NUSTAR SPECTROSCOPY OF MULTI-COMPONENT X-RAY REFLECTION FROM NGC 1068

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ABSTRACT

We report on observations of NGC 1068 with NuSTAR, which provide the best constraints to date on its > 10 keV spectral shape. The NuSTAR data are consistent with past instruments, with no strong continuum or line variability over the past two decades, consistent with its classification as a Compton-thick AGN. The combined NuSTAR, Chandra, XMM-Newton, and Swift BAT spectral dataset offers new insights into the complex secondary emission seen instead of the completely obscured transmitted nuclear continuum. The critical combination of the high signal-to-noise NuSTAR data and the decomposition of the nuclear and extranuclear emission with the chandra allow us to break several model degeneracies and greatly aid physical interpretation. When modeled as a monolithic (i.e., a single $N_H$) reflector, none of the common Compton-reflection models are able to match the neutral fluorescence lines and broad spectral shape of the Compton reflection without requiring unrealistic physical parameters (e.g., large Fe overabundances, inconsistent viewing angles, poor fits to the spatially resolved spectra). A multi-component reflector with three distinct column densities (e.g., with best-fit values of $N_H = 1.5 \times 10^{23}, 5 \times 10^{24}$, and $10^{25}$ cm$^{-2}$) provides a more reasonable fit to the spectral lines and Compton hump, with near-solar Fe abundances. In this model, the higher $N_H$ component provides much of the line emission, effectively decoupling two key features of Compton reflection. We also find that ≈30% of the neutral Fe Kα line flux arises from $>2''$ (~140 pc) and is clearly extended, implying that a significant fraction of the <10 keV reflected component arises from regions well outside of a parsec-scale torus. These results likely have ramifications for the interpretation of Compton-thick spectra from observations with poorer signal-to-noise and/or more distant objects.

Subject headings: Galaxies: active — galaxies: individual (NGC 1068) — X-rays: galaxies

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1. INTRODUCTION

At a distance of $\approx 14.4$ Mpc (Tully 1988), NGC 1068 is one of the nearest and best-studied Active Galactic Nuclei (AGN). It is traditionally classified as a Seyfert 2 galaxy, and was the first type 2 AGN observed to possess polarized optical broad-line emission; these broad line regions seen only in scattered light are presumably obscured by a dusty edge-on structure (a.k.a. the “torus”; Antonucci & Miller 1985; Miller et al. 1991), thereby establishing the standard orientation-based model of AGN unification as we know it today (Antonucci 1993; Urry & Padovani 1995). NGC 1068 has continued to be an exceptionally rich source for studying AGN in general and Compton-thick AGN in particular if they are spatially resolved of the AGN structure down to $\approx 0.5–70$ pc over many critical portions of the electromagnetic spectrum ($1'' = 70$ pc at the distance of NGC 1068). In many ways, NGC 1068 is considered an archetype of an obscured AGN.

In terms of its basic properties and structure, H$_2$O megamaser emission coincident with the nucleus and associated with a thin disk, has constrained the supermassive black hole (SMBH) mass at the center of NGC 1068 to be $\approx 1 \times 10^7$ M$_\odot$ within 0.65 pc, although the observed deviations from Kep-lerian rotation leave some ambiguity about the overall mass distribution (e.g., Greenhill et al. 1996; Gallimore et al. 2003; Lodato & Bertin 2003). A dynamical virial mass estimate based on the width of the H$_\beta$ line, $\sigma_{H\beta}$, from the scattered “polarized broad lines” in the hidden broad region (BLR) has found a consistent mass of $(9.0 \pm 6.6) \times 10^6$ M$_\odot$ (e.g., Kuo et al. 2011). NGC 1068’s bolometric luminosity has been estimated to be $L_{bol} = (6-10) \times 10^{44}$ erg s$^{-1}$ (Woo & Urry 2002; Alonso-Herrero et al. 2011) based on mid-infrared (MIR) spectral modeling assuming reprocessed AGN emission. Combined with the SMBH mass estimate, this luminosity approaches $50–80\%$ of the Eddington luminosity, indicating rapid accretion.

Very Long Baseline Interferometry (VLBI) observations of the maser disk constrain it to lie between radii of 0.6–1.1 pc at a position angle (PA) of $\approx 45^\circ$ (east of north; e.g., Greenhill et al. 1994). At centimeter wavelengths, a weak kpc-scale, steep-spectrum radio jet is seen to extend out from the nucleus, initially at PA = $12^\circ$ before bending to PA = $30^\circ$ at large scales (e.g., Wilson & Ulvestad 1987; Gallimore et al. 1996). Farther radio structures close to the nucleus are also observed to trace both the maser disk and an inner X-ray-irradiated molecular disk extending out to $\approx 0.4$ pc with a PA $\approx -60^\circ$ (e.g., Gallimore et al. 2004).

At MIR wavelengths, a complex obscuring structure has been spatially resolved in NGC 1068 via Keck and VLT interferometry (e.g., Bock et al. 2003; Jaffe et al. 2004) and appears to be comprised of at least two distinct components (Raban et al. 2009; Schartmann et al. 2010). The first is a $\approx 800$ K, geometrically thin, disk-like structure extending $\approx 1.35$ pc by 0.45 pc in size (full-width half maximum, FWHM) and aligned at PA = $-42^\circ$, which is likely associated with the maser disk. The second is a $\approx 300$ K, more flocculent, filamentary, torus-like structure $\approx 3–4$ pc in size (FWHM) which has been identified with the traditional torus. The parameters of the spectral modeling to the overall MIR light are consistent, with a torus radius of $\approx 2$ pc and angular width of $26'' \pm 4$ deg, a viewing angle of $88'' \pm 3$ deg with respect to the line-of-sight, and a covering factor of $\approx 25–40\%$ (Alonso-Herrero et al. 2011). While no dust reverberation studies have been published on NGC 1068, the sizes from interferometry are consistent with the inner radii determined from dust reverberation studies of type 1 AGN (Suganuma et al. 2006; Koshida et al. 2014).

NGC 1068 also displays a striking extended narrow-line region (NLR) that is roughly co-spatial with the radio jet and lobe emission (e.g., Wilson & Ulvestad 1987). The NLR has been extensively characterized by narrow-band imaging and IFU studies (Evans et al. 1991; Macchetto et al. 1994; Capetti et al. 1997; Veilleux et al. 2003). The biconical ionization cone has been observed out to radii of $\approx 150''$, with an apparent opening angle of $\approx 60''$ centered at PA $\approx 35\sim 45\sim$ (Unger et al. 1992; Veilleux et al. 2003). The narrow-line emitting clouds are part of a large-scale, radiatively accelerated outflow with velocities up to $\approx 3200$ km s$^{-1}$ (e.g., Cecil et al. 1999; Crenshaw & Kraemer 2000; Cecil et al. 2002). The morphology of the NLR seems to primarily trace the edges of the radio lobe, suggesting that the radio outflow has swept up and compressed the interstellar gas, giving rise to enhanced line emitting regions. The energetics of the line emission indicate that it is probably photoionization dominated (Dopita et al. 2002; Groves et al. 2004). Various studies have reported strongly non-solar abundances in the ionized gas of NGC 1068, which either require large or underabundances of some elements (e.g., due to shocks, supernovae pollution of Nitrogen, Phosphorus, etc, or that elements like C and Fe are predominantly locked in dust grains; Kraemer et al. 1998; Oliva et al. 2001; Martins et al. 2010), or can also be explained by multi-component photoionization models with varying densities (e.g., Kraemer & Crenshaw 2000).

As we now know, the primary AGN continuum of NGC 1068 from the optical to X-rays is completely obscured along our line of sight due to the relative orientations of the disk and obscuring torus, which has a column density $N_{HI} > 10^{24}$ cm$^{-2}$ (e.g., Matt et al. 2000). Thus the only X-ray emission that we see is scattered into our line of sight. Past observations have suggested that there are two “reflectors” which contribute to the X-ray spectrum (e.g., Matt et al. 1997; Guainazzi et al. 1999). The dominant component is from Compton scattering off the inner “wall” of the neutral obscuring torus, which gives rise to the so-called “cold” Compton reflection continuum (e.g., Lightman & White 1988). This emission is characterized by a hard X-ray spectral slope with a peak around 30 keV as well as high equivalent-width fluorescent emission lines (e.g., the dominant 6.4 keV iron line; Iwasawa et al. 1997). A second reflector arises from Compton scattering off highly ionized material associated with the ionization cone. The spectral shape of the “warm” reflector should crudely mirror the intrinsic continuum, apart from a high-energy cutoff due to Compton downscattering and potentially significant absorption edges/lines in the spectrum up to a few keV due to various elements and near $\sim 7$ keV due to Fe (e.g., Krolik & Kriss 1995). Radiative recombination continuum and line emission (hereafter RRC and RL, respectively) from a broad range of ions and elements can also be observed in relation to the warm reflector due to photoionization followed by recombination, radiative excitation by absorption of continuum radiation and inner shell fluorescence (Guainazzi et al. 1999; Brinkman et al. 2002; Kinkhabwala et al. 2002; Ogle et al.

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27 With a line-of-sight column density exceeding $N_{HI} = 1.5 \times 10^{24}$ cm$^{-2}$ and therefore optically thick to Compton scattering.
The NuSTAR observatory is the first focusing satellite with sensitivity over the broad X-ray energy band from 3–79 keV (Harrison et al. 2013). It consists of two co-aligned X-ray optics/detector pairs, with corresponding focal plane modules FPMA and FPMB, which offer a 12.5′×12.5′ field-of-view, angular resolutions of 18′′ Full Width Half Max (FWHM) and 1′ Half Power Diameter (HPD) over the 3–79 keV X-ray band, and a characteristic spectral resolution of 400 eV (FWHM) at 10 keV. NGC 1068 was observed by NuSTAR between 2012 December 18–21.

The NuSTAR data were processed using the standard pipeline (nupipeline; Perri et al. 2014) from the NuSTAR Data Analysis Software (v1.3.0) within the HEAsoft package (v6.15), in combination with CALDB v20131007. The unfiltered event lists were screened to reduce internal background at high energies via standard depth corrections, as well as to remove South Atlantic Anomaly (SAA) passages. The NUPRODUCTS program was used to extract data products from the cleaned event lists for both focal plane modules FPMA and FPMB.

NGC 1068 is the only well-detected source in the NuSTAR FOV (see Figure 1 and appears unresolved. The campaign was spread over three observations (60002030002, 60002030004, and 60002030006) comprising 123.9 ks in FPMA and 123.7 ks in FPMB. NGC 1068 appeared as a point source for NuSTAR (Figure 1), and thus spectral products and lightcurves from both the nucleus and the galaxy emission (diffuse + point sources) were extracted using 75′′ radius apertures (corresponding to ≈81% encircled energy fraction), with backgrounds estimated from blank regions free of contaminating point sources on the same detector (see Figure 1). We find that NGC 1068 is securely detected up to ≈ 55 keV at 3σ confidence with NuSTAR, and has a maximum signal-to-noise of ≈26 around the peak of Fe Kα.

We also generated a model of the expected background for each FPM within our adopted aperture using NUSKY (Wik et al. 2014). NUSKYBGD uses several user-defined background regions to sample all four detectors in each FPM, which it simultaneously fits in order to model the spectral and angular dependencies for several background components (e.g., instrumental, focused, and unfocused), before ultimately generating the expected background within the adopted aperture. We confirmed the similarity, particularly at high energies where the background makes a significant contribution, between the local and model backgrounds to a few percent. Ultimately we adopted the local background for simplicity.

Custom position-dependent response matrices and ancillary response files were generated for the spectra of each module, which provide nominal vignetting and PSF aperture corrections. In total, we have ≈27,300 and ≈26,100 counts between 3–79 keV in FPMA and FPMB, respectively. As can be seen in Figure 2 the FPMA and FPMB spectra are in excellent agreement, and thus we merged them into a single spectrum using exposure-weighting for convenience and we use this spectrum for all fitting and plotting purposes (from Figure 3 on). With respect to the XMM-Newton EPIC pn instrument, preliminary results suggest NuSTAR normalization offsets of 1.11±0.01; this value is fully consistent with other NuSTAR/XMM-Newton cross-calibration studies (e.g., Walton et al. 2013, 2014). Due to the high signal-to-noise of the NuSTAR data, we also find that we need to apply a ≈ 40 eV energy offset (i.e., ≈1 spectral bin) to bring the intrinsic Fe Kα line energy (6.4007 keV) into agreement with
We processed both data sets using SAS (v13.0.0) and selected only single and double events with quality flag=0. The events files were filtered to exclude background flares selected from time ranges where the 10–12 keV count rates in the pn camera exceeded 0.3 c/s. The remaining good exposures are 32.8 ks for the first observation and 28.7 ks for the second observation, with ≈760,000 counts between 0.2–10.0 keV.

