Compton-thick AGN in the \textit{NuSTAR} Era. IV. A Deep \textit{NuSTAR} and \textit{XMM-Newton} View of the Candidate Compton-thick AGN in ESO 116-G018

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Received 2018 November 8; revised 2018 December 5; accepted 2018 December 10; published 2019 January 30

Abstract

We present a 2–78 keV spectral analysis of the deep \textit{NuSTAR} and \textit{XMM-Newton} observation of a nearby Seyfert 2 galaxy, ESO 116-G018, which is selected as a candidate Compton-thick (CT) active galactic nucleus (AGN) based on a previous \textit{Chandra–Swift–BAT} study. Through our analysis, the source is, for the first time, confirmed to be a CT AGN at a $>3\sigma$ confidence level, with the “line-of-sight” column density $N_{\text{H,LS}} = [2.46–2.76] \times 10^{24} \text{ cm}^{-2}$. The “global average” column density of the obscuring torus is $N_{\text{H,T}} = [0.46–0.62] \times 10^{24} \text{ cm}^{-2}$, which suggests a clumpy, rather than uniform, distribution of the obscuring material surrounding the accreting supermassive black hole. The excellent-quality data given by the combined \textit{NuSTAR} and \textit{XMM-Newton} observations enable us to produce a strong constraint on the covering factor of the torus of ESO 116-G018, which is found to be $f_c = [0.13–0.15]$. We also estimate the bolometric luminosity from the broadband X-ray spectrum to be $L_{\text{bol}} = [2.57–3.41] \times 10^{44} \text{ erg s}^{-1}$.

Key words: galaxies: active – galaxies: individual (ESO 116-G018) – galaxies: nuclei – X-rays: galaxies

1. Introduction

The intrinsic emission from an accreting supermassive black hole (SMBH), i.e., the center of active galactic nuclei (AGNs), is commonly believed to be at least partly obscured by the circumnuclear matter. AGNs are classified as Compton-thick (CT) AGNs when the column density of the obscured matter is $N_H \geq \sigma_T^{-1} \sim 10^{24} \text{ cm}^{-2}$, where $\sigma_T$ is the Thomson cross section. Knowing the distribution of the absorbing column density is not only important to understand the physics of the accreting SMBHs, but is also essential to properly model the cosmic X-ray background (CXB), i.e., the diffused X-ray emission observed between 0.5 and 300 keV, which is believed to be mainly produced by both obscured and unobscured AGNs. While most of the CXB emission below 10 keV has been resolved thanks to \textit{Chandra} and \textit{XMM-Newton} (see, e.g., Worsley et al. 2005; Hickox & Markovitch 2006), only $\sim 35\%$ of the CXB emission at its peak ($\sim 30$ keV, Ajello et al. 2008) has been resolved, mostly by different \textit{NuSTAR} surveys (Aird et al. 2015; Harrison et al. 2016). In this energy range, CT AGNs are expected to be numerous (up to 50\% of the overall population of Seyfert 2 galaxies, see, e.g., Risaliti et al. 1999). Different CXB synthesis models predict that the fraction of CT AGNs should be $\sim 20\%$–$30\%$ (Alexander et al. 2003; Gandhi & Fabian 2003; Gilli et al. 2007; Treister et al. 2009; Ueda et al. 2014). However, as of today CT AGNs have never been detected in large numbers, e.g., their observed fraction in the local universe is $\sim 5\%$–$10\%$ (see, e.g., Burlon et al. 2011; Ricci et al. 2015) in X-ray and is $\sim 12\%$ when performing a multi-wavelength search (Goulding et al. 2011).

