2 AGNs roughly agree and result in a Kolmogorov–Smirnov (KS) P-value of 0.07, i.e., the distributions differ.

Figure 3. Best-fit spectra for the next six of our sources. The models are as follows: 1018+3722: single absorbed power law + thermal component, 1111+0228: double absorbed power law, 1123+4703: single absorbed power law + thermal component, 1136+5657: double absorbed power law, 1147+5226: double absorbed power law + thermal component + Gaussian component to accommodate Fe Kα line, 1157+5249: double absorbed power law + Gaussian component to accommodate Fe Kα line. The color coding is the same as Figure 1.
Figure 4. Best-fit spectra for the remainder of our sources. The models are as follows: 1218+4706: double absorbed power law, 1238+0927: double absorbed power law + Gaussian component to accommodate Fe Kα line, 1323+4318: double absorbed power law + Gaussian component to accommodate Fe Kα line, 1346+6423: single absorbed power law, 1437+3634: single absorbed power law. The color coding is the same as Figures 1 and 2, with the exception of 1218+4706 where the black and red lines indicate the MOS1 and MOS2 spectra, respectively.

at a significance of only \(\sim 1.5\sigma\) (note that the KS test does not incorporate errors in the data points of the samples being compared). We also compare our results to X-ray observations of higher redshift (0.3 < \(z\) < 0.8) Type II AGNs selected based on [O iii] luminous quasars from SDSS (Zakamska et al. 2003). Ptak et al. (2006) and Vignali et al. (2006) find that a high fraction of their sources likely suffer from significant absorption: six out of eight (Ptak et al. 2006, based on spectral fits for five sources and the \(L_{2-10\text{ keV}}/L_{[\text{O iii}]\text{, obs}}\) ratio for one source) and 10 out of 16 (Vignali et al. 2006, based on spectral fits for two sources and the \(L_{2-10\text{ keV}}/L_{[\text{O iii}]\text{, obs}}\) ratio for eight sources).

The [O iii] λ5007 line will be affected by dust obscuration associated with the NLR and the interstellar medium (ISM) of its host galaxy. Thus, a better indicator of the intrinsic AGN luminosity is provided by the extinction-corrected [O iii] λ5007 luminosity (e.g., Lamastra et al. 2009). In the right panel of Figure 5, we show the distribution of \(L_{2-10\text{ keV}}/L_{[\text{O iii}]\text{, corr}}\) for our sample. For comparison, we show the distribution for Type 1 AGN taken from Mulchaey et al. (1994), corrected for extinction using their published Balmer decrement. These sources are represented by the dashed blue line in the right panel of Figure 5 and blue left arrow. Again, we find that the Type 2 AGNs in our complete sample span a very large range in the
relative strength of the hard X-rays and are significantly weaker hard X-ray emitters than the Type 1 AGNs. All but one of our targets are more heavily obscured while the larger dispersion in the relative strength of the hard X-ray emission in Type 2 AGNs. In both plots, all the Type 2 AGNs lie below the mean values for Type 1 AGNs: log \((L_{2-10 keV}/L_{[OIII]})\) ~ 2.1 with a dispersion of 0.3 dex (Meléndez et al. 2008) and log \((L_{2-10 keV}/L_{[MgII]})\) ~ −0.70 with a dispersion of 0.25 dex (Marconi et al. 2004; Elvis et al. 1994). The majority of our results lie about an order of magnitude or more below this value, and 11 of the 17 lie about an order of magnitude or more below this value, the nominal Compton-thick boundary \((L_{2-10 keV}/L_{[OIII]})\sim 1\), e.g., Bassani et al. 1999, where Compton-thick sources, classified as such by \(N_H\) and/or Fe Kα EW measurements, mostly fall below this boundary). Our results agree with those targets as suffering from heavy obscuration: 0053−0846, 0804+2345, 1018+3722, 1111+0228, 1123+4703, 1136+5656, 1147+5226, 1157+5249, 1218+4705, 1346+6423, and 1437+3634.

4.2. Clues from the Fe Kα Line

One immediate question is whether the wide range in the relative strength of the hard X-rays seen above is mostly due to obscuration, or whether it could indicate that the hard X-ray emission is intrinsically weak in Type 2 AGNs (in violation of the standard unified model). Several such cases of “unabsorbed” Type 2 AGNs have been proposed (e.g., Panessa & Bassani 2002; Brightman & Nandra 2008). One way to discriminate between these possibilities is to use the Fe Kα emission line to look for evidence of a heavily obscured AGN (e.g., Bassani et al. 1999; Levenson et al. 2006). In such cases, the equivalent width of the Kα line can be very large (∼ a keV) because the X-ray continuum at 6.4 keV traverses a significantly larger gas column than the Kα line emission, and is therefore much more highly obscured (e.g., Kroll & Kallman 1987; Levenson et al. 2006; Murphy 2008).