Source spectra were extracted from a circular region of 75′′ radius (corresponding to an ≈93.5% encircled energy fraction) centered on the nucleus, to match the NuSTAR extraction region. Background photons were selected from a source-free region of equal area on the same chip as the source. We constructed response matrices and ancillary response files using the tasks RMFGEN and ARFGEN for each observation. Given that the two observations are consecutive and constant within their errors, we merged the spectral products using exposure-weighting. As mentioned previously, we base all of the normalization offsets relative to the pn in the 3–7 keV band. However, entries denoted by *'s are in fact relative to combined NuSTAR FPMA/FPMB spectrum in the 20–60 keV band.

### 2.2. XMM-Newton

NGC 1068 was observed on 2000 July 29–30 with XMM-Newton using the EPIC pn and MOS1/MOS2 instruments (Jansen et al. 2001), which provide respective angular resolutions of ≈5–6′′ FWHM and 14–15′′ HPD over the 0.15–12 keV X-ray band, respectively. Although the energy resolution of the EPIC detectors (FWHM≈45–150 eV between 0.4–8 keV) is poorer than the HETG, the difference narrows to a factor of only ≈5 by 6–8 keV, and the three EPIC detectors have substantially larger effective areas compared to Chandra. This improvement in counting statistics allows us to obtain novel constraints on the nuclear spectrum of NGC 1068 compared to the HETG spectra alone.

The XMM-Newton observation of NGC 1068 was split into two segments made using the Medium filter in Large Window mode (48 ms frame-time) for the pn, in Full Frame mode (1.4 s frame-time) for MOS1, and in Small Window mode (0.3 s frame-time, 110′′×110′′ FOV) for MOS2. Given the X-ray flux from the AGN, these options mean that MOS1 will be slightly piled-up while MOS2 will not sample the entire 75′′ radius extraction region (missing some extended emission and requiring a larger PSF correction). To limit systematic uncertainties, we opted to only extract counts for the pn instrument, which comprises 60% of the total XMM-Newton collecting area (i.e., MOS1+MOS2+pn). These are effectively the same conclusions arrived at by Matt et al. (2004, hereafter M04).

We noted that the established redshift of NGC 1068 and the high significance line energy determined by the Chandra High Energy Transmission Grating (HETG Canizares et al. 2000), the reason for the offset is not known, however, its value is within the nominal calibration precision of NuSTAR and somewhat smaller offsets have been observed in other sources.

### 2.3. Chandra HETG and ACIS-S

NGC 1068 was observed on multiple occasions with Chandra with both the ACIS-S detector (Garmire et al. 2003) by itself and the HETG placed in front of the ACIS-S. By itself, ACIS-S has a angular resolution of < 0.5″ FWHM and ≲ 0.7″ HPD, and a spectral resolution of FWHM≈110–180 eV between 0.4–8 keV. The HETG consists of two different grating assemblies, the High Energy Grating (HEG) and the Medium Energy Grating (MEG), which provide...
**Multiple Reflections in NGC 1068**

The Chandra data were reduced following standard procedures using the CIAO (v4.5) software package and associated calibration files (CALDB v4.5.5.1). The data were reprocessed to apply updated calibration modifications, remove pixel randomization, apply the energy-dependent sub-pixel event-repositioning (EDSER) techniques, and correct for charge transfer inefficiency (CTI). The data were filtered for standard ASCA grade selection, exclusion of bad columns and pixels, and intervals of excessively high background (none were found). Analysis was performed on reprocessed Chandra data, primarily using CIAO, but also with custom software.

The 1st-order HETG spectral products were extracted using standard CIAO tools using a HEG/MEG mask with a full-width of 4" in the cross-dispersion direction centered on the NGC 1068 nucleus; anything smaller than this will suffer from significant energy-dependent PSF losses. The intrinsic ACIS-S energy resolution allows to separate the overlapping orders of the dispersed spectra. The plus and minus sides were combined to yield single HEG and MEG 1st-order spectra. All of the HETG data were combined after double-checking that they did not vary to within errors; obsID 332 appears to have a modestly higher count rate, but this difference is largely below 2 keV and does not materially affect the combined >2 keV spectra. In total, we have 438.7 ks of HETG-resolution nuclear spectra available for spectral fitting (see Table 1 for details), with ∼12,500 HEG counts between 0.8–10.0 keV and ∼34,000 MEG counts between 0.4–8.0 keV. We consider these to be the least contaminated AGN spectra available below 10 keV (hereafter, simply the HETG “AGN” spectra). The normalization offset between the HEG and MEG was found to be 1.03±0.07, while the offsets with respect to the pn were 1.05±0.06 and 1.09±0.06, respectively. This is consistent with the cross-calibration finding in Marshall (2012) and Tsujimoto et al. (2011).

In principle, we have a similar amount of HETG 0th-order data, in addition to 47.7 ks of normal ACIS-S data that could be used to model the extranuclear contamination which strongly affects the lower-energy NuSTAR and XMM-Newton spectra. However the calibration of the HETG 0th-order still remains somewhat uncertain above ~5 keV (M. Nowak, private communication), which we consider critical for extrapolating into the NuSTAR band. Thus we chose to model the contamination spectra solely using ACIS-S obsid 344. These data were taken with the nominal 3.2s frame time, such that the nucleus is heavily piled-up (~40%) within 1–2″. We therefore excluded the inner 2″ from the contamination analysis and consider the 2–75″ ACIS-S spectrum to be predominantly emission from the host galaxy (hereafter “host”), although we must consider contributions from the broad wings of the PSF (which only contribute ∼5–10% beyond 2″ based on PSF simulations) and any truly extended Compton reflec-

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**Fig. 1.** (top) NuSTAR 3–79 keV FPMA image of NGC 1068 showing the 75″ radius source (solid red circle) and polygon background (dashed red circle) extraction regions. (middle) XMM-Newton 0.2–10 keV pn image of NGC 1068 showing the 75″ radius source (solid red circle) and polygon background (dashed red circle) extraction regions. The central point source dominates, although there are hints of faint extended emission. (bottom) Chandra 0.5–8.0 keV ACIS-S image of NGC 1068 showing the 75″ radius aperture used for NuSTAR and XMM-Newton (large solid red circle). The nucleus is denoted by the small 2″ radius (solid red) aperture and is strongly piled up. The obvious off-nuclear point sources (denoted by 2–3″ radius magenta circles) and diffuse emission between 2–75″ were extracted separately. The rough positions of the radio jet (blue dashed region) and counter jet (red dashed region) are shown (Wilson & Ulvestad 1983). The brightest off-nuclear point source in the Chandra image (green circle) is not present after 2000-12-04 and thus has been excluded from analysis.
Figu re 2.— Comparison of the NuSTAR FPMA/FPMB (black/grey) and XMM-Newton pn (green) spectra with other past observations of NGC 1068 from Suzaku XIS+PIN (blue), BeppoSAX MECS+PDS 1996 (magenta), BeppoSAX MECS+PDS 1998 (cyan), and Swift BAT (orange), all modeled with the best-fitted two-reflector model M04a. The top panel shows the observed spectra while the bottom panel shows the data-to-model ratios for each spectrum. There is good overall consistency between the various datasets once known normalization offsets are accounted for, with only a few marginally discrepant points seen from the 1996 BeppoSAX data. It is clear from the bottom panel that the model provides a poor fit to the data near the Compton reflection hump, with the data peaking at $\sim 30$ keV while the $\text{pexrav}$ model peaks at $\sim 20$ keV. There are some additional residuals around 10–15 keV indicating the curvature of the reflection is more severe than the model predicts, as well as around the Fe/Ni line region ($\approx 6–8$ keV), suggesting that a few Gaussian lines are insufficient for modeling the complex Fe/Ni emission.

2.4. BeppoSAX

NGC 1068 was observed by BeppoSAX on 1996 December 30 and on 1998 January 11 with the Low Energy Concentrator Spectrometer (LECS), the three Medium Energy Concentrator Spectrometers (MECS), and Phoswich Detector System (PDS). We use only the MECS and PDS here. The MECS contains three identical gas scintillation propor-
tional counters, with an angular resolution of \( \approx 0.7 \) FWHM and \( \approx 2.5 \) HPD, and a spectral resolution of FWHM=200–600 eV between 1.3–10 keV. MECS1 failed a few months after launch and thus only MECS2 and MECS3 data are available for the 1998 observation. The MECS event files were screened adopting standard pipeline selection parameters. Spectra were extracted from 3′ radii apertures and the spectra from individual units were combined after renormalizing to the MECS1 energy-PI relation. Background spectra were obtained using appropriate blank-sky files from the same region as the source extraction. The resulting MECS spectra have \( \approx 5900 \) counts between 3–10 keV in 100.8 ks of good exposure for the first observation and \( \approx 1550 \) counts in 37.3 ks for the second observation. We find that the MECS normalization is systematically offset from the pn by a factor of 1.12±0.02 in the 3–7 keV band and thus by a factor of 1.02±0.02 with respect to NuSTAR in the same band.

The PDS has no imaging capability, but does have sensitivity between 15–220 keV and can potentially provide some constraints above the NuSTAR band. The PDS data were calibrated and cleaned using the SAXDAS software within HEASoft, adopting the ‘fixed Rise Time threshold’ method for background rejection. The PDS lightcurves are known to show spikes on timescales of fractions of second to a few seconds, with most counts from the spikes typically falling below 30 keV. We screened the PDS data for these spikes following the method suggested in the NFI user guide arriving at \( \approx 16,600 \pm 3010 \) counts between 15–220 keV in 62.5 ks of good exposure for the first observation and \( \approx 4720 \pm 1560 \) counts in 17.7 ks for the second observation. The PDS spectra were logarithmically rebinned between 15–220 keV into 18 channels, although we cut the spectrum at 140 keV due to poor statistics. With the data quality/binning, it is difficult to appreciate the presence of a bump at 30 keV. The PDS normalization is known to be low by \( \approx 20–30\% \) (Grandi et al. 1997; Matt et al. 1997) compared to the MECS, which we accounted for by using a fixed normalization constant of 0.7±0.1 when modeling the data with respect to NuSTAR.

We note that the statistics for the second BeppoSAX observation are poorer, with many of the channels statistically consistent with zero.

### 2.5. Suzaku

The Suzaku observatory observed NGC 1068 with the X-ray Imaging Spectrometer (XIS) and Hard X-ray Detector (HXD) PIN instruments on 2007 February 10. Our reduction follows the recommendations of the Suzaku Data Reduction Guide.

For the XIS, we generated cleaned event files for each operational detector (XISO, XIS1, and XIS3) and both editing modes (3x3 and 5x5) using the Suzaku AEP pipeline with the latest calibration, as well as the associated screening criteria files in HEASoft. Using XSELECT, source spectra were extracted using a 260′′ radius aperture, while background spectra were extracted from remaining regions free of any obvious contaminating point sources. Responses were generated for each detector using the XISRESP script with a medium resolution. The spectra for the front-illuminated detectors XISO and XIS3 were consistent, and were subsequently combined using ADDASCASPEC; for simplicity, we adopt this composite spectrum to represent the XIS. We obtained \( \approx 33,300 \) counts with a good exposure of 61.5 ks. We find that the XIS spectrum is systematically offset from the pn by a factor of 1.17±0.02, which is slightly (i.e., \( < 3\sigma \)) above the expected normalization offset of 1.10±0.01 assessed by Tsujimoto et al. (2011).

Similar to the PDS, the PIN has poor angular resolution (\( 0.56\times0.56 \) FOV) but does have sensitivity between 15–70 keV and thus provides another point of comparison with NuSTAR. We reprocessed the unfiltered event files following the data reduction guide to obtain \( \approx 15,500 \) counts with a good exposure of 39.0 ks. No significant detection was found in the GSO. Since the HXD is a collimating instrument, estimating the background requires separate consideration of the non X-ray instrumental background (NXB) and cosmic X-ray background (CXB), which comprise \( \approx 89\% \) of the total counts. We used the response and NXB files provided by the Suzaku team adopting the model D ‘tuned’ background. Spectral products were generated using the XHDPINXBPI tool, which extracts a composite background using the aforementioned NXB and a simulated contribution from the expected CXB following Boldt (1987). We find the PIN normalization to be systematically offset from NuSTAR by a factor of 1.2±0.05, which is consistent with the current cross-calibration uncertainty (K. Madsen et al., submitted).