Due to the heavy obscuration, CT AGNs are difficult to detect below $\sim 10$ keV in the local universe (see, e.g., Gilli et al. 2007; Koss et al. 2016), since the overall X-ray emission in these objects is suppressed below 10 keV and is dominated by the Compton hump at $\sim 20$–40 keV. CT AGNs at redshift $z > 1$ can instead be well studied using one of the several facilities sampling the $\sim 0.3$–10 keV energy range, such as \textit{Swift-XRT}, \textit{Chandra}, \textit{XMM-Newton}, and \textit{Suzaku} (see, e.g., Georgantopoulos et al. 2013; Buchner et al. 2015; Lanzuisi et al. 2015): the Compton hump of high-$z$ sources is redshifted in the energy range covered by these instruments. However, for sources in the local universe ($z < 0.1$), the proper characterization of heavily obscured AGNs requires an X-ray telescope sensitive above 10 keV. Thanks to the launch of \textit{Nuclear Spectroscopic Telescope Array} (hereafter, \textit{NuSTAR}, Harrison et al. 2013), which provides a two orders of magnitude better sensitivity than previous telescopes (e.g., \textit{INTEGRAL} and \textit{Swift-BAT}; Winkler et al. 2003; Barthelmy et al. 2005) at $\sim 10$–50 keV, one can study the physical and geometrical properties of heavily obscured AGNs with unprecedented accuracy (see, e.g., Baloković et al. 2014; Puccetti et al. 2014; Annuar et al. 2015; Marchesi et al. 2017b, 2018; Ursini et al. 2018). To properly constrain both the torus column density and the AGN photon index in heavily obscured sources, however, one needs to combine the excellent \textit{NuSTAR} effective area at energies $>10$ keV with a soft X-ray instrument, which covers the 0.5–10 keV energy range. Among these, \textit{XMM-Newton} is the best one in terms of both effective area in the 0.3–10 keV energy range and spectral energy resolution (150 eV, $\sim 2.5$ better than \textit{NuSTAR}, which has $\Delta E = 400$ eV) at the energy of the Fe K$\alpha$ line (the signature of obscured AGN at $E = 6.4$ keV).

The obscuration observed in AGNs across the electromagnetic spectrum, from X-ray to infrared, is usually explained with a parsec-scale, torus-like structure of dust and gas (see, e.g., Almeida & Ricci 2017). Consequently, several tori models, based on Monte Carlo simulations, have been developed to characterize the X-ray spectra of CT AGNs in the past two decades (Matt & Fabian 1994; Ikeda et al. 2009; Murphy & Yaqoob 2009; Brightman & Nandra 2011; Liu & Li 2014; Furui et al. 2016; Baloković et al. 2018). All of these models assume a continuous distribution of the obscuring material, but with a different assumption on the geometry of the torus. In particular, in the models proposed by Ikeda et al. (2009), Brightman & Nandra (2011), and Baloković et al. (2018), the half-opening angle of the torus, i.e., the torus covering factor, is a free parameter, thus allowing constraints to...
be put on the toroidal geometry. Given the intrinsic complexity of these models and the multiple free parameters involved, applying them in full capability requires high-quality X-ray spectra, with excellent statistics on a wide energy range, i.e., between 1 and 100 keV: at the present day, similar requirements can be satisfied only by a joint NuSTAR and XMM-Newton observation. The AGN emission can also be observed at infrared wavelengths, where part of the intrinsic accretion disk optical-UV emission is absorbed by the dust in the torus-like structure and then re-emitted in the infrared. Thus, the fraction of the luminosity of the torus with respect to the AGN bolometric luminosity ($L_{\text{torus}}/L_{\text{AGN}}$) can be used as a proxy of the torus covering factor (see, e.g., Stalevski et al. 2016). Indeed, in addition to the previously mentioned X-ray models, theory and models on the nature of the obscuration from an infrared perspective have also been developed (Krolik & Begelman 1988; Jaffe et al. 2004; Tristram et al. 2007; Nenkova et al. 2008; Höning & Kishimoto 2010; Stalevski et al. 2012).

In this work, we present the results of a deep, 50 ks combined NuSTAR and XMM-Newton observation of ESO 116-G018, a nearby Seyfert 2 galaxy, and a candidate CT AGN. The paper is organized as follows. In Section 2, we report the NuSTAR and XMM-Newton data reduction and spectral extraction process; in Section 3, we describe the different models that are used to fit the broadband X-ray spectra, and the results of the spectral analysis using above models; in Section 4, we compare our results with those already existent in the literature and discuss the constraints on the physical properties of ESO 116-G018, e.g., the equivalent width (EW) of the iron Kα line and the intrinsic luminosity, and the geometry, i.e., covering factor, of the obscuring “torus-like” structure. All reported uncertainties on spectral parameters are at 90% confidence level if not otherwise stated. Standard cosmological constants are adopted as follows: $(H_0) = 70 \text{ km s}^{-1} \text{Mpc}^{-1}$, $(\Omega_0) = 0.0$ and $(\Lambda) = 0.73$.

