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Published in:
Astrophysical Journal

Link to article, DOI:
10.1088/0004-637X/785/1/17

Publication date:
2014

Publisher's Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Lansbury, G. B., Alexander, D. M., Del Moro, A., Gandhi, P., Assef, R. J., Stern, D., ... Zhang, W. W. (2014). NuSTAR observations of heavily obscured quasars at z ~ 0.5. Astrophysical Journal, 785(1), [17]. DOI: 10.1088/0004-637X/785/1/17
**NuSTAR OBSERVATIONS OF HEAVILY OBSCURED QUASARS AT z ∼ 0.5**

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Received 2013 November 12; accepted 2014 February 10; published 2014 March 21

**ABSTRACT**

We present NuSTAR hard X-ray observations of three Type 2 quasars at z ∼ 0.4–0.5, optically selected from the Sloan Digital Sky Survey. Although the quasars show evidence for being heavily obscured, Compton-thick systems on the basis of the 2–10 keV to [O III] luminosity ratio and multiband X-ray diagnostics, their X-ray absorbing column densities (N_H) are poorly known. In this analysis, (1) we study X-ray emission at >10 keV, where X-rays from the central black hole are relatively unabsorbed, in order to better constrain N_H. (2) We further characterize the physical properties of the sources through broad-band near-UV to mid-IR energy distribution analyses. One of the quasars is detected with NuSTAR at >8 keV with a no-source probability of <0.1%, and its X-ray band ratio suggests near Compton-thick absorption with N_H ≥ 5 × 10²³ cm⁻². The other two quasars are undetected, and have low X-ray to mid-IR luminosity ratios in both the low-energy (2–10 keV) and high-energy (10–40 keV) X-ray regimes that are consistent with extreme, Compton-thick absorption (N_H ≥ 10²⁴ cm⁻²). We find that for quasars at z ∼ 0.5, NuSTAR provides a significant improvement compared to lower energy (<10 keV) Chandra and XMM-Newton observations alone, as higher column densities can now be directly constrained.

**Key words:** galaxies: active – X-rays: galaxies

**Online-only material:** color figures

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**1. INTRODUCTION**

Quasars are the sites of the most rapid black hole growth in the universe (Salpeter 1964; Soltan 1982). They represent the luminous end of the active galactic nucleus (AGN) population, often outshining their host galaxies. The first unobscured (“Type 1”) quasars were discovered over 50 yr ago (Schmidt 1963; Hazard et al. 1963), and more than 100,000 have now been spectroscopically identified (e.g., Véron-Cetty & Véron 2010; Päris et al. 2012). For obscured (“Type 2”) quasars, the situation is not as advanced. Similar to the early Type 1 quasars, Type 2 quasars were initially identified from radio selection (e.g., Minkowski 1960), and over the following decades several hundred powerful “radio galaxies” (as radio-selected Type 2 quasars are typically called) were identified (for reviews, see McCarthy 1993; Miley & De Breuck 2008). However, it has only been in the past decade that radio-quiet Type 2 quasars have been found in large numbers. Such sources are generally identified on the basis of either their relatively hard X-ray spectral slopes (e.g., Norman et al. 2002; Stern et al. 2002), optical spectral features (e.g., Steidel et al. 2002; Zakamska et al. 2003), or mid-infrared (mid-IR) colors (e.g., Lacy et al. 2004; Stern et al. 2005). Importantly, mid-IR color selection of Type 2 quasars using the all-sky Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010) survey identifies several million Type 2 quasars, roughly down to the bolometric luminosity of the primary Sloan Digital Sky Survey (SDSS; York et al. 2000) Type 1 quasar spectroscopic survey (Stern et al. 2012; Assef et al. 2013; Donoso et al. 2013).

The exact nature of Type 2 quasars is still under debate. A simple extension of the orientation-driven unified model of AGNs (Antonucci 1993; Urry & Padovani 1995) to high

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20 We define Type 2 quasars as AGNs with L_2–10keV ≥ 10⁴⁴ erg s⁻¹, X-ray absorbing column densities N_H > 10²² cm⁻², and optical spectra that show narrow line emission without broad (Hα or Hβ) components. This L_2–10keV threshold is consistent with (1) the classical optical quasar definition, M_B ≤ −23, when the α_ox relation of Steffen et al. (2006) and the composite quasar spectrum of Vanden Berk et al. (2001) are assumed; and (2) the L_X,α value derived by Hasinger et al. (2005) for unobscured AGNs.
having 22 Compton-thick absorption is that with 21 X-rays emitted from the immediate black hole environment are absorbed by the measurement of strong Fe Kα emission, with EW ≥ 1 keV, which results from the Fe Kα line being viewed in reflection against a suppressed continuum (e.g., Ghisellini et al. 1994; Levenson et al. 2002); or (2) measurement of high column densities through spectroscopic analysis at high energies above the photoelectric absorption cutoff (i.e., above observed-frame 8 keV for z ∼ 0.5 and N_H ≳ 10^{24} cm^{-2}), where X-ray emission is relatively unabsorbed.

The recent launch of the Nuclear Spectroscopic Telescope Array (NuSTAR; Harrison et al. 2013) will see a breakthrough in our understanding of heavily obscured AGNs and the CXB population in general. NuSTAR is the first orbiting observatory with the ability to focus high-energy (≥10 keV) X-rays using grazing incidence optics. It provides a second order of magnitude improvement in sensitivity and over an order of magnitude improvement in angular resolution over previous hard X-ray observatories. The high-energy range at which NuSTAR operates (3–79 keV) means that the intrinsic, unabsorbed emission of AGNs is observed for all but the most heavily obscured, Compton-thick objects. At z ≲ 1, it is now possible to directly constrain column densities an order of magnitude higher than those achievable with Chandra and XMM-Newton alone (e.g., Luo et al. 2013).