As shown in Bassani et al. (1999), this picture is supported by an inverse correlation observed between the equivalent width of the Kα line (EW) and the ratio of hard X-ray and [OⅢ] λ5007 emission-line luminosities. We therefore in-

| Target               | SFR (M_☉/yr) | \(L_{[OIII]}\)_{obs} (log L_☉) | \(L_{[OIII]}\)_{corr} (log L_☉) | \(L_{[OIV]}\) (log L_☉) | \(L_{[MgII]}\) (log L_☉) | \(M_{BH}\) (log M_☉) | SFR/M_☉ (log yr⁻¹) | \(L_{[OIII]}/M_{BH}\) (log L_☉/M_☉) |
|---------------------|--------------|--------------------------------|--------------------------------|--------------------------|--------------------------|----------------------|-------------------|----------------------|
| 0053−0846           | 1.04         | 7.14                           | 7.86                           | 7.71                     | 10.26                    | 7.11                 | −10.65            | 0.76                 |
| 0325−0608           | 12.0         | 7.74                           | 8.40                           | 7.69                     | 10.67                    | 7.80                 | −10.06            | 0.60                 |
| 0804+2368           | 0.74         | 7.29                           | 7.92                           | 7.64                     | 10.31                    | 7.74                 | −10.98            | 0.18                 |
| 0804+2345           | 0.52         | 7.43                           | 7.62                           | 7.65                     | 9.29                     | 7.25                 | −10.83            | 0.37                 |
| 0824+2959           | 0.64         | 7.53                           | 7.95                           | 7.03                     | 10.56                    | 6.99                 | −10.06            | 0.96                 |
| 0959+1259           | 0.85         | 7.78                           | 8.04                           | 7.44                     | 9.78                     | 6.78                 | −9.86             | 1.26                 |
| 1018+3722           | 1.33         | 7.79                           | 8.05                           | 7.56                     | 10.26                    | 7.14                 | −9.88             | 0.91                 |
| 1111+0228           | 0.47         | 7.49                           | 7.71                           | 7.27                     | 9.32                     | 7.33                 | −10.76            | 0.38                 |
| 1123+4703           | 0.57         | 7.24                           | 7.57                           | 6.86                     | 9.13                     | 7.29                 | −10.96            | 0.28                 |
| 1136+5657           | 5.11         | 7.89                           | 8.70                           | 8.35                     | 11.20                    | 7.99                 | −10.27            | 0.71                 |
| 1147+5226           | 2.88         | 7.80                           | 8.43                           | 7.60                     | 10.69                    | 7.85                 | −10.12            | 0.57                 |
| 1157+5249           | 0.60         | 7.58                           | 7.83                           | 7.57                     | 10.26                    | 7.17                 | −10.76            | 0.67                 |
| 1218+4706           | ...          | 8.46                           | 8.86                           | 8.30                     | 10.77                    | 8.17                 | ...               | 0.69                 |
| 1238+0927           | 6.30         | 8.39                           | 8.74                           | 8.37                     | 11.01                    | 8.40                 | −10.35            | 0.34                 |
| 1323+4318           | 2.17         | 7.27                           | 8.03                           | 7.82                     | 10.28                    | 7.65                 | −10.54            | 0.38                 |
| 1346+6423           | 0.36         | 7.16                           | 7.60                           | 6.80                     | 9.55                     | 6.81                 | −10.27            | 0.79                 |
| 1437+3634           | 0.05         | 6.85                           | 7.13                           | 6.90                     | 9.05                     | 7.44                 | −12.06            | −0.31                |
investigate the relationships between the Fe Kα EW and the luminosity ratios described above. For this analysis, we co-added the MOS spectra for the eight Compton-thick candidates \((L_{2-10\,\text{keV}}/L_{[\text{O\,iii\,corr}]}) \leq 1\) that had unconstrained Fe Kα EW or upper limits on the Fe Kα line flux \((0.053 - 0.0846, 0.0804+2.345, 1.018+3.722, 1.111+0.228, 1.123+4.703, 1.136+5.657, 1.346+6.423, \text{and } 1.437+3.634)\); these targets are flagged in Table 7. After stacking these spectra with the ftools routine addspec,\(^9\) we find a co-added total EW value of \(\sim 3.8^{+1.8}_{-1.5}\) keV and a co-added \(L_{2-10\,\text{keV}}\) value of \(\sim 6 \times 10^{40}\) erg s\(^{-1}\), compared with an EW value of \(1.96^{+0.90}_{-0.70}\) and \(L_{2-10\,\text{keV}}\) value of \(\sim 1 \times 10^{41}\) erg s\(^{-1}\) from simultaneously fitting the co-added MOS spectra for each of these sources. We performed a linear regression fit on both \(L_{2-10\,\text{keV}}/L_{[\text{O\,iii\,corr}]}\) and \(L_{2-10\,\text{keV}}/L_{[\text{O\,iv\,corr}]}\) versus Fe Kα EW using these co-added data for the eight Compton-thick cases and Fe Kα EW detections. The data and resulting fits are shown in Figure 7. We find a slope of \(-0.69\) with a dispersion \(\sigma = 0.23\) dex for \(L_{2-10\,\text{keV}}/L_{[\text{O\,iii\,corr}]}\) (compared to a slope of \(-0.37\) with \(\sigma = 0.05\) dex from the Bassani et al. 1999 sample\(^{10}\)) and a slope of \(-0.49\) and \(\sigma = 0.16\) dex for \(L_{2-10\,\text{keV}}/L_{[\text{O\,iv\,corr}]}\). Both correlations are significant at greater than the 99.8% confidence level.