2. Observation and Data Analysis

ESO 116-G018 ($z \sim 0.0185$, $d \sim 80$ Mpc, de Grijp et al. 1992) is a Seyfert 2 galaxy that is detected in the 100-month BAT catalog (A. Segreto et al. 2019, in preparation), a catalog of ~1000 AGNs detected by Swift-BAT in the 15–150 keV band. ESO 116-G018 was first selected as a candidate CT AGN by Marchesi et al. (2017a) using the selection technique described in the paper and was then targeted with a 10 ks follow-up observation with Chandra. The joint Chandra–Swift–BAT spectral fit allowed us to obtain a first measurement of the source “line-of-sight” column density, which is $N_{\text{H}2} = 9.5^{+0.6}_{-0.4} \times 10^{24} \text{cm}^{-2}$. The low quality of the Chandra spectrum (~50 net counts in the 0.5–7 keV band) prevented us from properly characterizing ESO 116-G018, or even confirming or rejecting its CT origin at a >3σ confidence level. Therefore, to further investigate this new candidate CT AGN, as well as another one, NGC 1358, which we analyze in a companion paper (Zhao et al. 2019), we proposed for a simultaneous NuSTAR (45 ks) and XMM-Newton (58 ks) follow-up observation, which was accepted in NuSTAR Cycle 3 (proposal ID 3258, PI: Marchesi). We report a summary of the observations in Table 1.

2.1. NuSTAR Observation

ESO 116-G018 was observed by NuSTAR on 2017 November 1–2 (ObsID 60301027002). The observation took place in a 95.5 ks time span and was divided into 15 (~3 ks) intervals. The gaps in the observation correspond to the periods of time in which the target was occulted by the Earth. The NuSTAR data is derived from both focal plane modules, FPMA and FPMB. The raw files are calibrated, cleaned, and screened using the NuSTAR nupipeline script version 0.4.5. The NuSTAR calibration database (CALDB) used in this work is version 20171002. The ARF, RMF, and light-curve files were obtained using the nuproducts script. For both modules, the source spectrum was extracted from a 30″ circular region, corresponding to ~50% of the encircled energy fraction (EEF) at 10 keV, centered on the source optical position. We then extracted a background spectrum for each module, choosing a 30″ circular region located nearby the outer edges of the field of view, to avoid contamination from the source: no flares were found in the background light curves. The NuSTAR spectra are grouped with a minimum of 15 counts per bin using the HEASoft task grppha.

2.2. XMM-Newton Observation

The XMM-Newton observation was taken quasi-simultaneously to the NuSTAR one with the EPIC CCD cameras (pn; Strüder et al. 2001) and two MOS cameras (Turner et al. 2001): the XMM-Newton observation started at the same time, but ended ~9 hr before the NuSTAR one. We reduced the XMM-Newton data using the Science Analysis System (SAS; Jansen et al. 2001) version 16.1.0. The source spectra are extracted from a 15″, corresponding to ~70% of the EEF at 1.5 keV, circular region, while the background spectra are obtained from an 80″ circle located nearby the source. We visually inspected the XMM-Newton image to avoid contamination to the background from sources nearby ESO 116-G018.

2.3. Variability

When visually inspecting the light curves of both NuSTAR (3–78 keV) and XMM-Newton (2–10 keV) of ESO 116-G018, we found no obvious evidence of variability during the observations. The background subtracted light curves of NuSTAR module FPMA and XMM-Newton EPIC MOS1 are presented in Figure 1. We further analyzed the two light curves by fitting them with a constant, $r$, which corresponds to the average count rate: we used the $\chi^2$ test to check for any statistical evidence of variability. The best-fit average count rate is $r_{\text{FPMA}} = 1.3 \pm 0.3 \times 10^{-2} \text{cts s}^{-1}$ for the NuSTAR module FPMA; the $\chi^2$ for the fit is $\chi^2_{\text{FPMA}} = 4.4$ with 10 degrees of freedom ( dof), while the light curve would be different from a constant at the >99% confidence level if $\chi^2 > 23.2$ for 10 dof. The best-fit average count rate of XMM-Newton EPIC MOS1 is $r_{\text{MOS1}} = 3.2 \pm 0.7 \times 10^{-3} \text{cts s}^{-1}$; the $\chi^2$ for the fit is $\chi^2_{\text{MOS1}} = 4.9$, while the light curve would be different from a constant at the >99% confidence level if $\chi^2 > 16.8$ for 6 dof.