In this paper, we present exploratory NuSTAR observations of three optically selected Type 2 quasars at z ≈ 0.4–0.5. All three have been identified as Compton-thick candidates in previous studies (Vignali et al. 2006, 2010; Jia et al. 2013). We use X-ray data from NuSTAR, Chandra, and XMM-Newton, and near-UV to mid-IR data from other observatories to determine the physical properties of the quasars. In particular, we use a combination of direct and indirect methods to constrain the absorbing column densities. The paper is organized as follows. Our sample selection is detailed in Section 2. We describe the observations, data reduction, and data analysis in Section 3. The main results regarding X-ray absorption constraints are presented in Section 4 and we summarize our main conclusions in Section 5. The cosmology adopted throughout this work is (Ω_M, Ω_ζ, h) = (0.27, 0.73, 0.71).

2. SAMPLE SELECTION

First, we selected objects at z ≈ 0.4–0.5 from the Chandra and XMM-Newton studies of SDSS-selected Type 2 quasars by Vignali et al. (2006, 2010) and Jia et al. (2013). Although the objects have narrow Hβ line emission, the Hα line lies outside the SDSS spectral range at these redshifts. Therefore, we cannot rule out that these quasars are luminous versions of the Type 1.9 Seyferts that show evidence for a broad Hα component but no broad Hβ component (Osterbrock 1981). Second, we selected quasars with low observed X-ray to [O III] luminosity ratios, L_{2–10 keV}/L_[O III] < 2.5. This threshold corresponds to a two orders of magnitude suppression of the observed X-ray luminosity, assuming the Mulchaey et al. (1994) relation between [O III] and intrinsic 2–10 keV flux (taking into account the variance of the relation), which is consistent with Compton-thick absorption. This is a conservative selection, since the Mulchaey et al. (1994) relation was calibrated for Type 2 Seyferts, and Type 2 quasars typically have larger X-ray to [O III] luminosity ratios (Netzer et al. 2006). Third, we made sub-selections of three quasars which show evidence for extreme obscuration on the basis of different diagnostics.

1. SDSS J001111.97+005626.3 (z = 0.409, L_{2–10 keV} = 3.1 × 10^{42} erg s^{-1}, L_[O III] = 1.8 × 10^{42} erg s^{-1}; Reyes et al. 2008; Jia et al. 2013) has a flat X-ray spectral slope...
at observed-frame 0.3–10 keV ($\Gamma = 0.6^{+1.17}_{-1.15}$; Jia et al. 2013), which suggests that the X-ray emission is rising steeply toward high energies (>10 keV). Unlike the other two quasars, there is no mid-IR spectroscopy available.

2. SDSS J005621.72+003235.8 (z = 0.484, $L_{2-10 \text{keV}} = 8.9 \times 10^{44}$ erg s$^{-1}$, $L_{[\text{OIII}]} = 6.8 \times 10^{42}$ erg s$^{-1}$; Reyes et al. 2008; Vignali et al. 2010) has the deepest 9.7 μm silicate (Si) absorption of the sample of Type 2 quasars observed with Spitzer-IRS in Zakamska et al. (2008). Such strong Si features are typically found in Compton-thick AGNs (e.g., Shi et al. 2006; Georganopoulos et al. 2011a; Gouliing et al. 2012).

3. SDSS J115718.35+600345.6 (z = 0.491, $L_{2-10 \text{keV}} < 1.5 \times 10^{42}$ erg s$^{-1}$, $L_{[\text{OIII}]} = 1.6 \times 10^{43}$ erg s$^{-1}$; Reyes et al. 2008; Vignali et al. 2010) is the most luminous quasar in the Vignali et al. (2010) sample at mid-IR wavelengths, but is undetected by Chandra (Vignali et al. 2006). The extremely low X-ray to mid-IR luminosity ratio is likely due to Compton-thick absorption (Vignali et al. 2010). The Spitzer-IRS spectrum for this source shows it to be quasar-dominated at mid-IR wavelengths, but that it also hosts ultraluminous star formation [$\log(L_{\text{SF}}/L_\odot) = 12.3$, Zakamska et al. 2008]. There is no evidence for significant Si-absorption; however, ≈50% of the best-studied, Compton-thick AGNs do not have significant Si-absorption (e.g., Goulding et al. 2012).

3. NuSTAR AND MULTIWAVELENGTH DATA

In our analysis of the three Type 2 quasars, we used NuSTAR observations in conjunction with lower energy X-ray observations from Chandra and XMM-Newton, and near-UV to mid-IR data primarily from large-area public surveys. Hereafter we refer to the quasars using abbreviated SDSS object names.

3.1. NuSTAR Observations

NuSTAR consists of two co-aligned X-ray telescopes (focal length = 10.14 m) which use grazing incidence optics to focus hard X-rays (3–79 keV) onto two focal plane modules (FPMs A and B; Harrison et al. 2013). Each FPM provides a 12' × 12' field of view at 10 keV, and a pixel size of 2.46. The NuSTAR point-spread function (PSF) is characterized by a FWHM of 18″, and a half-power diameter of 58″. The astrometric accuracy for bright X-ray sources is ±8″ (90% confidence; Harrison et al. 2013).

The Type 2 quasars, SDSS J0011+0056, SDSS J0056+0032, and SDSS J1157+6003, were observed by NuSTAR with nominal exposure times of 19.6 ks, 23.5 ks, and 23.3 ks, respectively. Details of the observations, including net exposure times, are provided in Table 1. We processed the data using the NuSTAR Data Analysis Software (NuSTARDAS) v. 1.3.0. Calibrated and cleaned event files were produced using the nupipeline script and the NuSTAR CALDB 20131007 release with the standard filter flags.

3.1.1. Photometry and Source Detection

To characterize the high-energy X-ray emission and determine whether sources are detected, we performed photometry in the observed-frame 3–24 keV, 3–8 keV, and 8–24 keV bands for both of the NuSTAR FPMs following Alexander et al. (2013). We avoided using photons above 24 keV, where the drop in effective area and the prominent background features (see Figures 2 and 10 of Harrison et al. 2013, respectively) hinder the analysis of faint X-ray sources such as Type 2 quasars. We split the NuSTAR event files into individual band images using dmcopy, part of the Chandra Interactive Analysis Observations software (CIAO, v4.4; Fruscione et al. 2006). We extracted the gross source counts (S) from a 45″ radius aperture centered on the SDSS position. For a source at the NuSTAR aim point, and for the energy range (3–24 keV) and spectral slopes ($\Gamma = 0.6–1.8$) used in this study, this aperture encloses ≈65% of the full PSF energy. We extracted the background counts (B) from an annulus with an inner radius 90″ from the source and an outer radius 150″ from the source, which allowed the local background to be sampled while minimizing contamination from the source. To obtain the background counts in the source extraction region ($B_{\text{src}}$), we multiplied B by the area scaling factor between the source and background regions ($A_S/A_B$). Net source counts were calculated as $S - B_{\text{src}}$, and corresponding 68.3% confidence level uncertainties were taken as $\sqrt{S + B(A_S/A_B)^2}$. For non-detections, we calculated 99.7% confidence level upper limits using the Bayesian method of Kraft et al. (1991). The NuSTAR photometry is given in Table 2.