These results, a statistically significant anti-correlation between \(L_{2-10\,\text{keV}}/L_{[\text{O\,iii\,corr}]}\) and Fe Kα EW, imply that the weak hard X-ray emission in our sample is due to obscuration, rather than intrinsically weak X-ray emission.

Ptak et al. (2003) suggested that the luminosity of the Fe Kα line itself could be used as an estimator of the AGN bolometric luminosity in obscured AGNs; they found a correlation between extinction-corrected \([\text{O\,iii]}\) luminosity and Fe Kα luminosity for both Seyfert 1 and 2 galaxies (slope of 1 with a scatter of \(\pm 0.5\) dex). As shown in Figure 8, we do see significant correlation between \(L_{[\text{O\,iii\,corr}]}\) and \(L_{\text{Fe Kα}}\). Using survival analysis to calculate the correlation coefficient between these two parameters (ASURV Rev 1.2; Isobe & Feigelson 1990; LaValley et al. 1992) for bivariate data (Isobe et al. 1986), we find a slope

\[ \sigma = 0.05 \text{ dex from the Bassani et al. 1999 sample}\(^{10}\) \]

\[ \text{and a slope of } -0.49 \text{ and } \sigma = 0.16 \text{ dex for } L_{2-10\,\text{keV}}/L_{[\text{O\,iv\,corr}]} \]

\[ \text{Both correlations are significant at greater than the 99.8% confidence level.} \]

\[ \text{These results, a statistically significant anti-correlation between } \]

\[ L_{2-10\,\text{keV}}/L_{[\text{O\,iii\,corr}]} \text{ and Fe Kα EW, imply that the weak hard X-ray emission in our sample is due to obscuration, rather than intrinsically weak X-ray emission.} \]

\[ \text{Ptak et al. (2003) suggested that the luminosity of the Fe Kα line itself could be used as an estimator of the AGN bolometric luminosity in obscured AGNs; they found a correlation between extinction-corrected } [\text{O\,iii}] \text{ luminosity and Fe Kα luminosity for both Seyfert 1 and 2 galaxies (slope of 1 with a scatter of } \pm 0.5 \text{ dex). As shown in Figure 8, we do see significant correlation between } L_{[\text{O\,iii\,corr}]} \text{ and } L_{\text{Fe Kα}}. \]

\[ \text{Using survival analysis to calculate the correlation coefficient between these two parameters (ASURV Rev 1.2; Isobe & Feigelson 1990; LaValley et al. 1992) for bivariate data (Isobe et al. 1986), we find a slope} \]

\[ \sigma = 0.05 \text{ dex from the Bassani et al. 1999 sample}\(^{10}\) \]
Figure 7. Left: $L_{2-10\text{ keV}}/L_{\text{[O iii]}}$ vs. Fe Kα EW with best-fit correlation overplotted. Right: $L_{2-10\text{ keV}}/L_{\text{[O iv]}}$ vs. Fe Kα EW with best-fit correlation overplotted. In both plots, the asterisk represents the co-added data for the Compton-thick candidates. Both relations are significant at greater than the 99.8% confidence level. The inverse correlations are consistent expectations for a heavily obscured hard X-ray source.