Based on the fit statistics given above, there is no significant variability in both the NuSTAR and the XMM-Newton light curve of ESO 116-G018.
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Table 1
Summary of NuSTAR and XMM-Newton Observations

| Instrument   | Sequence ObsID | Start Time (UTC) | End Time (UTC) | Exposure (ks) | Count Rate$^a$ $10^{-3}$ counts s$^{-1}$ |
|--------------|----------------|------------------|----------------|--------------|--------------------------------------|
| NuSTAR       | 60301027002    | 2017-11-01T18:56:09 | 2017-11-02T20:46:09 | 45           | 1.24 ± 0.06 1.31 ± 0.06                 |
| XMM-Newton   | 0795680201    | 2017-11-01T19:19:57  | 2017-11-02T11:32:32 | 58           | 0.33 ± 0.02 0.44 ± 0.03 1.58 ± 0.06   |

Note.$^a$ The reported NuSTAR count rates are those of the FPMA and FPMB modules between 3 and 78 keV, respectively. The reported XMM-Newton count rates are those of the MOS1, MOS2, and pn modules between 2 and 10 keV, respectively.

3. Spectral Modeling Results

We performed the spectral fit of ESO 116-G018 using XSPEC v12.9.1 (Arnaud 1996) and the $\chi^2$ statistic. The photoelectric cross section for all absorption components used are those from Verner et al. (1996). The element abundance is from Anders & Grevesse (1989) and metal abundance is fixed to Solar. The Galactic absorption column density is $N_H\text{Gal} = 3.1 \times 10^{20}\text{cm}^{-2}$ (Kalberla et al. 2005). The source redshift is fixed at $z = 0.0185$.

Following a standard approach in analyzing heavily obscured AGNs, we begin our spectral modeling using the phenomenological model. In Table 2 we report the results of the joint NuSTAR–XMM-Newton spectral fitted using the different models, which will be discussed in the following sections.

3.1. Phenomenological Model

We first fit the spectra with a phenomenological model composed of an absorbed power law with photon index $\Gamma$. The absorption caused by the obscuring gas and dust surrounding the accreting SMBH is modeled by zphabs, while the Galactic absorption is modeled by phabs. We also add a Gaussian (zgauss) to the model to characterize the prominent Fe Kα line typically observed in heavily obscured AGNs. We fix the center of the Gaussian at 6.4 keV and fix the line width $\sigma$ to 50 eV, assuming the line to be narrow, to minimize the number of free parameters: nonetheless, no significant improvement is found when leaving the line width free to vary. Below ~5 keV, the spectrum is dominated by the fraction (usually less than 5%–10%; see, e.g., Marchesi et al. 2018) of emission from the intrinsic X-ray continuum, which is not intercepted by the torus on the “line of sight,” and/or the intrinsic emission is deflected, rather than absorbed by the obscuring material into the “line of sight.” This scattered component is modeled by an unabsorbed power law having photon index $\Gamma_2 = \Gamma$: the fractional intensity with respect to the intrinsic emission, $f_\alpha$, is modeled by a constant (constant$_2$).

Finally, the cross calibration between NuSTAR and XMM-Newton is modeled by another constant (constant$_1$), noted as $C_{\text{NuS/XMM}}$. We also assume that there is no flux offset between different modules of the same instrument. The phenomenological model (Model A), in XSPEC nomenclature, is thus

$$\text{ModelA} = \text{constant}_1 \ast \text{phabs} \ast (\text{zphabs} \ast \text{zpowerlw} + \text{zgauss}) + \text{constant}_2 \ast \text{zpowerlw}).$$  \hfill (1)

The best-fit results of model A are reported in Table 2 and Figure 2 shows the best-fit of the spectra of ESO 116-G018 fitted with model A. The best-fit intrinsic photon index is $\Gamma = 0.99^{+0.13}_{-0.12}$ and the column density of the obscuring material along our “line of sight” is $N_H = 0.62^{+0.12}_{-0.12} \times 10^{24}\text{cm}^{-2}$.

Although the statistics ($\chi^2 = \chi^2$/degrees of freedom, dof hereafter, = 166/162 = 1.02) of the phenomenological model are acceptable, the best-fit photon index, $\Gamma = 0.99^{+0.13}_{-0.12}$, is not physically plausible (typical AGNs have photon indices within the range $\Gamma = 1.4$–2.6; see, e.g., Murphy & Yaqoob 2009). This is not an unexpected result, since the complexity of the spectral shape of a heavily obscured AGN cannot be properly treated by a standard absorption component alone such as zphabs: such a model cannot, for example, properly model the shape of the reprocessed component known as “Compton hump” observed at energies $E \sim 10$–40 keV.