### 2.6. Swift

The Swift observatory observed NGC 1068 with the X-ray Telescope (XRT; 7′′ FWHM, 20′′ HPD) for \( \approx 2 \) ks simultaneously with NuSTAR on 2012 December 19. The processed data were retrieved from the Swift archive, and analysis was performed using FTOOLS. With \( \approx 1200 \) counts between 0.5–10 keV in a 75′′ aperture, the Swift exposure is not long enough to provide additional constraints beyond those already obtained with NuSTAR, XMM-Newton, and Chandra. However, it does serve to determine if any transient point sources strongly contributed to the \( < 10 \) keV NuSTAR spectra of NGC 1068. To this end, we generated a 0.5–10 keV image with XSELECT, which is consistent with the Chandra images from 2008 to within the limits of the Swift XRT angular resolution and does not show any new strong off-nuclear point sources. We find the XRT 3–10 keV composite spectrum is consistent with the other instruments aside from its normalization, which is systematically offset from the pn by a factor of 1.12±0.25; the large error bar is due to the fact that the observation only has 64 counts in the 3–10 keV band. This offset is fully consistent with those found by Tsujimoto et al. (2011).

Since November 2004, the Burst Alert Telescope (BAT) onboard Swift (Gehrels et al. 2004) has been monitoring the hard X-ray sky (14–195 keV) and can potentially provide some constraints above the NuSTAR band. Swift BAT uses a 5200 cm\(^2\) coded-aperture mask above an array of 32,768 CdZnTe detectors to produce a wide field of view of 1.4 steradians of the sky and an effective resolution of \( \approx 20′ \) (FWHM) in stacked mosaic maps. Based on the lack of variability (see §3), we used the stacked 70-month spectrum, which is extracted from the central pixel (2′7; Baumgartner et al. 2013) associated with the BAT counterpart, to assess nature of the emission. The background-subtracted spectrum contains \( \approx 460 \) counts in the 14–195 keV band. We find the BAT normalization to be systematically offset from NuSTAR by a factor of 0.75±0.05, which is consistent with the current cross-calibration uncertainty (K. Madsen et al., in preparation).
several variables are fixed (left; model M04a), fit as free parameters (middle; model M04b), and with the addition of a leaky, absorbed transmission component (right; model M04c). The top panel shows the observed spectra while the bottom panel shows the data-to-model ratios for each spectrum. The overall fits with the parameters free and the addition of the transmission component (e.g., George et al. 2000) are better, with most of the residuals confined to the complex Fe/Ni line region.

3. X-RAY VARIABILITY CONSTRAINTS

Depending on the location and structure of the obscuration in NGC 1068, it may be possible to observe temporal variations in one or more of its spectral components on short or long timescales. Notably, there have been previous claims of low-significance variability from the warm reflection component between the BeppoSAX and XMM-Newton observations (Guainazzi et al. 2000; Matt et al. 2004).

As shown in Table [1], we find reasonable consistency between the count rates extracted from all instruments where NGC 1068 was observed more than once, with differences always less than 3σ based on counting statistics. These constraints imply there is no strong continuum variability below 10 keV over periods of 10–15 years. Since Swift BAT continuously observes the sky, a new snapshot image can be produced every ~1 week for persistent high-energy X-ray sources due to the wide field of view and large sky coverage. To study long-term variability of NGC 1068 (SWIFT J0242.6+0000) above 10 keV, we use the publicly available 70-month (9.3 Ms) lightcurves from Swift BAT (Baumgartner et al. 2013), which span 2004–2010. The wide energy range of Swift BAT allows us to test any underlying energy dependence of the lightcurve, assessing lightcurves in eight non-overlapping energy bands: 14–20, 20–24, 24–35, 35–50, 50–75, 75–100, 100–150, 150–195 keV. The cumulative 14–195 keV lightcurve, binned in half-year intervals due to the limited statistics, is shown in Figure [4] and is formally constant to within errors ($\chi^2 = 0.95$ for $v = 17$ degrees of freedom). Variability limits in the individual bands are consistent with the full band results, but generally are less constraining due to limited statistics.

To investigate short-term variability, we applied the Kolmogorov-Smirnov (K-S) test to individual observations, finding all observations to be constant in count rate with 3σ confidence. We searched for additional hints of short-term variability taking advantage of the high throughput of NuSTAR above 10 keV. The timescales covered by these light curves ($\sim$1–200ks) can only reveal rapid fluctuations, such as those expected from the intrinsic powerlaw emission. Therefore, any variability seen in this range would be indicative of a transmitted powerlaw component (e.g., Markowitz et al. 2003, McHardy et al. 2004, 2005, 2006, Markowitz et al. 2007). In Figure [5] we constructed power spectra from the high-energy NuSTAR lightcurves for NGC 1068 and a typical background region, which we compare to the expected power spectra for pure Poisson noise and for the expected variability of a pure transmitted component, as observed in unobscured AGN of similar mass and accretion rates. To produce this, we extracted 30–79 keV counts from our nominal source region and a background region of equal area on the same detector using XSELECT. We constructed lightcurves in 100 s equally spaced bins, retaining only those which had exposure ratios over 90%. Note that the nature of NuSTAR’s orbit means that for the given sky location we will have 2 ks gaps in the lightcurves every 6 ks. Moreover, since NuSTAR observed NGC 1068 in three distinct segments, we have larger gaps in between the observations. To mitigate these potential sources of aliasing, we calculated power spectra using the Mexican-hat filtering method described in Arevalo et al. (2012), which is largely unaffected by gaps in the lightcurves. Finally, we normalized the power as the variance divided by the square...
of the average count rate. As can be seen in Figure 3, the power spectrum detected from NGC 1068 is fully consistent with Poisson noise at better than $2\sigma$. Thus, if there is any transmitted component leaking through, it does not comprise the bulk of the $>10$ keV flux.

We conclude that if there has been any variability from NGC 1068 in the past $\approx 15$ years, it has been at a level comparable to either the cross-calibration uncertainties between instruments or the statistical uncertainty in the data and that the short-term behaviour as measured by the NuSTAR lightcurves is not consistent with a transmitted powerlaw component dominating the flux above 10 keV.

4. X-RAY SPECTRAL CONSTRAINTS

We begin by comparing the high-quality combined NuSTAR and XMM-Newton spectra to those from several past satellites to demonstrate the dramatic improvement in data quality. We compare all of these to a few common previously used models, which can eventually fit the data relatively well when pushed to extreme values. Following this, we develop a more realistic approach to quantify the non-negligible contamination from extranuclear emission and then model the AGN components using a few common models such as pexmon (Nandra et al. 2007), MYTorus (Murphy & Yaqoob 2009; Yaqoob 2012), and torus (Brightman & Nandra 2011).

Unless stated otherwise, modeling was performed with XSPEC v12.9.0 (Arnaud 1996), and quoted uncertainties on spectral parameters are 90% confidence limits for a single parameter of interest, and spectral fitting is performed through $\chi^2$ minimization. Neutral absorption is treated with the tbabs absorption code (Wilms et al. 2000), with appropriate solar abundances (wilms) and cross sections (vern; Werner et al. 1996).

31 It is important to stress here that the convolution kernel is broad in frequency, such that nearby power density spectral points will be correlated. Thus the fact that several consecutive points are above the PN level does not make the detection of variability more significant.

Throughout our analysis, we assume there is no angular dependence of the nuclear emission spectral shape (such that all scatterers see the same photon index) and we neglect any accretion disk reflection component (e.g., Ross & Fabian 2005; Dauser et al. 2013; García et al. 2014) when modeling the obscured nuclear radiation, which is justified due to the inclination and dominance of scattering and absorption from distant material.

Finally, we note that XSPEC has considerable difficulty arriving at the best-fit solution when dealing with large numbers of free parameters, such as we have in NGC 1068 associated with the considerable line emission. Thus, to mitigate this in cases in which we fit individual emission lines separately, we individually fitted the line centers, redshifts, widths, and heights of the Gaussian lines over small portions of the spectrum above a local powerlaw continuum, and then froze each line at its best-fit values. We then fit the relative contributions from the continuum and fluorescent line models.

4.1. Comparison to Previous Models

As mentioned in §1, NGC 1068 has been successfully modeled in the past above $\approx 3$–$4$ keV with a double-reflector comprised of both neutral “cold” (pexrav with $R = 1$; Magdziarz & Zdziarski 1995) and ionized “warm” (cutoffpo) Compton-scattered components, plus a few Gaussian emission lines to model the strong Fe and Ni emission (Matt et al. 1997; Guainazzi et al. 2000 hereafter model “M04a”, since it was adopted from M04; see also similar models from ). We therefore began by fitting this model (see Table 2) to the NuSTAR, XMM-Newton, BeppoSAX, Suzaku, and Swift BAT spectra above 3 keV.

We initially fixed most of the parameters to the values found by M04 (e.g., $\Gamma = 2.04$, $Z_{Fe} = 2.4Z_{\odot}$, $\theta_{inc} = 63^\circ$, $E_{cut} = 500$ keV), varying only the component normalizations and the redshifts of the emission lines. The normalizations were coupled between the different instruments while the redshifts differed for each instrument to account for the aforementioned linear energy offsets. The redshifts of the cold reflector and neutral lines (Ko, Kβ) were tied and allowed to vary as one parameter, while the redshifts of the ionized lines were tied and allowed to vary as another parameter. The best fit of this dual-reflector model, M04a, yielded a reduced $\chi^2$ of 1.40 for $\nu = 1785$. As can be seen in Figure 2, the fit has strong residuals near the Compton reflection hump due to a discrepancy between the peak of the reflection hump in the data ($\sim30$ keV) and the one from the pexrav model ($\sim20$ keV). We also see residuals around 10–15 keV, implying that there is stronger curvature in the actual reflection spectrum than has been modeled, as well as around the Fe/Ni line complex, suggesting that the Gaussians are not sufficient to describe the line complexity observed.

The bottom panel of Figure 2 shows the data-to-model ratios for several past hard X-ray missions compared against the best-fitted fixed-$\Gamma$ two-reflector model. As noted in [3] there have been previous claims of low-level variability in the warm reflection component (Guainazzi et al. 2006; Matt et al. 2004). After accounting for known cross-calibration offsets, we find that the NuSTAR, XMM-Newton pn, Suzaku XIS, and BeppoSAX MECS spectra in the 3–5 keV range, where the warm reflector should dominate, are consistent within their statistical uncertainties based on powerlaw fits to this
range; this applies to the 3–10 keV range overall as well. Uncertainties in the normalization offset between instruments, and hence flux differences, above 10 keV are considerably larger, making it more difficult to assess potential variability. Nonetheless, after accounting for known cross-calibration offsets, we find that the NuSTAR, Suzaku PIN, 1998 BeppoSAX PDS, and Swift BAT spectra above 10 keV are likewise consistent within their statistical uncertainties. The 1998 BeppoSAX PDS spectra, which lack the pronounced residuals around 30 keV that we observe from the other hard X-ray spectra, differ from the rest at marginal significance (2.5σ) and in fact appear to be relatively well-fitted by the fixed \cite{Matt04} model ($\chi^2 = 1.43$ for $\nu = 57$ by itself; perhaps this is no surprise since the model is based on these data). Here, it is important to remember that the BeppoSAX PDS, Suzaku PIN, and Swift BAT spectra are all strongly background-dominated (see \ref{2}, \ref{3}, \ref{6}, and minor variations in background levels (e.g., due to minor flares or how the data are screened) can potentially lead to large variations in the source spectra. The fact that we see an overall consistency in the spectral shape of the residuals, aside from the one discrepant point in the 1998 BeppoSAX PDS spectra around 30 keV, demonstrates that there has been no strong variability detected over at least the past $\approx 15$ years.

We note that the $\chi^2$ residues are dominated by the XMM-Newton pn and NuSTAR spectra, and thus, for clarity, we opt to use only the XMM-Newton pn and combined FPMA/FPMB NuSTAR spectra to represent the global spectrum of NGC 1068 hereafter. To this end, we plot the unfolded XMM-Newton pn and composite NuSTAR spectra along with the various components that comprise the M04a model again in the left panel of Figure\ref{fig3}, as well as the data-to-model residuals. This fit yielded a reduced $\chi^2 = 1.61$ for $\nu = 1234$. The continuum parameter values and errors are listed in Table\ref{tab3} while the normalizations of the various lines are given in Table\ref{tab4}. For NuSTAR, the redshifts for the neutral and ionized lines were $-0.006^{+0.005}_{-0.006}$ and $0.008^{+0.002}_{-0.008}$, respectively, while for XMM-Newton they were $0.0015^{+0.0003}_{-0.0008}$ and $0.0026^{+0.0013}_{-0.0013}$, respectively.