Figure 8. Left: extinction-corrected $L_{\text{[O iii]}}$ vs. Fe Kα luminosity with best-fit correlation from survival analysis overplotted. Right: $L_{\text{MIR}}$ vs. Fe Kα luminosity with best-fit correlation from survival analysis overplotted. The $L_{\text{[O iii]}}$–Fe Kα correlation is significant at about 94% confidence level, and the $L_{\text{MIR}}$–Fe Kα correlation is significant at about 99% confidence level. The inverse correlations are consistent with those expected in the cases of heavily obscured AGN.

of 0.7 ± 0.3 with a scatter of $\sigma = 0.5$ dex and a correlation significant at the $\sim$ 94% confidence level. When comparing $L_{\text{MIR}}$ with $L_{\text{Fe Kα}}$, we find a similar correlation: a slope of 0.7 ± 0.2, $\sigma$ of 0.4 dex, and a $\sim$ 99% correlation probability. However, the correlation between $L_{\text{[O iv]}}$ and $L_{\text{Fe Kα}}$ is only significant at the $\sim$ 85% confidence level.

4.3. Estimation of the Absorbing Column Density

The above results imply that the hard X-ray emission typically suffers significant attenuation. For a simple geometry of a foreground slab of absorbing gas, we would expect that the absorbing column densities we derive from our spectral fits would be consistent with the attenuation inferred from the relative strength of the X-ray continuum (Figures 5 and 6). This is clearly not always the case, as we show in Figure 9 which plots the fitted column density $N_{\text{H fitted}}$ versus log ($L_{2-10\text{ keV}}/L_{\text{[O iii]corr}}$). No correlation is present, and there are several noteworthy cases of apparently Compton-thick AGNs (on the basis of a low $L_{2-10\text{ keV}}/L_{\text{[O iii]corr}}$ ratio) with small values of $N_{\text{H fitted}}$. A similar result can be seen in Figure 10 where we plot the EW of the Fe Kα line versus $N_{\text{H fitted}}$. Krolik & Kallman (1987) predicted the observable Fe Kα equivalent width (EW) as a function of column density for the cases where the AGN is oriented face-on and where the torus completely blocks the central engine. Using the parameters from Ptak et al. (1996; $\Gamma = 1.8$, $N_{\text{H}} \leq 10^{24}$ cm$^{-2}$, and face-on orientation), we plot this relationship in Figure 10. The EW values are systematically higher than those predicted by Krolik & Kallman, and there are several cases with low apparent column densities
we plot the individual EW upper limits rather than the co-added value for the $N$ with the fitted $\alpha$ systematically higher than this relation, implying that the Fe K$_{\alpha}$ photons are not produced in regions consistent with transmission along the line of sight with the fitted $N_0$ values. Additional absorption, from matter out of the line of sight, may be required to accommodate the Fe K$_{\alpha}$ EW values. Unlike Figure 7, we plot the individual EW upper limits rather than the co-added value for the Compton-thick candidates without Fe K$_{\alpha}$ detections.

Yet strong K$_{\alpha}$ lines. This implies that the Fe K$_{\alpha}$ emission is produced in regions that are not consistent with transmission along the line of sight. Taken together, Figures 9 and 10 imply that the simple spectral models we have used do not adequately recover the true absorbing column densities in many cases as the transmitted component below 10 keV is obscured and only the reflected and/or scattered light is observed.

We have therefore taken a more complex (but more physically realistic) model for the absorption, based on using the observed relative strength of hard X-rays as a constraint: we compared the observed $L_{2–10\text{keV}}$ value with an expected X-ray luminosity in the absence of absorption and attributed the diminution between these two values to obscuration. Specifically, we have drawn 1000 random values of these two values to obscuration. Specifically, we have drawn the absence of absorption and attributed the diminution between $L_{2–10\text{keV}}$ for each source. We then recovered the true absorbing column densities in many cases as the transmitted component below 10 keV is obscured and only the reflected and/or scattered light is observed.