In the next section, we fit the data with physically motivated models, i.e., pexrav (Magdziarz & Zdziarski 1995), MYTorus (Murphy & Yaqoob 2009), and borus02 (Baloković et al. 2018), which are suitable to characterize heavily obscured AGNs with high-quality X-ray spectra.

3.2. Physical Models

3.2.1. Absorbed Power Law with Reflection Component

pexrav has historically been used to model heavily obscured AGN spectra where the observed emission is dominated by the photons reprocessed and upscattered by the obscuring material. pexrav models a power-law spectrum with an exponential cutoff reflected from a slab of neutral material. We first test the pexrav model utilized as a pure reflector by setting the reflection scaling factor to be $R = -1$, assuming the “line of sight” is heavily obscured (e.g., when $N_H \geq 10^{25}\text{cm}^{-2}$) such that the observed spectrum is entirely contributed by the reflection from the back-side of the obscuring matter. The photon index is $\Gamma = 1.57^{+0.09}_{-0.09}$ with the reduced $\chi^2$ as $\chi^2 = 167/163 = 1.02$. Although the pure reflection component fits the reprocessed emission at 10–40 keV well, it fails to describe the soft X-ray part at $E < 10$ keV. Therefore, we add an absorbed power law to model the “line-of-sight” continuum following the method adopted in Ricci et al. (2011).

In the XSPEC nomenclature, our pexrav model is written as follows.

$$\text{ModelB} = \text{constant}_1 \ast \text{phabs} \ast (\text{zphabs} \ast \text{zpowerlw} + \text{pexrav} \ast \text{zgauss} \ast \text{constant}_2 \ast \text{zpowerlw}),$$

where all the components other than pexrav are those already described in the previous section. While in pexrav, the inclining angle $i$, i.e., the angle between the axis of the AGN (normal to the disk) and the observer line of sight, is fixed to $i = 60^\circ$ (cos $i = 0.5$). We do not find any significant variation in the spectral fit results when adopting other two inclination angle values, i.e., $i = 87^\circ$ and $18^\circ$ (cos $i = 0.05$ and 0.95). The
cutoff energy is fixed at $E_{\text{cut}} = 500$ keV to be consistent with the MYTorus model, which will be discussed in detail in the following section: no significant improvement is found when we leave the cutoff energy free to vary. Finally, the reflection scaling factor $R$ is set to be less than 0 (i.e., the model describes only the reprocessed component) and is free to vary.

We show in Figure 3 the best fit of the joint XMM-Newton–NuSTAR spectra obtained using Model B. The best-fit photon index is $\Gamma = 1.54^{+0.18}_{-0.19}$ and the “line-of-sight” column density is $N_{\text{H,LS}} = 8.8^{+3.2}_{-0.26} \times 10^{22}$ cm$^{-2}$. It is worth noting that, although the pexrav result, with the reduced $\chi^2$ being $\chi^2 = \chi^2$/d.o.f. = 145/161 = 0.90, is improved with respect to that of Model A, different components of the spectrum, e.g., the iron line (modeled by a Gaussian), are not treated in a self-consistent way.

In summary, according to both model A and model B, ESO 116-G018 is heavily obscured but not CT. However, in model A, the photon index $\Gamma$ is significantly harder than the one of a typical obscured AGN; furthermore, the fraction of scattered emission is slightly larger than the typical 1%–10% value in both models, being $f_s \sim 11\%$. Model B (pexrav), in spite of a significant improvement in statistics and a reasonable photon index, fails to treat the reprocessed components, i.e., the reflection component and the fluorescent lines, self-consistently. Therefore, in order to better unveil the physics of the obscuring matter surrounding the accreting SMBH of ESO 116-G018, more self-consistent and realistic models are needed.