To test whether the quasars are detected in the individual NuSTAR band images, we looked for significant source signals at their SDSS positions. We assumed binomial statistics and calculated false probabilities, or “no-source” probabilities (P), using the following equation:

$$P(x \geq S) = \sum_{x=S}^{T} \frac{T!}{x!(T-x)!} p^x (1-p)^{T-x},$$

where $T = S + B$ and $p = 1/(1 + B/B_{\text{src}})$. P is the probability that, assuming there is no source at the SDSS position, the measured gross counts in the source aperture (S) are purely due to a background fluctuation (Weisskopf et al. 2007).

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Table 1

| Object Name      | z       | Observation ID | UT Date   | Exposure (ks) |
|------------------|---------|---------------|-----------|--------------|
| SDSS J001111.97+005626.3 | 0.409 | 60010065002   | 2013 Jan 27 | 18.3 ks |
| SDSS J005621.72+003235.8 | 0.484 | 60010061002   | 2013 Jan 27 | 21.9 ks |
| SDSS J115718.35+600345.6 | 0.491 | 60010071002   | 2012 Oct 28 | 21.7 ks |

Notes. (1) Full SDSS object name. (2) Redshift. (3) and (4) NuSTAR observation ID and start date. (5) Net on-axis NuSTAR exposure time. This value applies to both FPM A and FPM B. (6) Lower energy X-ray observatory data used (Chandra or XMM-Newton). (7)–(9) Chandra or XMM-Newton observation ID, observation start date, and net on-axis exposure time, corrected for flaring and bad events.

http://cxc.harvard.edu/ciao/index.html
above 8 keV (observed-frame). At these energies, NuSTAR to higher energies, and likely have flat X-ray spectra with emission rising steeply.

Figure 1.

![Graph showing background counts vs. gross source counts for different energy bands.](image)

**Table 2**  
X-Ray Photometry

| Object Name | Net Counts (FPMA) | Net Counts (FPMB) | Flux (NuSTAR) | Flux (Other) |
|------------|------------------|------------------|--------------|-------------|
|            | 3–24 | 3–8 | 8–24 | 3–24 | 3–8 | 8–24 | 3–24 | 3–8 | 8–24 |
| 0011+0056  | 17.5±7.7 | <16.3 | 16.8±6.4 | <24.7 | <18.3 | <19.7 | 0.99 | <0.74 | 1.32 | 0.18 |
| 0056+0032  | <19.1 | 10.9 | 20.9 | 23.5 | 17.8 | 19.6 | <1.14 | <0.52 | <1.58 | <0.16 |
| 1157+6003  | <31.4 | 16.6 | 29.1 | 23.3 | 20.0 | 17.7 | <1.35 | <0.63 | <1.68 | <0.22 |

**Notes.**  
(1) Abbreviated SDSS object name. The “SDSS J” prefix and all R.A. and decl. digits after the first four have been truncated.  
(2) and (3) Net source counts in the observed-frame 3–24, 3–8, and 8–24 keV bands for FPMA and FPMB, respectively.  
(4) Aperture-corrected NuSTAR flux in units of 10⁻¹³ erg s⁻¹ cm⁻² (for a power-law model with Γ = 1.8), in the observed-frame 3–24, 3–8, and 8–24 keV bands. For SDSS J0011+0056, the fluxes are for FPMA only, while for SDSS J0056+0032 and SDSS J1157+6003, the fluxes are averaged over FPMA and FPMB.  
(5) Aperture-corrected observed-frame 3–8 keV flux in units of 10⁻¹³ erg s⁻¹ cm⁻² (for a power-law model with Γ = 1.8), as measured using lower-energy X-ray data. XMM-Newton data have been used for SDSS J0011+0056, and Chandra data have been used for SDSS J0056+0032 and SDSS J1157+6003.  
99% confidence level upper limits are given.

Given that the three Type 2 quasars are faint at 3–8 keV (see Table 2 for Chandra and XMM-Newton fluxes and upper limits), and likely have flat X-ray spectra with emission rising steeply to higher energies, NuSTAR is most likely to detect the sources above 8 keV (observed-frame). At these energies, Chandra and XMM-Newton have little to no sensitivity. In Figure 1, we show the S and B_{src} values measured with NuSTAR for the 8–24 keV band (filled symbols), and the no-source probabilities to which they correspond (dashed lines). For the purposes of this figure, Poisson statistics have been assumed; for our sources, B is large and the Poisson integral thus provides a good approximation of Equation (1) (Weisskopf et al. 2007). Taking binomial no-source probabilities greater than 1% to indicate non detections, neither SDSS J0056+0032 nor SDSS J1157+6003 are detected in either FPM. SDSS J0011+0056, on the other hand, is detected in FPM with a binomial no-source probability of 0.093%. The NuSTAR image corresponding to this detection is shown in Figure 2. The source is not detected in FPMB, which has higher background noise relative to FPMA for this observation; indeed, the net source counts for FPMA are consistent with the upper limit for FPMB (see Table 2). SDSS J0011+0056 is also weakly detected in the 3–24 keV band for FPMA, with a binomial no-source probability of 0.58%. Aside from this, none of the quasars are detected in the 3–8 keV and 3–24 keV bands.