To account for Compton scattering, we ran the simulation using the $\text{plcabs}$ model in XSpec (Yaqoob 1997), with the number of scatters ($n_{\text{scatt}}$) set equal to 1 for $0 < N_{H,\text{sim}} < 10^{24}$ cm$^{-2}$, $n_{\text{scatt}} = 5$ for $10^{23}$ cm$^{-2} < N_{H,\text{sim}} < 5 \times 10^{24}$ cm$^{-2}$, and $n_{\text{scatt}} = 12$ for $N_{H,\text{sim}} \geq 5 \times 10^{24}$. The results for this simulation are listed in Table 13. Compared to the most conservative simulation above (i.e., covering fraction of 0.99 and $\Gamma = 1.8$), the

![Figure 10. Fitted column density $N_{H,\text{std}}$ vs. Fe K$_{\alpha}$ EW. The dashed line represents the relationship from Krolik & Kallman (1987) for Fe K$_{\alpha}$ EW as a function of $N_0$ for an AGN oriented face-on. Our Fe K$_{\alpha}$ EW values are systematically higher than this relation, implying that the Fe K$_{\alpha}$ photons are not produced in regions consistent with transmission along the line of sight.](image-url)
\(N_{\text{H, sim}}\) values from the \textit{plcabs} model do not change significantly for the least obscured sources and are reduced by a factor of about 2–3 for the more obscured sources. We fit our sources with the \textit{plcabs} model to compare the fitted \(N_{\text{H}}\) values from this model with the simulated values. Excluding 1346+6423 which had an unconstrained \textit{plcabs} fit due to low S/N, we find that six of our 16 sources have a fitted \(N_{\text{H}}\) an order of magnitude or lower than the simulated values, consistent with the results from comparing the partial covering model with the fitted values from the single or double absorbed power-law fits.\(^{11}\) Though the simulations using this model do not require Compton-thick absorption, our main result from the previous simulations still holds: the true column density, as assumed by X-ray attenuation, is underpredicted by an order of magnitude or more for several sources. Also, the \textit{plcabs} model assumes a spherical geometry, rather than the putative torus thought to obscure the central engine. When using a partial covering model, which moves to a more toroidal geometry as the covering fraction decreases, the simulated column density increases and in some cases, becomes Compton-thick.

In Figure 11, we plot the simulated values of the column density from the partial covering model with \(\Gamma = 1.8\) and covering fraction of 99\% versus those derived from the simple spectral fits. While the values agree reasonably well for many cases, the simulated column densities exceed the fitted values by more than one order of magnitude in six cases. We note that for five of the sources (1136+5657, 1157+5249, 1218+4706, 1238+0927, and 1323+4318), the fitted column density exceeds that of the simulated. However, this discrepancy is by a factor of about 3 or lower in all cases whereas the fitted column density can underpredict the simulated by as much as 4 orders of magnitude (e.g., 0053–0846). The large discrepancy between the fitted and simulated column density reaffirms the importance of using the \(L_{2–10\text{keV}}/L_{\text{[O III]}}\) ratio (or its equivalent) as a diagnostic of Compton-thickness rather than the fitted column density alone (as also found by Meléndez et al. 2008).

![Figure 11](image)

**Figure 11.** Fitted \(N_{\text{H}}\) vs. the simulated \(N_{\text{H}}\) from the partial covering model with \(\Gamma = 1.8\) and covering fraction set to 99\%. The dashed line indicates where the two quantities are equal. The simulated column densities are often significantly larger than the fitted values, and are more consistent with the large amounts of inferred X-ray absorption in these sources, as suggested by Figures 5–7.

\(^{11}\) We note, however, that there is a discrepancy between the targets that have underpredicted \(N_{\text{H}}\) values using the different models: with the partial covering model, 1437+3634 is underpredicted by an order of magnitude, while the fitted and simulated \(N_{\text{H}}\) values are more consistent using the \textit{plcabs} model, and the \textit{plcabs} model underpredicts the column density for 0053–0846, whereas these two values are consistent using the partial covering model. The remaining five targets (0325–0608, 0959+1259, 1018+3722, 1111+0228, and 1123+4703) have fitted \(N_{\text{H}}\) values underpredicted by both models, which could be due to the non-negligible dispersion in \(L_{2–10\text{keV}}/L_{\text{[O III]}}\); a high simulated \(L_{2–10\text{keV}}\) value can result in \(N_{\text{H, obs}} > N_{\text{H, sim}}\). The large discrepancy between the fitted and simulated column density reaffirms the importance of using the \(L_{2–10\text{keV}}/L_{\text{[O III]}}\) ratio (or its equivalent) as a diagnostic of Compton-thickness rather than the fitted column density alone (as also found by Meléndez et al. 2008).