Allowing the powerlaw index, high-energy cutoff, and Fe abundance and inclination angle of the reflector to vary, hereafter model “M04b”, improves the fit substantially, with a reduced $\chi^2_\nu = 1.20$ for $\nu = 1230$. As shown in Figure\ref{fig5} most of the residuals are now due to the Fe/Ni line complex with only very mild residuals seen from the Compton hump above 10 keV. The emission line parameters remained more or less constant, while the best fitted values of the other parameters are $\Gamma = 1.76^{+0.04}_{-0.09}$, $\theta_{inc} = 70.7^{\circ}$, $E_c = 105^{+39}_{-20}$ keV, and $\delta_F = 6.8^{+0.4}$. Parameter values and errors for model M04b are listed in Table\ref{tab4}.

Another possibility that could explain the spectrum is if the direct continuum is partially punching through above 20–30 keV, often called the “leaky" torus model, hereafter model "M04c". Given the high column density needed to produce flux only above $\sim 30$ keV, we need to account properly for the effects of Compton absorption, which we do through the use of the multiplicative transmission component from the MYTorus set of models (hereafter MYTZ). The best-fitted values of the other parameters are $\Gamma = 2.2^{+0.2}_{-0.3}$, $\theta_{inc} = 70.7^{\circ}$, $E_c = 105^{+39}_{-20}$ keV, and $\delta_F = 6.8^{+0.4}$. Parameter values and errors for model M04c are listed in Table\ref{tab4}.

Clearly the best-fitted M04a model fails to provide an adequate description of the NuSTAR data, while both of the alternative models, M04b and M04c appear to yield more reasonable fits. The Fe abundance constraints from M04b are substantially super-solar, which is consistent with past constraints on NGC 1068 (e.g., \cite{Kinkhabwala02, Kraemer02}).

\begin{table}
\centering
\caption{X-ray Spectral Fitting Models}
\begin{tabular}{|l|l|}
\hline
Model & XSPEC Components \\
\hline
\hline
M04ab & \texttt{tbabs(\texttt{pexrav+cutoffpl+gauss(F\texttt{NuBorn}, F\texttt{NuEnd}, Ni\texttt{Born})})} \\
M04c & \texttt{tbabs(\texttt{MYTZ+cutoffpl+cutoffpo+pexrav+gauss(F\texttt{NuBorn}, F\texttt{NuEnd}, Ni\texttt{Born})})} \\
\hline
\hline
\text{Total} & \texttt{P : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpl+C\texttt{RL}+pow+edge+N\texttt{RRC})}+\texttt{gauss(Ni\texttt{Born})})}} \\
& \texttt{M1 : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpl+C\texttt{RL}+pow+highcut+edge+N\texttt{RRC})}+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{cutoffpo}+\texttt{pexrav}+\texttt{gauss(Ni\texttt{Born})})})}} \\
& \texttt{M2 : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpo+C\texttt{RL}+pow+highcut+edge+N\texttt{RRC})}+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{cutoffpo}+\texttt{pexrav}+\texttt{gauss(Ni\texttt{Born})})})}} \\
& \texttt{T : \texttt{tbabs(\texttt{C\texttt{RL}+C\texttt{RL}+pow+highcut+edge+\texttt{gsmooth(torus)})}} \\
\hline
\text{Nucleus Only} & \texttt{P : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpl+C\texttt{RL}+pow+edge+N\texttt{RRC})}+\texttt{gauss(Ni\texttt{Born})})}} \\
& \texttt{M1 : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpl+C\texttt{RL}+pow+highcut+edge+N\texttt{RRC})}+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{cutoffpo}+\texttt{pexrav}+\texttt{gauss(Ni\texttt{Born})})})}} \\
& \texttt{M2 : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpo+C\texttt{RL}+pow+highcut+edge+N\texttt{RRC})}+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{cutoffpo}+\texttt{pexrav}+\texttt{gauss(Ni\texttt{Born})})})}} \\
& \texttt{T : \texttt{tbabs(\texttt{C\texttt{RL}+C\texttt{RL}+pow+highcut+edge+\texttt{gsmooth(torus)})}} \\
\hline
\text{Host Only} & \texttt{P : \texttt{tbabs(\texttt{tcfabs(C\texttt{RL}+C\texttt{RL}+pow+highcut+edge+N\texttt{RRC})}+\texttt{gauss(Ni\texttt{Born})})}} \\
& \texttt{M1 : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpl+C\texttt{RL}+pow+highcut+edge+N\texttt{RRC})}+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{cutoffpo}+\texttt{pexrav}+\texttt{gauss(Ni\texttt{Born})})})}} \\
& \texttt{M2 : \texttt{tbabs(\texttt{tbabs(MYTZ+cutoffpo+C\texttt{RL}+pow+highcut+edge+N\texttt{RRC})}+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{MYTS(\texttt{Ni\texttt{Born}})+\texttt{cutoffpo}+\texttt{pexrav}+\texttt{gauss(Ni\texttt{Born})})})}} \\
& \texttt{T : \texttt{tbabs(\texttt{C\texttt{RL}+C\texttt{RL}+pow+highcut+edge+\texttt{gsmooth(torus)})}} \\
\hline
\end{tabular}
\end{table}
Multiple Reflections in NGC 1068

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<th>$E_c$</th>
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<th>$\theta_{open}$</th>
<th>$Z_{Fe}$</th>
<th>S/L ratio</th>
<th>$\log F_{X,cold}$</th>
<th>$\log F_{X,warm}$</th>
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<tr>
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**Nuclear Only**

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<th>$Z_{Fe}$</th>
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<th>$\log F_{X,cold}$</th>
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<th>$\chi^2$ ($\nu$)</th>
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**Host Only**

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<th>$\theta_{in}$</th>
<th>$\theta_{open}$</th>
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<td>90</td>
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<td>78*</td>
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<td>40</td>
<td>80*</td>
<td>3.3*</td>
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<td>87</td>
<td>64*</td>
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<td>-11.92*</td>
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</table>

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**Note.** Column 1: Model used. Model name beginning with "M04" denote variations of M04 model; "P" denote variations of pexmon models; "M1" denote variations of coupled MYTorus models; "M2" denote variations of decoupled MYTorus models; "T" denote variations of torus models. See [3] and [4] for details. When multiple rows are listed, the first or two rows represent the nucleus model while the second or third row represents the host model. Column 2: Spectra fit, where X=XM-M-Newton pn, A=Chandra ACIS-S, H=Chandra HEG+MEG, N=NuSTAR, and B=Swift BAT. Column 3: Energy range fit, in keV. Column 4: Photon index of the primary transmitted powerlaw continuum. Note that some reported limits are poorly constrained since the allowed ranges for $\Gamma$ are confined to between 1.1–2.5 for the pexmon model, between 1.4–2.6 for the MYTorus model, and between 1–3 for the torus model. Column 5: Neutral hydrogen column density of the obscuring torus/clouds, in units of $10^{24}$ cm$^{-2}$. Column 6: Energy of the exponential cutoff rollover of primary transmitted powerlaw continuum, in keV. Column 7: Inclination angle with respect to a face-on geometry, in degrees. Note that some reported limits are poorly constrained since the allowed ranges for $\theta_{in}$ are confined to 0°–72° for the M04 (pexmon) model, 0°–85° for the pexmon model, and 18°–87° for the torus model. Columns 8: Torus opening angle, in degrees. This parameter is not meaningful for the M04 and pexmon models, as it is fixed at 60° for the MYTorus model, and is confined to 25°–84° for the torus model. Column 9: Fe abundance with respect to our adopted value of Z$_{Fe}$. The overall abundance of metals (not including Fe) is assumed to be solar (Z$_{Fe}$). Note that entries denoted by * are for pexmon, where the Fe abundance is driving the peak of the Compton reflection hum to higher energy and has no effect on the Fe line emission. Note that the parameter is not meaningful for the M04 and pexmon models, as it is fixed at 60° for the MYTorus model, and is confined to 25°–84° for the torus model. Column 10: Fe abundance with respect to our adopted value of Z$_{Fe}$. The overall abundance of metals (not including Fe) is assumed to be solar (Z$_{Fe}$). Note that entries denoted by * are for pexmon, where the Fe abundance is driving the peak of the Compton reflection hum to higher energy and has no effect on the Fe line emission. Note that the parameter is not meaningful for the M04 and pexmon models, as it is fixed at 60° for the MYTorus model, and is confined to 25°–84° for the torus model. Column 11: Fe abundance with respect to our adopted value of Z$_{Fe}$. The overall abundance of metals (not including Fe) is assumed to be solar (Z$_{Fe}$). Note that entries denoted by * are for pexmon, where the Fe abundance is driving the peak of the Compton reflection hum to higher energy and has no effect on the Fe line emission. Note that the parameter is not meaningful for the M04 and pexmon models, as it is fixed at 60° for the MYTorus model, and is confined to 25°–84° for the torus model. Column 12: Reduced $\chi^2$ and degrees of freedom for given model. Values with no quoted errors were fixed at their specified values.
One might be tempted to stop here, having modeled the global NuSTAR and XMM-Newton spectra to a reasonably acceptable level. However, higher spectral and angular resolution data from Chandra exist, allowing us to remove potential host contamination and thus probe the nature of the scattering medium in more detail. Additionally, a critical drawback of the pexrav model, for instance, is that it models a simple slab-like geometry for the Compton scatterer assuming an infinite column density, which almost certainly fails to adequately describe the true physical situation (e.g., a smooth or clumpy torus) present in NGC 1068. To this end, we also explore a variety of models which adopt more realistic geometrical scenarios for AGN scattering in section 4.2.

4.2. Detailed Spectral Modeling

At this point, it is critical to define which spectral models we will fit to the data, as there are a variety of models of Compton-scattered emission which have been used to fit reflection-dominated spectrum to account for the possible different geometries of the scattering material. These include

- **pexmon** — a modified version of the standard pexrav model (Magdziarz & Zdziarski 1995) already used in §4.1 which self-consistently computes the continuum (based on pexrav) as well as the neutral Fe Kα, Fe Kβ and Ni Kα emission lines (based on Monte Carlo simulations by George & Fabian 1991) and the Fe Kα Compton shoulder (Nandra et al. 2007). As with pexrav, this model assumes that the scattering structure has a slab geometry and infinite optical depth. Moreover, the total and Fe abundances can be adjusted to account for non-solar values. The Ni edge is not included in this model, so we add this as a zedge component at the systemic redshift, the depth of which is tied to the measured Ni Kα flux (a value of $\tau = 0.1$ in zedge achieved this). Results for the series of pexmon Compton scattering models are detailed below and summarized in Table 3. We caution that the pexmon model is limited to photon indices between $\Gamma = 1.1-2.5$ and inclination angles $\theta = 0^\circ-85^\circ$.

- **MYTorus** — functions for a smoothly distributed toroidal reprocessor composed of gas and dust with finite optical depth and with a fixed $60^\circ$ opening angle (Murphy & Yaqoob 2009). MYTorus is comprised of three separate spectral components: a transmitted intrinsic continuum component (MYTZ, incorporated as a multiplicative table) which represents the photons along the direct line of sight to the nucleus which remain after scattering, and Compton-scattered continuum (hereafter MYTS) and fluorescent line and Compton shoulder (hereafter MYTL) components which represent photons scattered into our line of sight from a different viewing angle to the nucleus (both additive table models). The neutral Fe lines are modeled self-consistently with the Compton-scattered component. By using multiple scatterers, varying their relative normalizations and/or inclination angles with respect to our line of sight, disentangling their column densities, and so forth, Yaqoob (2012) demonstrated that one could model a wide range of possible geometries surrounding the central engine. The Ni edge is not included in this model, so we must add this as a zedge component at the systemic redshift, the depth of which is tied to the measured Ni Kα flux (which empirically equates to fixing $\tau = 0.1$). The model does not allow dynamic fitting for a high-energy cutoff, and table models are only computed for a handful of fiducial “termination” energies ($E_T$, which effectively is an instant cutoff). For expediency, we chose to implement a dynamic cutoff separately using the $E_T = 500$ keV model multiplied by the highcut model with a fixed pivot energy of $10$ keV and an e-folding energy that is tied to the transmitted powerlaw cutoff energy.

33 Below energies of $\approx 20$ keV, the MYTorus models with different termination energies are virtually identical, while above this value the lower termination energy models have pseudo-exponential cutoffs, the forms of which depend modestly on input parameters. Using a sharp termination compared to an exponential cutoff should lead to mild differences in the shape of the cutoff. Unfortunately, the lack of any continuum above the termination energy imposes parameter limitations when fitting, e.g., the Swift BAT spectrum. While there may be merits to the arguments given in the MYTorus manual against applying a cutoff, we find the alternative, a dramatic cutoff, to also be unsatisfactory from a physical standpoint.