3.2.2. MYTorus

MYTorus models the intrinsic emission of an AGN reprocessed by obscuring matter with uniform density. The obscuring matter has a “torus-like” structure with circular cross section, and the half-opening angle of the torus is fixed to $\theta_{\text{obs}} = 60^\circ$, i.e., the covering factor of the torus is fixed to $f_c = \cos(\theta_{\text{obs}}) = 0.5$. The angle between the observer “line of sight” and the torus axis (norm to the accretion disk), $\theta_{\text{obs}}$, however, is a free parameter in MYTorus and can vary in the range $0^\circ$–$90^\circ$, where $\theta_{\text{obs}} = 0^\circ$ models a “face-on” scenario and $\theta_{\text{obs}} = 90^\circ$ models an “edge-on” scenario. Notably, the direct continuum will not intercept the circumnuclear matter when the inclination angle is less than $\theta_{\text{obs}} = 60^\circ$.

An advantage of the MYTorus model is that the different components observed in the spectrum of an obscured AGN can be treated self-consistently. More in detail, the MYTorus model is composed of three components: the direct continuum (MYTZ), the Compton-scattered component (MYTS), and the fluorescent emission-line component (MYTL).

The direct continuum (MYTZ), which is also called zeroth-order continuum, is the “line-of-sight” observed continuum, i.e., the intrinsic X-ray continuum attenuated by the obscuring material in the torus. MYTZ is a multiplicative factor applied to the intrinsic continuum. In principle, the intrinsic continuum can be any continuum spectral shape: in our modeling we choose a power law to be consistent with the scattered continuum and fluorescent emission-line components, which assume a power-law incident continuum in MYTorus. The direct-continuum emission is an energy-dependent “line-of-sight” quantity but is independent of the geometry of the torus.

The second component is the Compton-scattered continuum (MYTS), which is responsible for the “Compton hump” observed at $\sim$10–40 keV. The Compton-scattered continuum models those photons that are Compton scattered into the “line of sight” by the gas in the torus. The cutoff energy of the Compton-scattered component can vary in the range of $E_T = [160–500]$ keV; we choose to fix this parameter to a standard $E_T = 500$ keV value, since we verified that assuming a different cutoff energy does not significantly affect the other best-fit parameters. The covering factor of the MYTorus model is fixed to be $f_c = 0.5$; however, if the geometry of the torus differs significantly from the fixed MYTorus value or if there is a non-negligible time delay between the intrinsic continuum emission and the Compton-scattered continuum one, i.e., the central region is not compact and the intrinsic emission varies rapidly, the scattered component normalization can significantly differ from the main component one. To take these effects into account, the scattered continuum is multiplied by a constant, which we hereby define as $A_S$.

Finally, the third component (MYTL) models the most prominent fluorescent emission lines, i.e., the Fe Kα and Fe Kβ lines, at 6.4 keV and 7.06 keV, respectively. Analogously to $A_S$,
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Table 2
Summary of Best Fits of XMM-Newton and NuSTAR Data Using Different Models

| Model          | Phenom | Pexrav | MYTorus (coupled) | MYTorus (decoupled face on) | MYTorus (decoupled edge on) | borus02 |
|----------------|--------|--------|------------------|-----------------------------|-----------------------------|---------|
| $\chi^2$/dof  | 166/162| 145/161| 140/161          | 150/161                     | 144/161                     | 140/160 |
| $C_{\text{ins}}$ | 0.99±0.12 | 1.03±0.13 | 1.06±0.08        | 1.04±0.14                   | 1.07±0.14                   | 1.07±0.08 |
| $\Gamma$      | 0.99±0.18 | 1.54±0.18 | 1.79±0.12        | 1.51±0.37                   | 1.74±0.40                   | 1.80±0.06 |
| norm $^{b}$ 10^{-3} | 0.07±0.03 | 0.17±0.09 | 0.53±0.34        | 1.02±0.47                   | 5.02±5.90                   | 6.03±0.23 |
| $R$           | ...     | 2.52±2.61 | ...              | ...                         | ...                         | ...     |
| $N_{\text{H,eq}}$ | ...     | ...     | 5.31±2.34        | ...                         | ...                         | ...     |
| $\theta_{\text{ins}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $f_r$         | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $\theta_{\text{abs}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $A_3$         | ...     | ...     | 60.70±0.40       | ...                         | ...                         | 84.78±0.88 |
| $N_{\text{H,LZ}}$ | 0.62±0.12 | 0.80±0.26 | ...              | 1.46±0.10                   | 2.58±0.83                   | 2.60±0.16 |
| $N_{\text{H,LZ}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $f_c$         | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $\theta_{\text{ins}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $f_{\text{f},10^{-2}}$ | 10.69±3.92 | 1.44±0.40 | 1.67±0.86        | 0.77±0.59                   | 0.27±0.56                   | 0.16±0.03 |
| $f_{\text{f},10^{-2}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $f_{\text{f},10^{-4}}$ | 3.15±0.26 | 3.07±0.21 | 3.07±1.89        | 3.04±0.14                   | 3.02±0.21                   | 3.00±0.70 |
| $f_{\text{f},10^{-4}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $f_{\text{f},10^{-4}}$ | 3.33±0.28 | 3.45±0.40 | 3.49±1.38        | 3.34±0.33                   | 3.47±0.25                   | 3.41±0.35 |
| $f_{\text{f},10^{-4}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $L_{\text{2},10^{44}}$ | 0.066±0.004 | 0.066±0.008 | 0.14±0.02        | 0.42±0.04                   | 1.44±0.16                   | 1.68±0.18 |
| $L_{\text{2},10^{44}}$ | ...     | ...     | ...              | ...                         | ...                         | ...     |
| $L_{\text{10},10^{44}}$ | 0.25±0.02 | 0.11±0.01 | 0.16±0.02        | 0.74±0.07                   | 1.81±0.21                   | 1.86±0.21 |