### Table 12

Simulated \(N_{\text{H}}\) \((10^{22} \text{ cm}^{-2})\) for \(\Gamma = 0.99\)

| Target      | \(\Gamma = 1.6\) | \(\Gamma = 1.7\) | \(\Gamma = 1.8\) | \(\Gamma = 1.9\) | \(\Gamma = 2.0\) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0053–0846   | 65              | 65              | 64              | 64              | 63              |
| 0325–0608   | 2.5             | 2.5             | 2.5             | 2.6             | 2.6             |
| 0800+2636   | 1.1             | 1.1             | 1.2             | 1.2             | 1.2             |
| 0804+2345   | 202             | 204             | 205             | 207             | 208             |
| 0824+2959   | 31              | 30              | 30              | 30              | 29              |
| 0959+1259   | 11              | 11              | 11              | 11              | 11              |
| 1018+3722   | 67              | 67              | 67              | 67              | 66              |
| 1111+0228   | 83              | 83              | 84              | 84              | 84              |
| 1123+4318   | 132             | 133             | 133             | 134             | 134             |
| 1136+5657   | 25              | 24              | 23              | 22              | 20              |
| 1147+5262   | 40              | 40              | 39              | 38              | 37              |
| 1157+5249   | 76              | 76              | 76              | 78              | 78              |
| 1218+4706   | 111             | 111             | 111             | 112             | 111             |
| 1238+0927   | 20              | 19              | 19              | 18              | 18              |
| 1323+4318   | 27              | 26              | 26              | 26              | 26              |
| 1346+6423   | 224             | 227             | 228             | 230             | 233             |
| 1437+3634   | 106             | 108             | 108             | 111             | 112             |

### Table 13

\(N_{\text{H}}\) \((10^{22} \text{ cm}^{-2})\) Values Using \textit{plcabs}

| Target      | \(N_{\text{H}}\) Fitted | \(N_{\text{H}}\) Simulated |
|-------------|--------------------------|---------------------------|
| 0053–0846   | 0.05                     | 49                        |
| 0325–0608   | 0.04                     | 2.7                       |
| 0800+2636   | 1.1                      | 1.2                       |
| 0804+2345   | 68                       | 87                        |
| 0824+2959   | 25                       | 27                        |
| 0959+1259   | 0.89                     | 11                        |
| 1018+3722   | 0.23                     | 46                        |
| 1111+0228   | 5.7                      | 57                        |
| 1123+4318   | 2.2                      | 70                        |
| 1136+5657   | 63                       | 22                        |
| 1147+5262   | 32                       | 37                        |
| 1157+5249   | 138                      | 51                        |
| 1218+4706   | 120                      | 72                        |
| 1238+0927   | 41                       | 20                        |
| 1323+4318   | 50                       | 23                        |
| 1346+6423\(a\) | ...                      | 93                        |
| 1437+3634   | 14                       | 60                        |

\(^{a}\) Due to low S/N, \textit{plcabs} could not adequately fit the spectrum.
Figure 12. Compton-thick diagnostics plotted against proxies of intrinsic AGN luminosity. No correlations are present between the amount of implied X-ray absorption and the AGN intrinsic luminosity.

Figure 13. Left: $L_{2-10\text{keV}}/L_{\text{[O III]corr}}$ vs. $L_{\text{[O III]corr}}/M_{\text{BH}}$, a proxy for the Eddington ratio. There is no correlation between the amount of implied X-ray absorption and the AGN luminosity relative to the Eddington limit. Right: $L_{2-10\text{keV}}/L_{\text{[O III]corr}}$ vs. $M_{\text{BH}}$. No correlation is seen.

Finally, in Figure 13 (right) we plot $L_{2-10\text{keV}}/L_{\text{[O III]corr}}$ versus the black hole mass. Again, no correlation is present.

Some of the best-known Compton-thick AGNs are found in nuclei that are also undergoing intense bursts of star formation (e.g., Levenson et al. 2004, 2005). It would be plausible that there is some physical connection between the high gas column densities necessary for such starbursts and high column densities in the X-ray obscuring material. To investigate this possibility...
in our sample, we show in the left panel of Figure 14 a plot of $L_{2-10\text{keV}}/L_{[\text{OIII]}\text{,corr}}$ versus the SFR within the SDSS spectroscopic fiber (typical projected size of a few kpc in our sample). In the right panel of Figure 14, we plot $L_{2-10\text{keV}}/L_{[\text{OIII]}\text{,corr}}$ versus the SFR per unit stellar mass (SFR/$M_*$). Neither of these figures shows any correlation between the amount of X-ray obscuration and the amount (relative or absolute) of circumnuclear star formation. The lack of correlation between obscuration and host galaxy properties indicates that the obscuration affecting X-ray emission is likely due to the torus rather than the large-scale ISM of the host galaxy. As our sample was selected on the basis of bright [OIII] emission, this could be in part a selection effect against AGNs with large amounts of extinction produced by the host galaxy (which would affect the [OIII] flux).