34 While applying exponential cutoffs outside of MYTorus is expressly warned against in the MYTorus manual, we found that this method yielded reasonable consistency compared to the various MYTorus termination energy models over the ranges of parameters we fit, such that constraints on the cutoff energies typically were less than a factor of two different from the termination energy considered.
It is argued in the MYTorus manual that applying a high-energy cutoff ruins the self-consistency of the MYTorus; therefore, once we determined an approximate $E_{\text{cut}}$ for our best-fit model, we dropped the use of $\text{highcut}$ and replaced the $E_T = 500 \text{ keV}$ model with one which best approximates $E_{\text{cut}} = E_T$. Results for the series of MYTorus Compton scattering models are detailed below and summarized in Table 3. We caution that the MYTorus model is computed only for photon indices between $\Gamma = 1.4–2.6$, to energies between 0.5–500 keV, and solar abundances.

- torus — this model describes obscuration by a spherical medium with variable $N_H$ and inclination angle, as well as a variable biconical polar opening angle (Brightman & Nandra [2011]). torus self-consistently predicts the $\text{K} \alpha$ and $\text{K} \beta$ fluorescent emission lines and absorption edges of all the relevant elements. The key advantage of this model is it can fit a range of opening angles and extends up to $N_H = 10^{26} \text{ cm}^{-2}$, but a major drawback is that it does not allow the user to separate the transmitted and Compton-scattered components. As such, it can only be applied to the nuclear emission and is not appropriate to model the host component, which should include only the Compton-scattered emission. As with MYTorus, torus does not allow dynamic fitting for a high-energy cutoff, so we implemented a cutoff using $\text{highcut}$ in the same manner as for MYTorus. Results for the series of torus Compton scattering models are detailed below and summarized in Table 3. We caution that the torus model is limited to photon indices between $\Gamma = 1.0–3.0$, inclination angles $\theta_{\text{inc}} = 18^\circ 1–87.1^\circ$, opening angles $\theta_{\text{tor}} = 25^\circ 8–84.3^\circ$, and solar abundances.

Both MYTorus and torus provide significant and distinct improvements over the geometric slab model which manifest in the spectral shapes of both line and continua. Nonetheless, the reader should keep in mind that they too only sample a small portion of the potential parameter space that likely improves over the geometric slab model which manifest in the spectral shapes of both line and continua. Nonethe-
neutral Fe Kα (see §4.2.3). Similar to the transmitted component, we fixed the reflection component inclination angle to θ_{inc} = 90°, which is close to the nominal viewing angle associated with NGC 1068, and the high-energy exponential cutoff rollover energy to E_c = 500 keV for all models. Finally, we included two neutral absorption (tbabs) components, one of which was fixed at the Galactic column while the other was fit as N_H = (1.5 +0.3 −0.2) × 10^{22} cm^{-2} to constrain the host column density in NGC 1068.

We now proceed to fit the cold reflection with various prescriptions. For all of the models below, we list the best-fit parameter values in Table 3 (“Nucleus Only”) and show the resulting data-to-model residuals in Figure 6. Fitting the pe xm on model (model P in Table 2) yielded a reduced χ^2 = 1.60 for ν = 1471 in the 0.5–9 keV range. The best-fit redshifts for the neutral and ionized lines were 0.00392±0.0004 and 0.00371±0.00008, respectively, while the best-fit powerlaw index, Fe abundance, and normalizations were Γ = 2.46 ±0.24, Z_{Fe} = 4.5 ±1.6, A_{cold} = (8.9 ±0.5) × 10^{-2} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, and A_{warm} = (2.8 ± 0.2) × 10^{-4} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, respectively. The powerlaw slope is poorly constrained due to parameter limitations of the pe xm on model.

We also fit the cold reflection with the MY Torus model in two distinct configurations (models M1 and M2 in Table 2). The first (M1) is a standard coupled configuration, wherein the neutral hydrogen column densities N_H, intrinsic powerlaw slopes Γ, inclination angles θ_{inc}, and normalizations of the MYTZ (A_{pow}), MYTS (A_{MYTS}), and MYTL (A_{MYTL}) components are tied and fit together self-consistently to model a uniform torus geometry. The second (M2) is a decoupled configuration which employs two Compton scatterers, one edge-on and one face-on, where the corresponding normalizations for the different angles (e.g., A_{MYTS,90} and A_{MYTS,00}) vary independently but the continuum and line components of a given angle are fixed as in model M1. This corresponds to a patchy torus whereby a portion of the Compton-scattered photons which “reflect” off the facing side of background clouds can bypass clouds which obscure photons along our direct line of sight (more details can be found in [14] and we refer interested readers particularly to their Figure 15).

Fitting model M1 yielded a reduced χ^2 = 1.64 for ν = 1472 in the 0.5–9 keV range. The best-fit redshifts for the neutral and ionized lines were 0.00391±0.0004 and 0.00373±0.00008, respectively, while the best-fit powerlaw index, scattering-to-line component (S/L) ratio, Γ = 1.40_{-0.12}^{+0.11}, S/L ratio = 0.42_{-0.08}^{+0.12}, A_{MYTS,cold} = 7.4_{-1.8}^{+2.9} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, and A_{warm} = (2.63 ± 0.3) × 10^{-4} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, respectively. Meanwhile, model M2 yielded a reduced χ^2 = 1.62 for ν = 1471 in the 0.5–9 keV range, best-fit powerlaw index, scattering-to-line component ratio, and normalizations were Γ = 2.60_{-0.19}^{+0.19}, S/L ratio = 0.67 ± 0.09, A_{MYTS,00} = 0.19_{-0.09}^{+0.09} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, A_{MYTS,90} = 0.09^{+1.74}_{-0.00} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, and A_{warm} = (4.1 ± 0.2) × 10^{-4} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, respectively. As before, the powerlaw slope is not very well-constrained over this particular energy range due to parameter limitations of the MY Torus model.

Finally, we fit the cold reflection with the torus model (model T in Table 2). The best fit yielded a reduced χ^2 = 1.65 for ν = 1472 in the 0.5–9 keV range. The best-fit redshifts for the neutral and ionized lines were 0.00363±0.0004 and 0.00370±0.0009, respectively, while the best-fit powerlaw index, opening angle, and normalizations were Γ = 1.30_{-0.09}^{+0.07}, θ_{open} = 67_{-13}^{+11} deg, A_{cold} = (2.6_{-0.2}^{+0.8}) × 10^{-2} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, and A_{warm} = (3.0 ± 0.2) × 10^{-4} photons keV^{-1} cm^{-2} s^{-1} at 1 keV, respectively. We note that the relatively low Γ value and small errors are largely dictated by the Fe lines, since there is no way to change the Fe line to continuum ratio through a metalllicity parameter for this model.

As can be seen from Figure 6 and Table 3 all of the models are able to fit the 0.5–9 keV nucleus spectra equally well, with only very mild deviations in the residuals between them. In all cases, the residuals are almost exclusively due to low-level line emission (i.e., the strong ratio outliers in the lower pan-
els of Figure 1, most of which is below 2 keV, that remains unaccounted for despite modeling ≥90 emission lines. We found that these residuals bias the relative normalization of the bremsstrahlung component downward by ≈20%, but do not appear to significantly affect the bremsstrahlung temperature nor normalizations of the higher energy components (this holds for all of the cold reflection models). Notably, there are wide variations in the power-law slopes between models, which should be constrained better upon incorporating the >10 keV data. If we limit the fit to the 2–9 keV spectra and fix the bremsstrahlung and tbabs components, the reduced \( \chi^2 \) values drop to ≈1 and the photon indices become significantly harder (\( \Gamma = 1.4–1.5 \)) in all cases, leading to decreased fractional contributions from the cold reflection in the 2–10 keV band. In the case of model M2, the 2–9 keV fit led to a reversal in the dominant cold reflection component from 0° to 90°. These large swings primarily demonstrate that the spectral properties of the cold and warm reflection are poorly constrained by the <10 keV data alone, even when high signal-to-noise and well-resolved emission lines can be fit.

4.2.2. Diffuse Emission and Point Source Contamination From Host Galaxy

Both extended and off-nuclear point source emission are evident in the Chandra images, particularly along the direction of the AGN radio jet and counter jet (see Figure 1). We modeled this emission in the Chandra ACIS-S data with several components to reproduce the main features in the galaxy, noting in particular that there are several key spectral signatures present in the nuclear spectra which are also prevalent in the host spectrum.

First, we include in the host galaxy model an absorbed power law with slope \( \Gamma_{\text{pul}} \) to account for the combined emission from extranuclear point sources, which we constrain separately. A composite Chandra ACIS-S spectrum of all of the point sources together is shown in Figure 1 (green data and model). There are some notable bumps in the soft portion of the spectrum, which could either be intrinsic or more likely are produced by poor background subtraction due to an inhomogeneous extended emission component. As such, we fitted this spectrum only above 1.5 keV with a single cutoff power law model. Unfortunately, the limited 0.5–9.9 keV energy range is not sufficient to unambiguously determine the average spectrum slope, high-energy cutoff, and normalization of the host galaxy point-source population. Following Swartz et al. (2004) and Walton et al. (2011), we assume that NGC 1068 hosts an ultraluminous X-ray source (ULX) population and that emission characteristic of this population likely dominates the point source emission. Recent evidence from NuSTAR (e.g., Bachetti et al. 2013; Rana et al. 2014; Walton et al. 2013, 2014) suggests that ULXs exhibit relatively hard spectra with spectral turnovers between 6–8 keV, and thus we adopt fixed values of \( \Gamma = 1.2 \) and \( E_c = 7 \text{ keV} \) to represent the composite ULX-like spectrum. With these values, the normalization of the power law is \( 8.9 \times 10^{-5} \) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV. This component makes only a relatively small contribution to the overall host contamination in the 1.5–9.0 keV (≈25%) range and quickly becomes negligible above 15 keV. We fixed the normalization of this fit and added this fixed off-nuclear point-source component to the overall host model.

At soft energies, we still see signs of extended RRC and line emission, which we again model as a \( kT_{\text{brems}} = 0.31^{+0.01}_{-0.01} \) keV bremsstrahlung component (\( \text{brems, } A_{\text{brems}} = 0.0168^{+0.0004}_{-0.0003} \) cm\(^{-2}\) s\(^{-1}\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\)) plus a subset of the 20 strongest emission lines found in the nuclear spectra; at the spectral resolution of ACIS-S, these 20 lines were sufficient to model nearly all of the spectral deviations from a smooth continuum. There may also be a contribution from hot gas associated with star formation, but since our main focus is to derive an empirical model to describe the soft emission, we simply absorb this into the normalization for the bremsstrahlung line emission model. The character of the ionized lines differs from those found in the nucleus spectrum, in the sense that lower ionization line species such as S, Si, Mg are stronger in the host spectra relative to the ionized Fe lines, as might be expected for a UV/X-ray radiation field which is radiating from the central SMBH.

At hard energies, we additionally see traces of warm and cold AGN reflection as extended emission, which we model as a scattered power law and Compton-scattered continuum plus neutral lines, respectively. We continue to model the latter with either the pexmon or MYTS+MYTL; we do not fit the torus model, since one cannot explicitly separate out the transmitted component. As before, we will assume that the warm and cold reflection components result from the scattering of the same direct transmitted power law (\( \text{cuttoffpl} \)) with slope \( \Gamma_{\text{inc}} \) and exponential cutoff rollover energy \( E_{\text{fcut}} \), which is absorbed along the line of sight by a Compton-thick absorber (e.g., an edge-on torus). As before, we fixed the quantities \( E_{\text{fcut}} = 500 \text{ keV}, \theta_{\text{inc}} = 90° \) and \( N_H = 10^{23} \text{ cm}^{-2} \), since these are poorly constrained by the <10 keV data alone.

Finally, we note that the absorption toward the counter-jet region is significantly stronger than that toward the jet region, so we initially fix all the components to the jet and counter-jet regions, allowing only for the \( N_H \) of the cold absorber to vary between them. This fit produced \( N_H = 3.1 \times 10^{22} \text{ cm}^{-2} \) toward the jet, consistent with the Galactic column, and \( N_H = 2.4 \times 10^{21} \text{ cm}^{-2} \) toward the counter jet. As such, the 2–75" host region was modeled through a layer of cold Galactic absorption (tbabs) and a cold partial coverer (pcfabs) with \( N_H = 2.4 \times 10^{21} \text{ cm}^{-2} \) and covering fraction of 50%. For all of the models, we list the best-fit parameter values in Table 3 ("Host Only") and show the resulting data-to-model residuals in Figure 1.