The no-source probability is sensitive to the background region sampled. To partially address this we also measured the background from model background maps produced using NUSKYBD (D. R. Wik et al., in preparation), summing counts within the 45" radius source aperture. These measurements are shown as empty symbols in Figure 1. SDSS J0011+0056 is still detected in FPMA using this approach, with a no-source probability of 0.033% at 8–24 keV.

### 3.1.2. Flux Calculation

For each NuSTAR energy band we determined the conversion factor between net count rate and source flux using XSPEC v12.8.1j (Arnaud 1996), taking into account the response matrix file (RMF) and ancillary response file (ARF) for each FPM. We assumed a power-law model with Γ = 1.8, consistent with that found for AGNs at observed-frame 3–24 keV (Alexander et al. 2014). We corrected fluxes to the 100% encircled-energy fraction of the PSF. The NuSTAR fluxes are given in Table 2. For the NuSTAR-detected quasar, SDSS J0011+0056, we measure an observed-frame 8–24 keV flux of 1.32 × 10⁻¹³ erg s⁻¹ cm⁻². This value is consistent with extrapolations from the XMM-Newton 0.5–10 keV count rate given the photon index constraints of Jia et al. (2013), Γ = 0.6±1.1, and assuming a simple unabsorbed power-law model. Additionally, as we later show in Section 4.2, our X-ray flux measurement for SDSS J0011+0056 is consistent with that expected from its 6 μm luminosity, which is assumed to result from the reprocessing of AGN emission by obscuring dust.

### 3.2. Lower Energy X-Ray Data

For SDSS J0011+0056 we used the archival XMM-Newton EPIC observation, first published in Jia et al. (2013). We analyzed the Pipeline Processing System data products for

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24 We avoid overplotting the errors for individual S and B_{src} measurements, since these are not used in the calculation of no-source probabilities.

25 We note that in this case, using a 50" (as opposed to 45") source aperture results in a lower no-source probability of 0.049%.
this observation using the Science Analysis Software26 (SAS v.12.0.1). The MOS1 and MOS2 data were co-added with the SAS task epicspeccombine. The PN data were excluded, since SDSS J0011+0056 is close to a chip gap. The source counts were extracted from a 15′′ radius aperture and the background counts were extracted using an 80′′ radius source-free aperture, selected to sample the local background while avoiding chip gaps and nearby serendipitous sources. We used XSPEC to convert from count rate to flux, assuming a power-law model with $\Gamma = 1.8$ and using the XMM-Newton RMF and ARF. Throughout this work, we neglect the cross-calibration constants between MOS and NuSTAR as the current best estimates are $\sim 7 \pm 5\%$ (K. K. Madsen et al., in preparation), and a change on this scale does not affect our results.

For SDSS J0056+0032 and J1157+6003, we used the archival Chandra observations, first published in Vignali et al. (2006, 2010). We reprocessed the data using CHANDRA_REPRO27, a CIAO pipeline, to create event files. The source counts were extracted from a 3′′ radius aperture, and the background counts were extracted from an annulus with an inner radius 10′′ from the source and an outer radius 30′′ from the source. As SDSS J0056+0032 and J1157+6003 are non-detections at observed-frame 3–8 keV, we calculated 99.7% confidence level upper limits for the source counts using the Bayesian method of Kraft et al. (1991). To calculate fluxes, we converted from Chandra count rates with the HEASARC tool WebPIMMs28 ($v=6.6$) assuming a power-law model with $\Gamma = 1.8$, and corrected to the 100% encircled-energy fraction of the PSF.

As the Type 2 quasars are faint at X-ray wavelengths, we are unable to fit the spectra accurately. For instance, SDSS J0011+0056 is detected with XMM-Newton, but using the combined MOS1+MOS2 data we only extract 5.6 and 20.6 net source counts in the observed-frame 0.5–3 keV and 3–8 keV bands, respectively. We list the Chandra and XMM-Newton 3–8 keV fluxes and upper limits in Table 2.

### 3.3. Near-UV to Mid-IR Data and SED Decomposition

To investigate the multiwavelength properties of the three Type 2 quasars, in particular the mid-IR emission from the AGN, we collected photometric data at 0.3–30 μm (i.e., at near-UV through mid-IR wavelengths). We used imaging data from public large-area surveys, primarily the SDSS (York et al. 2000), the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), and the WISE all-sky survey (Wright et al. 2010). Additionally, for SDSS J0056+0032 and J1157+6003, we used Spitzer photometry from the Spitzer Enhanced Imaging Products Source List.29 The photometric data set, not corrected for Galactic extinction, is provided in Table 3. We note that since the observations are not contemporaneous, AGN variability may affect the spectral energy distribution (SED) analysis at longer wavelengths, where the AGN is bright with respect to the host galaxy.

We used the near-UV through mid-IR photometric data to produce broad-band SEDs for our sample. We modeled the SEDs using the Assef et al. (2010) 0.03–30 μm empirical low-resolution AGN and galaxy templates. Each SED was modeled as a best-fit combination of an elliptical, a spiral and an irregular galaxy component, plus an AGN. We refer the reader to Assef et al. (2008, 2010, 2013) for further details. In Figure 3, we present the SEDs and best-fitting model solutions. For SDSS J1157+6003, we also show the IRAS 60 μm flux measured by Zakamska et al. (2004, green data point in Figure 3), which lies beyond the wavelength range of the galaxy templates and was therefore excluded from the SED modeling. The data point is consistent with a simple extrapolation of the best-fitting model from shorter wavelengths. Zakamsa et al. (2004) also detect SDSS J0056+0032 at 60 μm, but at a low significance level (80% confidence). In Table 3, we provide the best-fitting parameters $\hat{a}$ (the fractional contribution from the AGN component to the 0.1–30 μm emission after correction for dust reddening; Assef et al. 2010) and $L_{6\mu m}$ (the luminosity of the AGN component at rest-frame 6 μm after correction for dust reddening; $\nu L_{\nu}$). The uncertainties on $\hat{a}$ and $L_{6\mu m}$ are standard deviations, derived from the Monte Carlo re-sampling of the data according to the photometric uncertainties. Both parameters are well constrained.30 Since our SED modeling uses a single AGN template, it does not account for the fact that AGNs show a range of heated dust emission relative to the bolometric emission of the accretion disk. For instance, assuming the