6. OBSCURATION AT HIGHER ENERGIES

We have shown that the amount of X-ray obscuration in the 2–10 keV band is highly significant for optically selected Type 2 AGNs. Over half of the sources have attenuations exceeding an order of magnitude, implying absorbing column densities in excess of $10^{24}$ cm$^{-2}$. Do X-ray surveys at higher energies recover these highly obscured AGNs? To investigate this, we compare our results to those for samples of AGN detected in the Swift BAT survey in the 15–195 keV band: the Landi et al. (2007) sample, based on AGN identification of previously unidentified Swift sources (4 Sy2s); the Winter et al. (2008) sample, based on XMM-Newton observations of AGNs detected by Swift with high significance (10 Sy2s with $z = 0.01–0.09$, though only four had published $f_{[\text{OIII}]}$, $f_{\text{H}\alpha}$, and $f_{\text{H}\beta}$ values, see below); and the radio quiet Type 1.8, 1.9, and 2 Seyfert galaxies in the Meléndez et al. (2008) sample, based on the first three months of the Swift BAT high Galactic latitude survey (14 targets with $z = 0.001–0.03$, complete to $(1–3) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$).

First, we use the extinction-corrected luminosity of the [OIII] line as our proxy for the intrinsic luminosity. To do so, we use the published $L_{2-10\text{keV}}$ values from Winter et al. (2008) and the published $L_{2-10\text{keV}}$ and [OIII] flux values ($f_{[\text{OIII}]}$) from the Landi et al. (2007) and Meléndez et al. (2008) samples (restricted to just the radio-quiet Type 1.8, 1.9, and 2 Seyfert galaxies). We also use the Landi et al. H$\alpha$ ($f_{\text{H}\alpha}$) and H$\beta$ ($f_{\text{H}\beta}$) flux values to correct for extinction. For the Winter et al. (2008) and Meléndez et al. (2008) samples, we used $f_{[\text{OIII}]}$, $f_{\text{H}\alpha}$, and $f_{\text{H}\beta}$ values from the literature where available and include only those sources that have published flux values for all three parameters. In some cases, the published $f_{\text{H}\beta}$ values were upper limits, providing a lower limit on $L_{[\text{OIII]}\text{,corr}}$ and an upper limit on the $L_{2-10\text{keV}}/L_{[\text{OIII]}\text{,corr}}$ ratio.

A plot of $L_{2-10\text{keV}}/L_{[\text{OIII]}\text{,corr}}$ versus $L_{[\text{OIII]}\text{,corr}}$ for AGN selected in the softer 3–20 keV band (from the Sazonov & Revnivtsev 2004 sample), as found by Heckman et al. (2005): the distribution is relatively narrow and there is no significant difference between the Type 1 and Type 2 AGNs. This is because such samples exclude the Compton-thick Type 2 AGNs.

Next, we use the [OIV] 25.89 $\mu$m line luminosity as a tracer of the AGN luminosity. In the right panel of Figure 15, we compare the distribution of $L_{2-10\text{keV}}/L_{[\text{OIV}]}$ for AGN selected in the BAT-selected sample of radio-quiet Type 2 AGN in Meléndez et al. (2008). The distributions are similar, with 8/15 of the BAT-selected objects and 10/17 of our optically selected objects having ratios of $L_{2-10\text{keV}}/L_{[\text{OIV}]}$ more than an order of magnitude lower than the mean value for radio-quiet Type 1 AGN in Meléndez et al. ($L_{2-10\text{keV}}/L_{[\text{OIV}]} \sim 2.1 \pm 0.3$ dex).

Taken together, the results in Figure 15 imply that selection in the 14–195 keV band is recovering a significant fraction of the sources that are heavily obscured in the 2–10 keV band. This agrees at least qualitatively with the conclusions of Winter et al. (2009): of 22 AGNs in the sample detected in the 14–195 keV band, 5 are Compton-thick candidates and an additional 4 were hidden/buried, or very Compton-thick, AGNs that would be missed in sample selection at lower energies. However, this contrasts with the results of Treister et al. (2009) who found a low number of Compton-thick AGNs using high-energy X-ray observations.
energy \((E > 10\) keV) surveys: 5 of the 130 AGNs detected with \textit{INTEGRAL} and 8 of the 130 AGNs detected with \textit{Swift} were Compton-thick.

7. CONCLUSIONS

In this paper, we have undertaken a study of the hard X-ray properties (2–10 keV) of a nearly complete sample of the 17 brightest Type 2 (obscured) AGNs selected from a sample of 480,000 galaxies in the Fourth Data Release of the SDSS. These are representative of optically bright Type 2 AGNs in the low-redshift universe \((z < 0.1)\).