Fitting the pexmon (P) version of our host model yielded a reduced \( \chi^2 \) of 1.42 for \( \nu = 163 \) in the 0.5–9 keV range. Given the quality and spectral resolution of the ACIS-S spectrum, we fixed the redshift at 0.00379. The best-fit powerlaw index, Fe abundance, and normalizations were \( \Gamma = 2.49^{+0.25}_{-0.31}, Z_{\text{Fe}} = 43^{+19}_{-19}, A_{\text{cold}} = (2.5^{+0.4}_{-0.5}) \times 10^{-2} \) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV, and \( A_{\text{warm}} = (6.7 \pm 0.2) \times 10^{-4} \) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 1 keV, respectively. It is worth noting here that the abundance value, albeit poorly constrained, is exceptionally high and probably highlights a critical breakdown of the model in this regime rather than an extreme intrinsic value. We also fit the host spectrum with the MYTorus (M1 and M2) versions of our host model. Fitting model M1 produced a reduced \( \chi^2 \) of 1.44 for \( \nu = 163 \) in the 0.5–9 keV range. The best-fit powerlaw index, scattering-to-line component ratio, and normalizations were \( \Gamma = 2.55^{+0.06}_{-0.05}, S/L = 2.46^{+0.39}_{-1.01}, A_{\text{MYTS, cold}} = 1.2^{+0.8}_{-0.7} \) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) at 0.5 keV. The \( \text{torus} \) transmitted component could be made negligible by increasing the column density to \( 10^{26} \text{ cm}^{-2} \), but this would mean we would have to model all clouds as extremely Compton-thick, which is a major limitation.
1 keV, and $A_{\text{warm}} = \left(6.8 \pm 0.2\right) \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, respectively. Meanwhile, model M2 yielded a reduced $\chi^2_r = 1.46$ for $\nu = 162$ in the 0.5–9 keV range, best-fit powerlaw index, scattering-to-line component ratio, and normalizations were $\Gamma = 2.56 \pm 0.05$, S/L ratio of $2.25 \pm 0.65$, $A_{\text{MYTS,00}} = (1.7 \pm 1.1) \times 10^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{MYTS,90}} = 0.00 \pm 0.58$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, and $A_{\text{warm}} = \left(6.7 \pm 0.2\right) \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, respectively. We note that the reflection component from the host emission should be comprised almost exclusively of inclination $0^\circ$ ("far-side, face-on") reflection spectra whose line-of-sight does not intercept any torus material (see further discussion in Yaqoob 2012); thus we can effectively neglect the $90^\circ$ component altogether.

Similar to the nucleus fits, the powerlaw slopes for models P, M1, and M2 were not well-constrained due to parameter limitations of the various models and data bandpass limitations. The bulk of the residuals arise from unaccounted-for line emission below 2 keV. As seen in Table 3, when we fit the models to the $>2$ keV spectrum and fix the bremsstrahlung component, the reduced $\chi^2$ values drop considerably for all models.

4.2.3. Empirical Constraints on Extended Fe Line Emission

An alternative, more empirical approach can be made to understand the contribution from extended cold and warm reflection. For this, we simply measure the line fluxes from the two strongest tracers, the fluorescent Fe K line and the ionized Fe He-like line, respectively. For simplicity, we use the M04a model (although we replace *pexmon* by *pexrav* in order to remove emission lines from the model) to estimate the continuum in both the *Chandra* HETG nuclear and ACIS-S host spectra, and then model the remaining lines with Gaussians as before in §4.1. The line fluxes from the nuclear and host spectra are shown in Table 4 alongside the total line fluxes measured from the pn spectra. Reassuringly, the sum of the nuclear plus host are consistent with the total line fluxes, at least when we factor in statistical errors and cross-calibration differences.

After we account for contributions from the extended wings of the PSF using simulations from the *MarX* ray-trace simulator (v4.5; Wise et al. 1997), we find that the extended Fe K line emission beyond $2''$ (>140 pc) comprises $28 \pm 8\%$ of the total. If the torus size is of order $\sim 4$–10 pc, then we should probably consider the extended fraction above to be a lower limit to the cold reflection contribution from extended (i.e., non-torus) clouds, since there are likely to be contributions from similar material at $\sim 10$–140 pc. Making a similar calculation for the ionized Fe He-like line, we find an extended fraction of $24 \pm 18\%$.

4.2.4. Combined Fit

We now combine the models of the nucleus and host galaxy from the *Chandra* spectra to fit the total spectra from *NuSTAR*, *XMM-Newton*, and *Swift* BAT. As highlighted previously, the emission below $\approx 2$ keV is dominated by the numerous line and bremsstrahlung components, and thus does not provide much constraint on the properties of the reflectors. At the same time it contributes substantially to $\chi^2$, so for the remainder of the modeling we only consider the data above 2 keV. All of the spectral components that are well-constrained by the previous nuclear and host spectral fitting, such as the extranuclear point-source, RRC and line emission, are fixed, as we are primarily concerned with constraining the relative contributions from the warm and cold reflection, as well as any potential direct AGN continuum. For modeling simplicity, we also chose to ignore the regions between 2.3–2.5 keV and 6.5–6.8 keV, which correspond to regions of ionized Si and Fe line emission, respectively; these regions always have considerable residuals which are not modeled by the continuum reflection components but bias the component normalizations during the fitting process. We assume below that all of the components share a single intrinsic powerlaw slope and that any transmitted component, if present, must arise only from the nuclear portion of the spectrum. For selected relevant models below, we list the best-fit parameter values in Table 3 ("Total") and/or plot their residuals in Figures 8–11.

**Model P** — We begin by fitting model P to the combined 2–195 keV spectra of NGC 1068. We fit $\Gamma$ and $Z_{\text{Fe}}$, as well as...
the normalizations $A_{\text{cold, nuc}}$, $A_{\text{cold, host}}$, $A_{\text{warm, nuc}}$ and $A_{\text{warm, host}}$ as free parameters, while we fix $\theta_{\text{inc}} = 85^\circ$, $E_c = 500$ keV and $N_H = 10^{25}$ cm$^{-2}$. This model, hereafter “Pa”, yielded a poor fit, with a reduced $\chi^2 = 1.34$ for $\nu = 1666$. The Pa model residuals, which are shown in Figure 8, highlight a general problem with fitting the spectral shape above 8 keV that we encountered with many of the adopted models, namely that the models either fit the spatially resolved < 10 keV data well but present clear > 10 keV residuals, or vice versa. Allowing the cutoff energy to vary failed to yield any improvement in $\chi^2$, with a best-fit value of $E_c = 500_{-17}^{+76}$ keV, hereafter model “Pb”. Alternatively, allowing the inclination angle to also vary to $\theta_{\text{inc}} = 24_{-7}^{+7}$ deg, hereafter model “Pb”, significantly improved the fit, with a new reduced $\chi^2 = 1.28$. We note that this inclination angle suggests a face-on configuration, perhaps indicative of scattering off of the back wall of a fiducial torus, while the best-fit photon index ($\Gamma = 1.65 \pm 0.02$) is somewhat lower than one would expect for such a high accretion rate source like NGC 1068 (e.g., $\Gamma = 2.5$ [Fanali et al. 2013]). Critically, although the high-energy residuals have improved, significant deviations of the form shown in Figure 8 from the observed continuum shape still remain. Again, varying the cutoff energy to $E_c = 387_{-13}^{+17}$ keV fails to yield any substantial improvement in $\chi^2$.

Model M1 — We now turn to the cold reflection as modeled by MYTorus. As before, we initially adopt a “standard” fully coupled, uniform torus geometry, hereafter “M1a”. While there is no physical reason for the nuclear and extended components to be the same, we begin with such a scenario because it represents how previous studies would model the entire XMM-Newton or NuSTAR spectrum. For the M1a model, we fit $\Gamma = 1.40^{+0.09}_{-0.05}$ and the component normalizations, and fix the other parameters to $N_H = 10^{23}$ cm$^{-2}$, $\theta_{\text{inc}} = 90^\circ$, $E_{\text{cut}} = 500$ keV, and the S/L ratio to 1. Aside from allowing the reflection component normalizations to vary, the properties of the nucleus and host reflectors were tied together. The resulting fit was poor, with $\chi^2 = 3.78$ for $\nu = 1666$, and large residuals around both the neutral Fe Kα line and to a lesser extent the Compton hump. Moreover, the powerlaw slope is quite flat. From the residuals, it is clear that a S/L ratio of 1 is insufficient, and allowing the S/L ratio to vary to $26_{-14.2}^{+14.2}$, hereafter “M1b”, substantially improved the fit with $\chi^2 = 1.78$. Such a S/L ratio is unreasonably high, however, and implies
that the adopted values for some of the fixed parameters are likely wrong. Varying $E_{\text{cut}}$ to 55.7 keV (“M1c”) lowered the S/L ratio to 15.0$^{+12.2}_{-12.9}$ and resulted in $\chi^2_f = 1.61$. Finally, further varying the inclination angle and column density improves the fit to $\chi^2_f = 1.31$, with $\Gamma = 1.40^{+0.12}_{-0.12}$, $N_{\text{H,host}} = (9.4^{+3.3}_{-3.3}) \times 10^{24}$ cm$^{-2}$, $\theta_{\text{inc}} = 78^{+3}_{-3}$, $E_{\text{cut}} = 41^{+5}_{-5}$ keV, and an $S/L_{\text{nuc-host}}$ ratio of 3.8$^{+0.5}_{-0.6}$ (“M1d”). This last model fits the >10 keV continuum significantly better, but at the expense of producing residuals in the <10 keV continuum (see Figure 9) while retaining a flat power-law slope. Ultimately, we conclude that none of the coupled MYTorus models provides a reasonable fit to the continuum shape. It is important to point out that if we had only modeled either the <10 keV spectra or the total aperture spectra, we would have arrived at a satisfactory $\chi^2_f$.

As an alternative to the fully coupled models, we tried fitting separate MYTS+MYTL parameters for the nucleus and the host spectra, as might be expected for the combination of a thick torus and more tenuously distributed larger scale molecular clouds, which has been found from mid-IR constraints on NGC 1068. We began by fitting a single photon index $\Gamma = 1.80^{+0.05}_{-0.05}$, the various component normalizations, and independent column densities $N_{\text{H,nuc}} = (9.8^{+2.7}_{-2.7}) \times 10^{24}$ cm$^{-2}$ and $N_{\text{H,host}} = (2.4^{+0.3}_{-0.3}) \times 10^{23}$ cm$^{-2}$ and S/L ratios 12.2$^{+1.8}_{-1.9}$ and 0.5$^{+0.5}_{-0.5}$ for the nucleus and host components, respectively, while fixing $\theta_{\text{inc}} = 90^\circ$ and $E_{\text{cut}} = 500$ keV (“M1e”). This fit produced a reduced $\chi^2_f = 1.54$ for $\nu = 1663$. Allowing $E_{\text{cut}}$ to 33$^{+3}_{-3}$ keV improved the fit to $\chi^2_f = 1.30$, with modest changes to the other free parameters such that the $\Gamma$ remained pinned at its minimum while $N_{\text{H,nuc}} = (5.3^{+0.4}_{-0.4}) \times 10^{24}$ cm$^{-2}$, $N_{\text{H,host}} = (0.09 \pm 0.03) \times 10^{24}$ cm$^{-2}$, $S/L_{\text{nuc}} = 10^{1.8^{+0.3}_{-0.8}}$ and $\theta_{\text{inc}} = 1.0^{+0.5}_{-0.5}$ (“M1f”). Finally, allowing the inclination angles to vary (“M1g”) only marginally improves the fit to $\chi^2_f = 1.28$, with free parameters $\Gamma = 1.40^{+0.34}_{-0.34}$, $E_{\text{cut}} = 34^{+28}_{-28}$ keV, $N_{\text{H,nuc}} = (8.0^{+1.6}_{-1.6}) \times 10^{24}$ cm$^{-2}$, $N_{\text{H,host}} = (1.3^{+1.3}_{-1.3}) \times 10^{24}$ cm$^{-2}$, $S/L_{\text{nuc}} = 3.5^{+8.8}_{-0.5}$ and $S/L_{\text{host}} = 1.5 \pm 0.3$.