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26 http://xmm.esa.int/sas/
27 http://cxc.harvard.edu/ciao/ahelp/chandra_repro.html
28 http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html
29 http://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/Imaging/
30 Constraining $\hat{a}$ and $L_{6\mu m}$ is the primary purpose of our SED analysis. We do not read deeply into the host-galaxy properties of the best fitting solutions.
distribution of quasar covering factors found by Roseboom et al. (2013) would introduce an additional uncertainty to the 6 μm luminosities of ≈±0.5L_{6μm}. Our three Type 2 quasars have high ḻ values, which indicates that they are AGN-dominated at 0.1–30 μm. For SDSS J0056+0032 and SDSS J1157+6003, this is in agreement with the Spitzer-IRAS spectroscopy of Zakamska et al. (2008), which shows the sources to be AGN-dominated at mid-IR wavelengths (for SDSS J0011+0056 there is no mid-IR spectroscopic available).

4. RESULTS

The three Type 2 quasars in this work bear the signatures of heavily obscured, Compton-thick AGNs based on multi-wavelength diagnostics (see Section 2 of this work; Zakamska et al. 2008; Vignali et al. 2010; Jia et al. 2013). Here we present the results of our analysis, which is aimed at assessing the prevalence of extreme absorption in these systems.

X-rays provide a direct measure of AGN emission that has been subject to circumnuclear absorption. As such, the characterization of X-ray spectra is necessary to obtain reliable estimates of absorbing column densities (N_{HI}). For SDSS J0011+0056, we detect X-rays over the observed-frame 3–24 keV energy range, and for SDSS J0056+0032 and SDSS J1157+6003, we place upper limits on the 3–24 keV emission (see Table 2). As the quasars are at best weak detections at 3–24 keV, detailed modeling of their X-ray spectra is unfeasible. For SDSS J0011+0056, we characterize the observed-frame 3–24 keV X-ray spectrum using the ratio of hard (8–24 keV) to soft (3–8 keV) emission, which provides a direct absorption constraint (see Section 4.1). For the remaining two quasars, we are limited to indirect absorption constraints from the comparison of the observed X-ray emission with the intrinsic X-ray emission implied by infrared measurements (see Section 4.2).

4.1. Direct (X-Ray) Absorption Constraints

SDSS J0011+0056 is detected with NuSTAR in the 8–24 keV band, but not in the 3–8 keV band. We measure a 99.7% confidence level lower limit for the NuSTAR X-ray band ratio (i.e., the ratio of 8–24 keV counts to 3–8 keV counts), of >1.0. In Figure 4, we show the NuSTAR band ratio against redshift for SDSS J0011+0056 and the first 10 sources detected in the NuSTAR All Source Catalog.

Figure 3. Near-UV to mid-IR SEDs for the three Type 2 quasars. The best-fitting model solutions (black line) were achieved using the AGN (blue dashed line) and galaxy (elliptical: red dotted line; spiral: purple dotted line; irregular: orange dotted line) templates of Assef et al. (2010). The photometric data (black data points) and best-fitting parameters are given in Table 3. The IRAS 60 μm flux for SDSS J1157+6003 (green data point) was not used in the SED decomposition.

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

Table 3

Near-ultraviolet to Mid-infrared Source Properties

| Object Name | 0011+0056 | 0056+0032 | 1157+6003 |
|-------------|-----------|-----------|-----------|
| a (0.355 μm)^b | 23.51 ± 0.99 | 23.25 ± 0.71 | 20.53 ± 0.06 |
| g (0.468 μm)^b | 21.50 ± 0.05 | 21.60 ± 0.069 | 20.10 ± 0.01 |
| r (0.616 μm)^b | 20.26 ± 0.05 | 20.72 ± 0.05 | 19.61 ± 0.02 |
| i (0.748 μm)^b | 19.60 ± 0.04 | 19.82 ± 0.04 | 18.90 ± 0.01 |
| z (0.892 μm)^b | 19.25 ± 0.09 | 19.81 ± 0.12 | 19.02 ± 0.05 |
| y (1.03 μm)^b | 18.25 ± 0.04 | ... | ... |
| J (1.25 μm)^r | 17.70 ± 0.03 | 18.42 ± 0.07 | ... |
| H (1.63 μm)^r | 16.81 ± 0.04 | 17.31 ± 0.07 | ... |
| K (2.20 μm)^r | ... | 16.64 ± 0.05 | ... |
| WISE (3.4 μm)^d | 14.94 ± 0.04 | 15.53 ± 0.05 | 12.78 ± 0.02 |
| WISE (4.6 μm)^d | 14.45 ± 0.07 | 14.51 ± 0.08 | 11.24 ± 0.02 |
| WISE (12 μm)^d | 10.62 ± 0.09 | 9.77 ± 0.05 | 8.0 ± 0.02 |
| WISE (22 μm)^d | ... | 6.55 ± 0.07 | 5.37 ± 0.03 |
| Spitzer (3.6 μm)^f | ... | 0.173 ± 0.003 | 2.860 ± 0.009 |
| Spitzer (4.5 μm)^f | ... | 0.220 ± 0.003 | 4.511 ± 0.010 |
| Spitzer (5.8 μm)^f | ... | 0.591 ± 0.009 | 8.215 ± 0.017 |
| Spitzer (8.0 μm)^f | ... | 2.474 ± 0.016 | 13.165 ± 0.022 |
| Spitzer (24 μm)^f | ... | 18.088 ± 0.058 | 57.318 ± 0.062 |
| IRAS (60 μm)^g | ... | ... | 260.0 ± 46.0 |
| ḻ (L_{6μm}) | 0.590 ± 0.029 | 0.946 ± 0.003 | 0.977 ± 0.001 |
| L_{6μm} | 1.14 ± 0.15 | 15.19 ± 0.60 | 51.44 ± 1.12 |

Notes.