We have used the value of the luminosity of the \([\text{O}\,\text{iii}]\), 5007 emission line for the AGN’s NLR—corrected for dust extinction using the observed \(H\alpha/H\beta\)—as a proxy for the intrinsic luminosity of the AGN (e.g., Bassani et al. 1999; Kauffmann & Heckman 2009). We have also used the \textit{Spitzer Space Telescope} to measure the luminosity of the mid-infrared \([\text{O}\,\text{iv}]\) 25.89 \(\mu\)m line from the NLR (e.g., Meléndez et al. 2008) and the luminosity of the mid-infrared continuum from the obscuring torus (e.g., Nenkova et al. 2008) as additional indicators of the AGN intrinsic luminosity. The \([\text{O}\,\text{iii}]\) and \([\text{O}\,\text{iv}]\) lines are useful because they originate well outside the torus and should therefore be unaffected by its obscuration. In contrast, the hard X-rays originate inside the torus and can be strongly attenuated in Type 2 AGN for a Compton-thick torus with \(N_H > 10^{24}\text{ cm}^{-2}\). We have therefore used the ratio of the observed hard X-ray luminosity to the luminosities of the \([\text{O}\,\text{iii}]\) and \([\text{O}\,\text{iv}]\) emission lines and to the mid-infrared continuum luminosity as an indicator of the amount of obscuration of the hard X-ray source. We have also used the equivalent width of the Fe K\(\alpha\) emission line at 6.4 keV as an additional diagnostic of a heavily obscured hard X-ray source.

We found that the ratio of the hard X-ray luminosity to that of the \([\text{O}\,\text{iii}]\) and \([\text{O}\,\text{iv}]\) lines and of the mid-infrared continuum in our sample spans an enormous range (nearly 4 orders of magnitude). In a majority \((11/17)\) of the cases, the luminosity ratios are more than an order of magnitude lower than the mean value for Type 1 (unobscured) AGNs, and these objects are likely to be Compton-thick. While similar results have been reported before (e.g., Bassani et al. 1999; Heckman et al. 2005), our results are the first that have been determined for a complete sample of Type 2 AGNs selected in a homogeneous way on the basis of their optical emission-line flux.

In principle, the relative weakness of the hard X-ray emission could be an intrinsic property of the AGNs, rather than a consequence of obscuration (e.g., Brightman & Nandra 2008). We have used the properties of the Fe K\(\alpha\) line at 6.4 keV to distinguish between these possibilities. We found that there is a good inverse correlation in our sample between the equivalent width of the K\(\alpha\) line and relative luminosity of the 2–10 keV continuum. We have argued that this is consistent with an obscured X-ray source in which the emergent spectrum has been significantly reprocessed. In such a case, the K\(\alpha\) photons traverse significantly lower column densities of absorbing gas than do the underlying \((\sim 6–7\) keV) continuum photons, and large K\(\alpha\) equivalent widths result (e.g., Krolik & Kallman 1987; Levenson et al. 2006). Our results are consistent with those reported by Bassani et al. (1999), which were based on a heterogeneous sample of Type 2 AGN.

We have shown that in some cases the high amount of inferred obscuration is inconsistent with the estimate of the column of absorbing gas derived from fits of simple spectral models to the data (e.g., single or double power-law spectra transmitted through a homogeneous foreground screen). We have constructed more physically realistic models with partial covering of the X-ray source plus a homogeneous foreground screen. We run simulations of these models constrained by the ratio of the 2–10 keV and \([\text{O}\,\text{iii}]\), 5007 fluxes and found that in some cases significantly higher absorbing column densities were implied than those derived from the simple spectral fits. We have concluded that the latter columns are not reliable for heavily obscured (Compton-thick) AGNs. Similar results have been obtained by Meléndez et al. (2008).

We found that the populations of Compton-thick and Compton-thin Type 2 AGNs in our sample do not differ systematically in terms of the luminosity of the AGN, the mass of the black hole, or the luminosity with respect to the Eddington limit. Likewise, we found no differences in the SFR or the SFR per unit stellar mass (measured in the central few-kpc-scale region covered by the SDSS spectra).

We have also compared our results for an optically selected sample of Type 2 AGN to those for samples selected in the \textit{Swift} BAT 14–195 keV energy band (Landi et al. 2007; Winter et al. 2009). We found that the results of our sample are consistent with those reported by Brightman et al. (2008).
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