We note that freeing the column density and normalization toward the transmitted component (“M1h”) to $N_{\text{H,trans}} = (6.0^{+1.3}_{-0.8}) \times 10^{24}$ cm$^{-2}$ results in a reduced $\chi^2_f = 1.13$, with best-fit values of $\Gamma = 2.29^{+0.07}_{-0.07}$, $E_{\text{cut}} = 72^{+21}_{-21}$ keV, $N_{\text{H,nuc}} = (2.6^{+0.5}_{-0.5}) \times 10^{23}$ cm$^{-2}$ and $N_{\text{H,host}} = 10^{2.5} \text{cm}^{-2}$ (unconstrained), $S/L_{\text{nuc}} = 1.0^{+0.3}_{-0.3}$ and $S/L_{\text{host}} = 2.0^{+0.6}_{-0.6}$ and inclination angles of 0.7$^{+4.5}_{-0.5}$ deg and 1.9$^{+10.5}_{-0.5}$ deg for the nucleus and host components, respectively. This model is the best version of the “standard” MYTorus configuration and crudely models the key continuum and line features, but ultimately predicts that NGC 1068 should be dominated by the transmitted component above 20 keV. The normalizations of the various continuum components are $A_{\text{trans}} = 2.6^{+1.3}_{-1.2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{warm,nuc}} = (3.0^{+1.3}_{-1.3}) \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{cold,nuc}} = (4.0^{+0.3}_{-0.3}) \times 10^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{warm,host}} = (3.9^{+1.4}_{-1.4}) \times 10^{-3}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, respectively, implying a covering fractions of $\sim 0.008$ and $\sim 0.002$ for the nucleus and host cold reflection components. Such low covering fractions run contrary to the variability constraints presented in [2.1] and [6.6]. As such, the good fit appears to be a consequence of allowing freedom for several spectral components to fit small portions of the overall spectrum, and is presumably degenerate in this sense.

We conclude that the “standard” configuration of MYTorus has considerable difficulty reproducing the main spectral and temporal X-ray characteristics of NGC 1068.

**Model M2** — We now turn to the second MYTorus configuration, which employs two MYTorus Compton scatterers fixed at 0$^\circ$ and 90$^\circ$, representing a potential clumpy torus-like distribution. Following the discussion in §2.2 we only invoke the 0$^\circ$ component to fit the host spectrum. We began by fitting a basic form of this model, hereafter “M2a”, with varying $\Gamma = 2.29^{+0.02}_{-0.02}$ and component normalizations with the remaining parameters fixed to $N_{\text{H}} = 10^{23}$ cm$^{-2}$, $S/L_{\text{nuc-host}} = 1.0$, and $E_{\text{cut}} = 500$ keV for all scattering components. The best fit returns a $\chi^2_f = 1.84$ for $\nu = 1666$, which is a significant improvement over model M1a. However, the continuum is still not well-fit and the best-fit $A_{\text{nuc,MYTS,90}}$ normalization is consistent with zero ($\sim 1\%$ of cold reflector flux). Fitting the $S/L_{\text{nuc-host}}$ ratio to 4.3$^{+3.4}_{-3.3}$ (“M2b”) reduces $\chi^2_f = 1.51$, and yields $\Gamma = 1.49 \pm 0.04$ plus moderate variations in the component normalizations. M2b offers a significant improvement
over model M1b. Additionally varying $E_{\text{cut}} = 146^{+25}_{-50}$ keV ("M2c"), provides only very marginal improvement ($\chi^2 = 1.48$) and leaves the parameters largely unmodified. Finally, varying the three column densities ("M2d") improves the fit to $\chi^2 = 1.14$, with $\Gamma = 2.10^{+0.06}_{-0.07}$, a S/L$_{\text{nuc-host}}$ ratio of $1.0 \pm 0.1$, $E_{\text{cut}} = 128^{+14}_{-44}$ keV $N_{\text{H,nuc,90}} = (10.0^{+4.4}_{-4.4}) \times 10^{24}$ cm$^{-2}$, $N_{\text{H,nuc,0}} = (1.5 \pm 0.1) \times 10^{23}$ cm$^{-2}$, $N_{\text{H,host,0}} = (5.0^{+1.9}_{-1.9}) \times 10^{23}$ cm$^{-2}$, and normalizations of $A_{\text{warm,nuc}} = (2.5^{+0.3}_{-0.4}) \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{cold,nuc,90}} = (3.0 \pm 0.5) \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{cold,nuc,0}} = (3.6^{+0.3}_{-0.3}) \times 10^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{warm,host}} = (3.4^{+0.4}_{-0.4}) \times 10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV, $A_{\text{cold,host,0}} = (1.0 \pm 0.2) \times 10^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV. Freezing the high-energy cutoff at $E_{\text{cut}} = 500$ keV ("M2e") leaves the above parameters virtually unchanged and $\chi^2 = 1.16$.

As can be seen in Figure 10, the data-to-model ratio residuals are now fairly flat out to $\approx 80$ keV. The primary difference between model M2d (or M2e) and all of the others lies in how the nuclear $\theta_{\text{inc}} = 0^\circ$ cold reflector component, due to its significantly lower $N_{\text{H}}$, is able to fill in the spectral gap around 4–8 keV between the “normal” cold and warm reflectors. One important aspect of this model which deserves highlighting is the fact that while the higher $N_{\text{H}}$ component provides the bulk of the flux to the Compton hump, it does not contribute much to the Fe fluorescence line emission. Instead, the lower $N_{\text{H}}$ component produces the bulk of the Fe fluorescence line emission and dominates the continuum peaking around 5–10 keV. Thus the two key features of Compton reflection, namely the hump and Fe line, need not arise from a single absorber and in fact likely arise from different obscuring clouds. Assuming a single absorber will likely lead to misinterpretations.

**Model T** — Finally, we fit the cold reflection model with the torus model. As noted in [4,2], this model is not suitable for fitting the host spectrum, so we instead modeled the host spectrum identically to the M2 case using MYTS+MYTL components with an inclination angle of $\theta_{\text{inc}} = 0^\circ$. Varying $\Gamma = 1.96^{+0.04}_{-0.04}$, $\theta_{\text{inc}} = 64^{+3}_{-3}$ deg, and component normalizations, with fixed values of $N_{\text{H}} = 10^{25}$ cm$^{-2}$, $\theta_{\text{inc}} = 87^\circ$, $E_{\text{cut}} = 500$ keV, and a S/L$_{\text{host}}$ ratio of 1.0, yielded a reduced $\chi^2 = 1.61$ for $\nu = 1666$ ("Ta"). This provides a relatively poor fit, with residuals near the Fe lines and >10 keV continuum (Figure 11). Freeing the torus inclination angle to $\theta_{\text{inc}} = 87^{−16}_{−16}$ ("Tb") does not improve the fit. Further varying the nuclear and host column densities to $N_{\text{H,nuc}} = (6.9^{+0.6}_{-0.6}) \times 10^{23}$ cm$^{-2}$, $N_{\text{H,host,0}} = (10.0^{+6.6}_{-6.6}) \times 10^{24}$ cm$^{-2}$ ("Tc") leads to a modest improvement $\chi^2 = 1.57$, with $\Gamma = 2.13^{+0.04}_{-0.06}$, $\theta_{\text{open}} = 69^{+3}_{-3}$ deg, and $\theta_{\text{incl}} = 87^{−12}_{−12}$ deg. As with other models, there are significant residuals as the model fails to fit the continuum shape well. In all cases, the host cold reflection normalization is consistent with zero. It seems that the torus model does not provide enough flexibility to model the transmission and scattered components separately and again we conclude that the torus model has considerable difficulty reproducing the main spectral X-ray characteristics of NGC 1068.

**4.2.5. Model Summary**

We tested a variety of cold reflection models earlier in this section. As has been traditionally done in the past, we modeled NGC 1068 with a single monolithic cold reflector using pexmon (models Pa–Pc), MYTorus (models M1a–M1d), and torus (models Ta–Tc). Alternatively, we also modeled NGC 1068 with multiple reflectors using two or three MYTorus components to fit the two spatially distinct nuclear and host regions (models M1e–M1h) and additional complexity in the nuclear spectrum (models M2a–M2d). We found
that many models are able to fit either the spatially resolved $< 10 \text{ keV}$ spectra or the total aperture spectra well, but generally not both.

The two models which do manage to fit all of the spectra well are M1h and M2d. In both cases, a cold reflection component with $N_H \sim 10^{23} \text{ cm}^{-2}$ peaking at $5–10 \text{ keV}$ is required to fill in a critical gap in the model where the declining warm reflector and the increasing cold reflector meet. Model M1h is rejected, however, because it requires a strong transmitted component, which runs contrary to our variability results (§3), leaving only M2d as our preferred model.

When modeling M2d, we find a best-fit power-law slope of $\Gamma = 2.10^{+0.06}_{-0.04}$, which is marginally higher than the average AGN value of $\Gamma \sim 1.9$ (e.g., Reeves & Turner 2000). Notably, high $\Gamma$ values are often associated with high Eddington ratio systems (e.g., Shemmer et al. 2006; Risaliti et al. 2009; Brightman et al. 2013), and thus the slope here is consistent with our initial accretion rate assessment in §1. The high-energy cutoff value for this model, $E_{\text{cut}} = 128^{+33}_{-44}$ keV is perhaps somewhat low. This could imply low coronal temperatures, although the error bars indicate this value is not well constrained. With this model, we derive total observed X-ray luminosities of $L_{\text{2-10 keV}} \text{obs} = 1.8 \times 10^{41} \text{ erg s}^{-1}$ and $L_{\text{10–40 keV}} \text{obs} = 5.6 \times 10^{41} \text{ erg s}^{-1}$, and intrinsic X-ray luminosities of $L_{\text{2–10 keV}} \text{intrinsic} = 2.2 \times 10^{43} \text{ erg s}^{-1}$ and $L_{\text{10–40 keV}} \text{intrinsic} = 1.5 \times 10^{43} \text{ erg s}^{-1}$, respectively. This intrinsic $L_{\text{2–10 keV}}$ value is only a factor of $\approx 1.6$ lower than that predicted by mid-IR to X-ray relation of Gandhi et al. (2009), despite the obvious spectral complexity that we find.

We stress that the scattered emission from NGC 1068 is clearly complex and thus the models attempted were by no means exhaustive. Alternative complex component combinations likely exist which can fit the obvious Compton hump and Fe fluorescence line as well as strike a balance in the overall reflection continuum levels. Nonetheless, we can conclude that simple configurations such as a single nuclear reflector or a patchy torus fail to match the data, and an additional lower column density component is needed.

5. DISCUSSION

From the combined modeling performed in the previous section, there are a few points worth stressing.

The quality of the NuSTAR data plays an important role in constraining the fits. With poorer quality data, such as that from Suzaku, BeppoSAX, or Swift BAT shown in Figure 2, several of the models we considered produce acceptable fits. Only with the NuSTAR data can we observe in detail the nature of the rising Compton hump and broad peak, which is difficult to fit with a single cold reflection model. Likewise, fitting the Chandra nuclear and host spectra separately, we find that the combination of good-quality nuclear and host spectra creates considerable tension for several models which would otherwise fit the total XMM-Newton and NuSTAR spectra at acceptable levels. This study demonstrates that it can be important to have both high-quality spectra above 10 keV and spatially resolved X-ray spectra in order to, e.g., reject simple monolithic cold reflection models. The recent analysis of the Circinus Galaxy by Arévalo et al. (2014) also benefited from the powerful combination of high-quality NuSTAR data and spatial separation of the nuclear and host components, demonstrating that there too a significant fraction of the warm and cold reflection components arise from well beyond 2″ (i.e., 38 pc at the distance of Circinus).

These two objects are among the closest and X-ray brightest Compton-thick AGN on the sky, and benefit from a wealth of high-quality X-ray data. Unfortunately, there are only a handful of nearby Compton-thick AGN where a similar analysis can be made, but it will be interesting to see how diverse parameter space might be with respect to this multiple cold reflector model. For fainter and more distant obscured X-ray AGN, however, we can only obtain modest- to poor-quality NuSTAR data. Moreover, with the angular resolution of currently available instruments, we will be unable to separate the 2–8 keV nuclear emission from its host. So while it may be possible to model the total emission from such AGN in reasonable detail and with acceptable results (e.g., Balokovic et al. 2014; Gandhi et al. 2014; Lansbury et al. 2014; Del Moro et al. 2014; Brightman et al. 2015 in prep), it will not be possible to investigate the detailed physical properties of such sources, as for NGC 1068 and Circinus (Arévalo et al. 2014). The work here and in Circinus highlight the potential issues of modeling a total spectrum from, e.g., XMM-Newton or NuSTAR with a monolithic model of the obscurer. For the multiple cold reflector model shown in Figure 19, different portions of the total reflection spectrum seen by NuSTAR and XMM-Newton appear to arise from different obscuring clouds, decoupling the two key features of cold reflection. The fact that cold reflectors occur on a variety of physical scales or with a variety of column densities is unlikely to change the basic requirement for a high column density associated with a mildly or heavily Compton-thick AGN. However, it is possible for this variety to change interpretations regarding the relative Fe abundance, inclination angle, covering factor for a given column density, and high-energy cutoff; we observed several of these to vary significantly from model to model in Figure 19.