^a Abbreviated SDSS object name.
^b SDSS DR7 Fiber magnitudes in the AB system.
^c UKIDSS DR9 2.8 diameter aperture magnitudes in the Vega system.
^d WISE profile-fit magnitudes in the Vega system.
^e Spitzer 3.6 diameter aperture flux densities in units of mJy.
^f Spitzer PSF-fit flux densities in units of mJy.
^g IRAS flux density in units of mJy (Zakamska et al. 2004). This data point was not used in the SED modeling.
^h Best-fit parameters (corrected for dust reddening) from the SED decomposition described in Section 3.3: ḻ is the fractional contribution of the AGN to the 0.1–30 μm emission; L_{6μm} is the rest-frame 6 μm luminosity (νL_ν) of the AGN in units of 10^{+s} erg s^{-1}. The uncertainties are standard deviations, derived from the Monte Carlo re-sampling of the photometric data.

31 All N_{HI} values in this section are line-of-sight column densities unless otherwise stated. In the MYTorus model, N_{HI} is related to the equatorial column density (N_{HI,eq}) via Equation (1) in Murphy & Yaqoob (2009).
in the NuSTAR extragalactic survey (Alexander et al. 2013); the SDSS J0011+0056 band ratio is amongst the most extreme. We compare the band ratio with predictions from a simple absorbed power-law (\textsc{zwars-pow}) model and the MYTorus model (Murphy & Yaqoob 2009), both of which are implemented in XSPEC. MYTorus is a self-consistent physical model that is valid for the energy range 0.5–500 keV, and for column densities of \(N_H = 10^{22} - 10^{25} \text{ cm}^{-2}\). It is more suitable than the \textsc{zwars-pow} model for column densities of \(N_H \geq 5 \times 10^{23} \text{ cm}^{-2}\), where a careful treatment of scattering and reflection is needed (for instance, see Figure 5). In the MYTorus model, an obscuring torus reprocesses X-rays from a central source, and the resulting X-ray spectrum has both transmitted and scattered components. In the current implementation of MYTorus, the half-opening angle of the obscuring medium is fixed to 60° (i.e., a covering factor of 0.5), a value inferred from the obscured AGN fraction of Seyfert galaxies. We note that a larger half-opening angle could be more appropriate in this study of Type 2 quasars, since the obscured AGN fraction is observed to decrease with luminosity (e.g., Ueda et al. 2003; Lusso et al. 2013). We assume a specific MYTorus model with an intrinsic photon index of \(\Gamma = 1.8\) (typical value for AGNs at observed-frame 3–24 keV; Alexander et al. 2013) and an inclination angle of \(\theta_{\text{obs}} = 70°\), referred to as Model A hereafter. Varying \(\theta_{\text{obs}}\) between 65° and 90°, where 90° corresponds to an edge-on view through the equatorial plane of the torus, makes a negligible difference to the MYTorus band ratio tracks in Figure 4. We avoid using \(\theta_{\text{obs}}\) values close to 60°, below which the line-of-sight X-ray emission does not intercept the torus and the MYTorus model therefore describes an unobscured AGN. As shown in Figure 4, the NuSTAR band ratio lower limit for SDSS J0011+0056 corresponds to an absorbing column density of \(N_H \geq 2.5 \times 10^{23} \text{ cm}^{-2}\). This implies heavy, but not necessarily Compton-thick, absorption.

Since XMM-Newton is more sensitive than NuSTAR at <8 keV, we also measure an X-ray band ratio for SDSS J0011+0056 using the XMM-Newton 3–8 keV data and NuSTAR 8–24 keV data, which gives a NuSTAR/XMM-Newton band ratio of 1.2 ± 0.6 (68% confidence level). One limitation of the measurement is that we are unable to assess whether the X-ray emission of SDSS J0011+0056 has varied significantly in the ~6.5 yr between the XMM-Newton and NuSTAR observations; if the XMM-Newton count rate is relatively low, we overestimate the band ratio, and vice versa. In Figure 5, we compare the measured NuSTAR/XMM-Newton band ratio with predictions from the MYTorus and \textsc{zwars-pow} models as a function of column density. We fixed the model redshifts to that of SDSS J0011+0056 (\(z = 0.409\)), used a range of intrinsic photon indices corresponding to those observed for unobscured AGNs (1.7 < \(\Gamma\) < 2.3; e.g., Mateos et al. 2010; Scott et al. 2011), and used a range of inclination angles in the MYTorus model (65° < \(\theta_{\text{obs}}\) < 90°). The resulting tracks in Figure 5 suggest that SDSS J0011+0056 is absorbed by \(N_H \geq 5 \times 10^{23} \text{ cm}^{-2}\), which is consistent with the NuSTAR band ratio analysis (Figure 4). Assuming Model A (\(\Gamma = 1.8\) and \(\theta_{\text{obs}} = 70°\)), the observed NuSTAR/XMM-Newton band ratio for SDSS J0011+0056 implies a column density of \(N_H = (8.1^{+2.9}_{-3.2}) \times 10^{23} \text{ cm}^{-2}\) (i.e., heavy, but not clearly Compton-thick, absorption is required to produce the observed 3–24 keV X-ray spectrum). This result is consistent with column density estimates from indirect methods, as shown in Section 4.2. For comparison, the highest column densities directly constrained by Vignali et al. (2006, 2010) in their <10 keV analysis of SDSS-selected Type 2 quasars are \(N_H \approx 3 \times 10^{23} \text{ cm}^{-2}\).

The above \(N_H\) constraint for SDSS J0011+0056 must be treated with a degree of caution, since it depends on the assumed...
Figure 6. Rest-frame X-ray luminosity against rest-frame 6 μm luminosity for (a) 2–10 keV luminosities calculated using XMM-Newton or Chandra data and (b) 10–40 keV luminosities calculated using NuSTAR data. The X-ray luminosities are not corrected for absorption. SDSS J0011+0056, SDSS J0056+0032, and SDSS J1157+6003 are shown as white, gray, and black circles, respectively. We compare with sources detected as part of the NuSTAR extragalactic survey (open squares; Alexander et al. 2013). We also compare with an intrinsic relation for 2–10 keV, calibrated using local AGNs (dotted line, with a shaded region indicating the scatter; Lutz et al. 2004). This relation has been extrapolated to the 10–40 keV band assuming (A color version of this figure is available in the online journal.)