Although unobscured AGN are dominated by the transmitted power-law, the Fe line and Compton hump do imprint themselves as secondary contributions. To test how our preferred model of NGC 1068 might affect the fitting of unobscured AGN, we inverted the inclination angles of the MYTorus components by 90° and added a relativistically blurred ionized disk reflection component (relconv * xillver; Dauser et al. 2013; García et al. 2014). We linked the disk reflection parameters to previously determined values (e.g., $\Gamma$, $E_{\text{cut}}$, $\theta_{\text{in}}, Z_{\text{Fe}}$), or fixed them to their default values. We normalized the disk reflection relative to the other components such that it provides the same contribution at 30 keV as the combined cold reflection components. In this configuration, the relative total reflection flux is high, comprising $\approx 30\%$ of the total at 30 keV, yet the narrow observed Fe Kα equivalent width (EW) is only 40 eV; the latter value is toward the low end of EW measurements made for Seyfert 1s (e.g., Yaqoob & Padmanabhan 2004), and implies that the narrow Fe Kα EW may not be a useful estimator for the relative strength of the cold reflection component, as is sometimes assumed, and even low EW Fe lines may signify important scattered-light contributions at higher energies.

We then varied the exponential cutoff energy for our unobscured version of NGC 1068 between three values (100, 300, and 500 keV). We simulated a 50 ks NuSTAR spectrum, resulting in $\approx 10^6$ 3–79 keV photons, and fit this with a model typical of those used in unobscured AGN studies (i.e., where the transmitted, disk reflection, and cold reflection are modeled as

39 This does not include contributions from scattered components or contamination.
Multiple Reflections in NGC 1068

(cutoffpl+relcov*xillver+pexrav+zgauss, respectively, absorbed by a low column density tbabsSgal). We allowed $\Gamma$, $E_{\text{cut}}$, $Z_{\text{Fe}}$, and the component normalizations to vary, and fixed the remaining parameters at typical values (e.g., $X = 3.1$, $Z_{\text{Fe}} = 3$, $a = 0.9$, $\cos \theta_{\text{pexrav}} = 0.3$, $\theta_{\text{xillver}} = 20^\circ$). In all cases, we obtained reasonable fits with $\chi_r \approx 1.0$–1.1 and found that the powerlaw slope was consistent with its input value. For input $E_{\text{cut}}$ values of 100, 300, and 500 keV, we obtained best-fit values of $312^{+32}_{-33}$, $227^{+32}_{-37}$, $302^{+39}_{-35}$ keV, respectively, and $Z_{\text{Fe}} = (0.7–0.8) \pm 0.1$. We ran another simulation, naively assuming the M2d reflection components were globally the same, which yielded similar results for the cutoff energies. Such toy models are admittedly far from conclusive due to the likely large number of permutations of possible spectral shapes of components and degeneracies among various parameters, not to mention the manner in which we implemented the high-energy cutoff for MYTorus. Nonetheless, they do highlight how errors on some quantities such as the high-energy cutoff could be underestimated even in unobscured AGN and can strongly depend on what model assumptions are adopted.

The best-fit model for the composite X-ray dataset, M2d, could be visualized as follows. In the inner $2''$ (140 pc) region, we see a $\theta_{\text{inc}} = 90^\circ$ (fixed), $N_{\text{H}} \approx 10^{23}$ cm$^{-2}$ reflector with a covering factor of 0.5 (fixed), which to first order is presumably associated with a standard, compact, torus-like structure. Additionally, we find a $\theta_{\text{inc}} = 0^\circ$ (fixed), $N_{\text{H}} \approx 10^{23}$ cm$^{-2}$ reflector with an estimated covering factor of 0.13, based on the relative component normalizations, which appears to act as a screen. This less dense component could be more or less co-spatial with the dense torus or it could be material in the ionization cone. In both cases, we might expect a stratification of dense material stemming from instabilities associated with the photoionization of the dense molecular gas by AGN radiation field structures (e.g., akin to the structures at the boundaries between HII regions and molecular clouds; e.g., Pounds 1998). Or alternatively, it could simply be reflection from larger-scale interstellar clouds aggregating within the inner $\approx 100$ pc (e.g., Molnari et al 2011). In all cases, we should expect a range of clouds which follow a log-normal column density distribution (e.g., Lada et al 1999; Goodman et al 2009; Lombardi et al 2010; Tremblin et al 2014). This should in turn introduce considerable complexity into the AGN reflection components. We appear to be seeing the first hints of this anticipated complexity in NGC 1068. We note that this less dense reflection component produces the bulk of the Fe Kα line emission and, moreover, we see no strong long-term variability from the $<10$ keV continuum or line flux. Thus we conclude that this second reflection component likely arises light years from the central AGN and/or is distributed enough to wash out any variability.

We note that at a basic level, the above multi-component reflector configuration found in the nuclear region appears reasonably consistent with the picture stemming from mid-IR interferometry for NGC 1068 (e.g., Jaffe et al 2004; López-Gonzaga et al 2014), whereby a three-component model, comprised of a small obscuring torus and two dusty structures at larger scales (at least $5$–10 pc), best fits the data. The larger scale dust is off-center and could represent the inner wall of a dusty cone (e.g., the ionization cone). Based on the compactness and detailed modeling of spectral energy distributions in various AGN, these structures are believed to be clumpy and comprised of a range of torus clouds with column densities of $N_{\text{H}} \sim 10^{22}–10^{23}$ cm$^{-2}$ (e.g., Elitzur & Shlosman 2006; Nenkova et al 2008; Ramos Almeida et al 2009).

On more extended ($>2''$) scales, we find an additional $\theta_{\text{inc}} = 0^\circ$ (fixed), $N_{\text{H}} \approx (4–10) \times 10^{23}$ cm$^{-2}$ reflector with a covering factor of 0.03. The inclination angle, if left free, is not strongly constrained, and thus it is not clear whether this component is a screen, a mirror, or perhaps both. This material could be associated with clumpy molecular clouds either within the ionization cone or the general interstellar cloud population in the host galaxy. Intriguingly, our separation of nuclear and host spectra was purely based on instrumental reasons, and thus, if the distribution of clouds is strongly centralized and goes roughly as $1/r$ or $1/r^2$ (e.g., Bally et al 1988; Nenkova et al 2008), then we might expect at least a fraction of the Fe Kα line flux currently assigned to the $N_{\text{H}} \approx 10^{23}$ cm$^{-2}$ torus-like nuclear reflection component to in fact arise from reflection by extended material. This suggests that a non-negligible portion of the overall reflection component in NGC 1068 arises outside of the torus. As we find in E2.3, the empirical fraction of extended Fe Kα flux is substantially higher ($\approx 30\%$) than the estimate of the overall reflection, suggesting that perhaps there are multiple $N_{\text{H}}$ components responsible for the extended emission as well. Based on the same molecular cloud distribution argument as above, it may be possible for the majority of the narrow Fe Kα emission to originate from radii well beyond the classic torus.

6. CONCLUSIONS

We have characterized the X-ray spectra of the archetypal Compton-thick AGN, NGC 1068, using newly acquired NuSTAR data, combined with archival data from Chandra, XMM-Newton, and Swift BAT. We modeled NGC 1068 with a combination of a heavily obscured transmitted power law, scattering by both warm and cold reflectors, radiative recombination continuum and line emission, and off-nuclear point source emission, employing a handful of cold reflector models. Our primary results can be summarized as follows:

- The $>10$ keV NuSTAR data are consistent with past measurements to within cross-calibration uncertainties, but provide at least an order of magnitude more sensitivity, allowing us to constrain the high-energy spectral shape of NGC 1068 in better detail than ever before. We find no strong evidence for short- or long-term variability, consistent with the primary transmitted continuum being completely obscured from our line-of-sight.

- We use Chandra ACIS-S and HETG data to split the reflection-dominated spectrum of NGC 1068 into two spatial regimes representing the nuclear ($<2''$) and host ($2–75''$) contributions to the total spectrum measured by NuSTAR, XMM-Newton, and Swift BAT. Because reflection arises from the two distinct spatial regimes, modeling both components together allow us to break previously unexplored degeneracies to aid physical interpretation.

- Modeling NGC 1068 as a monolithic cold reflector with a single column density $N_{\text{H}}$ generally fails to reproduce some critical portion of the combined spectra accurately and/or yields parameters which are difficult to reconcile with robust independent observations, regardless of the Compton-reflection model used.

- Modeling NGC 1068 using a multi-component reflector (here as best-fit model M2d with two nuclear and one...
extended MYTorus components with best-fit values of $\Gamma \approx 2.1$, $E_{\text{cut}} \gtrsim 90$ keV, $N_H \approx 10^{25}$ cm$^{-2}$, and $N_H \approx 1.5 \times 10^{23}$ cm$^{-2}$, respectively, was able to reproduce all of the primary spectral lines and continuum shape around the Compton hump. In this best-fit multi-component reflector model, the higher $N_H$ components contributed flux primarily to the Compton hump above 10 keV while the lower $N_H$ nuclear reflector is needed to reproduce the curvature of the continuum around 10 keV and it also provides the missing Fe line flux to model the whole structure with solar (as opposed to highly supersolar) metallicity. Thus, this configuration effectively decouples the two key features of Compton reflection which are typically assumed to be coupled.

- There are strong differences in the ratios of the 2–10 keV fluxes of the warm and cold reflection components, depending on the model employed and the parameters being fit. Because of the decoupling mentioned above, it could be dangerous to extrapolate the full properties of the reflector using simple reflection models, as has typically been done in the past with either lower-quality data or in type 1 AGNs diluted by transmitted continuum. We note that this decoupling could be at least partially responsible for some of the apparently high Fe abundances which have been quoted in the literature (e.g., M04).

- Considering only the Chandra data, we find that $\approx 30\%$ of the neutral Fe Kα line flux arises from nuclei ($\approx 140$ pc) in an extended configuration. Extrapolating this fraction inward assuming an increasing solid angle of dense molecular clouds implies that a significant fraction (and perhaps the majority) of the Fe Kα line fluxes arise from Compton-scattering off of material well outside of the fiducial 1–10 pc torus material. A follow-up investigation looking into the spatial distribution of this material around several local AGN will be presented in Bauer et al. (2015, in preparation).

- The multi-component reflector configuration envisioned here comprises a compact Compton-thick torus-like structure covering 50% of the sky and more tenuous, extended $N_H \approx 10^{23}$ cm$^{-2}$ clouds covering $\approx 13\%$ of the sky within the nuclear region (3$\sigma$ pc), as well as larger-scale, low-covering factor Compton-thick clouds which extend out to 100s of pc. This scenario bears striking similarities to the multiple dust structures found via mid-IR interferometry for NGC 1068, and may eventually allow some independent corroboration of the clumpy torus model.

The benefits of combining high-quality >10 keV spectral sensitivity from NuSTAR and spatially resolved spectroscopy from Chandra are clear, and could offer novel constraints on the few dozen closest, brightest AGN on the sky. Moving on to fainter and more distant objects, however, is likely to be challenging with current instrumentation due to the extremely long integrations required and the increasingly poor intrinsic spatial resolutions obtained. Moreover, we should caution that our best-fit multi-component reflector, which we modeled only with three distinct column densities, could be an oversimplification, and in fact there might be a continuous distribution of different column-density reflectors, given that the Galactic molecular cloud probability distribution function is well represented by a power law over a wide range of column densities (e.g., Lada et al. 1999; Goodman et al. 2009; Lombardi et al. 2010). Each cloud might contribute something to the overall reflection spectrum, thereby modifying the spectral shape away from that of a single monolithic reflector. Hopefully by acquiring similar constraints in other nearby Compton-thick AGN to those found for NGC 1068 and Circinus, combined with an assessment of the parameter space for obscuring clouds from mid-IR interferometry studies, we can amass enough clues in the short term to model distant and/or faint objects in a more informed manner. Ultimately, if the Athena mission (Nandra et al. 2013; Nandra 2014) can achieve its best-case scenario for spatial resolution of a few arcseconds, it could open up spatially resolved Fe analysis to a significantly larger range of AGN and help us to place these local AGN in broader context.

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**Facilities:** CXO (ACIS, HETG), XMM (pn, MOS), NuSTAR (FPMA, FPMB), Swift (XRT, BAT), BeppoSAX (MECS, PDS), Suzaku (XIS, PIN).

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