X-ray spectral model. Here we assess the impact on our result of two spectral complexities, both of which are important in the case of Type 2 quasars. First, a soft “scattered” power law component is commonly observed for obscured AGNs which may be either nuclear emission scattered by hot gas (e.g., Turner et al. 1997), or “leakage” of nuclear emission due to partial covering (e.g., Vignali et al. 1998; Corral et al. 2011). Adding a scattered component which is 2% of the primary transmitted power law (a typical X-ray scattering fraction for Type 2 Seyferts; e.g., Turner et al. 1997) to Model A, we obtain a consistent result: $N_H > 4.9 \times 10^{23} \text{ cm}^{-2}$ (68.3% confidence level lower limit). Second, the absorbing medium may have a complex geometry (e.g., a clumpy torus) that requires the equatorial and line-of-sight column densities of the MYTorus model ($N_{\text{H,eq}}$ and $N_H$, respectively) to be treated independently. Decoupling these two parameters in Model A and setting $N_{\text{H,eq}}$ to the maximum possible value of $10^{25} \text{ cm}^{-2}$ yields a consistent result: $N_H = (7.7^{+2.3}_{-3.8}) \times 10^{23} \text{ cm}^{-2}$. Last, we emphasize that although MYTorus is a relatively complex model, the $N_H$ constraints do not differ significantly from those using a simple zwabs-power model in the Compton-thin regime (see Figure 5). We conclude that the inferred $N_H$ for SDSS J0011+0056 does not change significantly with the assumed spectral model.

4.2. Indirect Absorption Constraints

The X-ray emission in heavily obscured AGNs is subject to significant absorption along the line of sight. The mid-IR emission, on the other hand, has been reprocessed by the dust obscuring the AGN and is less sensitive to extinction. The mid-IR luminosity therefore provides an estimate of the intrinsic AGN power. As such, the presence of absorption in an AGN can be inferred from the observed X-ray to mid-IR luminosity ratio (e.g., Lutz et al. 2004; Alexander et al. 2008; LaMassa et al. 2009; Goulding et al. 2011; LaMassa et al. 2011). We note that the mid-IR emission is also significantly absorbed for $\approx 50\%$ of Compton-thick AGNs (e.g., Bauer et al. 2010; Goulding et al. 2012). Indeed, SDSS J0056+0032 has significant Si-absorption at 9.7 μm, in contrast to SDSS J1157+6003 (see Section 2). To account for this, we have corrected our mid-IR luminosities for dust reddening (see Section 3.3). In Figure 6, we compare the rest-frame X-ray luminosities ($L_X$) of our three Type 2 quasars with the rest-frame 6 μm luminosities ($L_{\text{6μm}}$), exploring both the low-energy (2–10 keV) and high-energy (10–40 keV) X-ray regimes. For SDSS J0011+0056, $L_{2,10\text{keV}}$ was obtained through photometry in the rest-frame 2–10 keV band using XMM-Newton data (see Section 3.2). For SDSS J0056+0032 and SDSS J1157+6003, $L_{2,10\text{keV}}$ was obtained through photometry in the observed-frame 0.5–8 keV band using Chandra data (see Section 3.2), and an extrapolation to the rest-frame 2–10 keV band assuming a power-law model with $\Gamma = 1.8$. The $L_{10,40\text{keV}}$ values were obtained through a photometric analysis in the rest-frame 10–40 keV band using NuSTAR data (see Section 3.1). The 6 μm luminosities are from SED fitting (Section 3.3) and relate specifically to the emission from the AGN.

In the rest-frame 2–10 keV band, the Type 2 quasars fall below the intrinsic X-ray–mid-IR luminosity relation found for AGNs in the local universe (Lutz et al. 2004; see Figure 6(a). For comparison, we also show the non-beamed sources detected in the NuSTAR extragalactic survey (Alexander et al. 2013), which lie within the scatter of the Lutz et al. (2004) relation. The 2–10 keV luminosity suppression of the three Type 2 quasars is expected given our selection and has previously been demonstrated for SDSS J0056+0032 and SDSS J1157+6003 (Vignali et al. 2006, 2010). Assuming the suppression of the X-ray emission is due to absorption, as opposed to intrinsic X-ray weakness, we estimate the column densities of these systems by comparing with the X-ray to mid-IR luminosity ratios for AGNs absorbed by $N_H = 10^{23} \text{ cm}^{-2}$ and $N_H = 5 \times 10^{24} \text{ cm}^{-2}$ (dash-dotted and dashed lines in Figure 6(a), respectively). On the basis of this analysis, the 2–10 keV luminosities of SDSS J0056+0032 and SDSS J1157+6003 are consistent with being absorbed by a factor of $\gtrsim 300$, and therefore lie well within the Compton-thick region with $N_H \gtrsim 5 \times 10^{24} \text{ cm}^{-2}$.
The X-ray emission from SDSS J0011+0056, on the other hand, is suppressed by a factor of ≈7, but is still consistent with being Compton-thick or near Compton-thick (N_H ≳ 10^{24} cm^{-2}). Since our 2–10 keV luminosities were calculated assuming a Γ = 1.8 power-law, which is probably not consistent with heavy absorption at z ∼ 0.5, we repeated the flux calculations in Section 3.2 assuming Γ = 0.6 (the spectral slope of SDSS J0011+0056 as measured by Jia et al. (2013); see Section 2). This results in L_{2–10keV} values which are higher by a factor of ≈1.9; not enough to significantly change the conclusions drawn from Figure 6(a).

In the rest-frame 10–40 keV band, the X-ray emission is only strongly suppressed for column densities of N_H ≥ 5 × 10^{24} cm^{-2}, and therefore NuSTAR observes the intrinsic X-ray emission for all but the most heavily obscured AGNs; see Figure 6(b). For comparison, Matsuta et al. (2012) studied Swift/BAT-detected AGNs and found that for 14–195 keV, only ≈60% of Compton-thick objects have significant X-ray suppression with respect to the intrinsic X-ray to mid-IR luminosity ratio. The results in Figure 6(b) suggest that the X-ray emission from SDSS J0011+0056 is not significantly suppressed at 10–40 keV, and is absorbed by N_H ≲ 10^{24} cm^{-2}. This is consistent with the X-ray band ratio analysis in Section 4.1. SDSS J0056+0032 is consistent with being Compton-thick, with N_H ≥ 10^{24} cm^{-2}. SDSS J1157+6003 is the strongest candidate for being Compton-thick based on this analysis. Its 10–40 keV luminosity is consistent with being absorbed by a factor of ≳10, despite the high X-ray energies being probed, which again suggests an extreme column density of N_H ≥ 5 × 10^{24} cm^{-2}. Assuming Γ = 0.6 rather than Γ = 1.8 for the NuSTAR count rate to flux conversion (Section 3.1.2) results in L_{10–40keV} values which are a higher by a factor of ≈1.4; again, not enough to significantly change the conclusions drawn from Figure 6(b). As an independent test, we repeated our indirect analyses using [O III] luminosity as a measure of intrinsic AGN power (i.e., using L_X/L_{[OIII]}). This yielded very similar results: NuSTAR observes the intrinsic X-ray emission of SDSS J0011+0056, while SDSS J0056+0032 and SDSS J1157+6003 are consistent with being heavily Compton-thick (N_H ≥ 5 × 10^{24} cm^{-2}). However, since our sample was originally selected on the basis of high [O III] luminosity (Zakamska et al. 2003; Reyes et al. 2008), we consider the L_X/L_{6μm} results to be more reliable. Nevertheless, the L_X/L_{6μm} ratio alone is not a robust indicator of Compton-thick absorption, even if the 6 μm emission accurately reflects the intrinsic power of the AGN. First, some quasars can be intrinsically X-ray weak (e.g., Gallagher et al. 2001; Wu et al. 2011; Luo et al. 2013; Teng et al. 2014). Second, inferred column densities depend on the assumed X-ray spectral model (e.g., Yaqoob & Murphy 2011; Georganopoulos et al. 2011b). For instance, adding an additional soft scattered component, with a scattering fraction of 2%, to the MYTorus model predicts a L_{2–10keV}/L_{6μm} ratio for N_H = 5 × 10^{24} cm^{-2} which is a factor of three higher than that shown in Figure 6(b). However, this is not enough to change our broad conclusions regarding the column densities of SDSS J0056+0032 and SDSS J1157+6003. Ultimately, deeper X-ray observations, with simultaneous coverage at low and high energies, are required to directly constrain N_H and provide more robust evidence for or against the presence of Compton-thick absorption in these Type 2 quasars.

5. SUMMARY AND FUTURE WORK

We have presented the first sensitive high-energy (>10 keV) analysis of optically selected Type 2 quasars. The sample consists of three objects that show evidence for Compton-thick absorption (N_H > 1.5 × 10^{24} cm^{-2}) on the basis of different diagnostics (see Section 2). Our results can be summarized as follows.

1. One of the Type 2 quasars, SDSS J0011+0056, is detected by NuSTAR with 16.8 ± 6.4 counts in the 8–24 keV band. The remaining two, SDSS J0056+0032 and SDSS J1157+6003, are not detected by NuSTAR; see Section 3.1.1.

2. For SDSS J0011+0056, we characterize the 3–24 keV spectrum using the X-ray band ratio and find evidence for near Compton-thick absorption with N_H ≥ 5 × 10^{23} cm^{-2}; see Section 4.1. This is consistent with the column densities inferred from the 2–10 keV to mid-IR ratio, the 10–40 keV to mid-IR ratio, and the X-ray to [O III] ratios; see Section 4.2.

3. For SDSS J0056+0032 and SDSS J1157+6003, we find evidence for a significant suppression of the rest-frame 10–40 keV luminosity with respect to the mid-IR luminosity. If due to absorption, this result implies that these Type 2 quasars are extreme, Compton-thick systems with N_H ≥ 10^{24} cm^{-2}; see Section 4.2.

The characterization of distant heavily obscured AGNs is clearly an extremely challenging pursuit. Nevertheless, as we have demonstrated, the sensitive high-energy observations of NuSTAR provide a significant improvement compared to Chandra or XMM-Newton observations alone; for quasars at z ∼ 0.5, high column densities of N_H ≥ 5 × 10^{23} cm^{-2} can now be directly constrained. Based on the results obtained in this exploratory study, we are now extending the analysis of optically selected Type 2 quasars to a larger sample which is currently being observed by NuSTAR. Furthermore, NuSTAR is undertaking deep surveys in the ECDFS (J. R. Mullaney et al., in preparation) and COSMOS (F. Civano et al., in preparation) fields, along with a large-area serendipitous survey (Alexander et al. 2013), that are likely to uncover a number of heavily obscured quasars. These upcoming studies will provide a leap forward in our understanding of the column density distribution of distant luminous AGNs.

We acknowledge financial support from the Science and Technology Facilities Council (STFC) grants ST/K001979/1 (G.B.L.), ST/I001573/1 (D.M.A. and A.D.M.) and ST/I003697/1 (P.G.), the Leverhulme Trust (D.M.A. and J.R.M.), Gemini–CONICYT grant 32120009 (R.J.A.), NSF AST award 1008067 (D.R.B.), the International Fulbright Science and Technology Award (M.B.), Basal–CATA PFB-06/2007 (F.E.B.), CONICYT-Chile grant FONDECYT 1101024 (F.E.B.), CONICYT-Chile grant Anillo ACT1101 (F.E.B.), Caltech NuSTAR subcontract 44A-1092750 (W.N.B. and B.L.), NASA ADP grant NNX10AC99G (W.N.B. and B.L.), NASA ADAP award NNX12AE38G (R.C.H.), National Science Foundation grant 1211096 (R.C.H.), and Swiss National Science Foundation grant PP00P2_138979/1 (M.K.). We thank the referee for the constructive comments, which helped improve our study. This work was supported under NASA contract No. NNG08FD60C, and made use of data from the NuSTAR mission, a project led by the California Institute of Technology, managed by the Jet Propulsion Laboratory, and funded by the National Aeronautics and Space Administration. We thank the NuSTAR Operations, Software and Calibration teams for support with the execution and analysis of these observations. This research has made use of the NuSTAR Data Analysis Software.