Notes.

a $C_{\text{ins}}$ = $C_{\text{NAOCHAXM}}$ is the cross calibration between NuSTAR and XMM-Newton.

b Normalization of components in different models at 1 keV in photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$.

c Reflection scaling factor.

d Angle between the axis of the torus and the edge of torus in degree.

e Covering factor of the torus: $f_c = \cos(\theta_{\text{line-of-sight}})$.

f “Line-of-sight” column density in 10$^{24}$ cm$^{-2}$.

g “Global average” column density of the torus in 10$^{24}$ cm$^{-2}$.

h Flux between 2 and 10 keV in 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$.

i Flux between 10 and 40 keV in 10$^{-12}$ erg cm$^{-2}$ s$^{-1}$.

j Intrinsic luminosity between 2 and 10 keV in 10$^{43}$ erg s$^{-1}$, computed using “clumin” command.

k Intrinsic luminosity between 10 and 40 keV in 10$^{43}$ erg s$^{-1}$, computed using “clumin” command.

previous works, the two relative normalizations are set to be equal, i.e., $A_3 = A_L$.

In XSPEC the MYTorus model is described as follows.

$$\text{ModelC} = \text{constant} \times \text{phabs} \times (\text{MYTZ} \times \text{zpowerlw})$$

$$+ A_3 \times \text{MYTS} + A_L \times \text{MYTL}$$

$$+ \text{constant} \times \text{zpowerlw}.$$ (3)

The MYTorus model can be applied in two different configurations, named “coupled” and “decoupled” (Yaqoob 2012). We apply both configurations to the ESO 116-G018 spectrum: the analysis details and results are reported in the following sections.

3.2.3. MYTorus in “Coupled” Configuration

In “coupled” mode, both the inclination angle and the column density are tied among the three components: MYTZ, MYTS, and MYTL. In this configuration, the column density is the torus equatorial one and the “line-of-sight” column density is $N_{\text{H,torus}} = N_{\text{H,eq}} \times (1-4 \times \cos(\theta_{\text{obs}}))^1/2$ (Murphy & Yaqoob 2009).

The best-fit photon index for “coupled” MYTorus model is $\Gamma = 1.79^{+0.13}_{-0.11}$; the photon indices of the Compton-scattered continuum and of the fluorescent emission-line component are tied to that of direct continuum. The equatorial column density is $N_{\text{H,eq}} = 5.31^{+2.34}_{-2.71} \times 10^{24}$ cm$^{-2}$ and the inclination angle is $\theta_{\text{obs}} = 60.70^{+0.82}_{-0.40}$ such that the “line-of-sight” column densities are $N_{\text{H,LZ}} = 2.60^{+1.19}_{-1.36} \times 10^{24}$ cm$^{-2}$.
While the best-fit statistics of the “coupled” model are good ($\chi^2 = 140/161 = 0.87$), the geometrical scenario that the model presents is physically unlikely, since we measure $\theta_{\text{obs}} = 60^\circ \sim 60^\circ = \theta_{\text{tor}}$, i.e., the AGN would be observed through the brink of the torus. Such a result also affects the reliability of the column density measurement, since $N_{\text{H,Z}}$ is a parameter highly dependent on $\theta_{\text{obs}}$, particularly when $\theta_{\text{obs}}$ gets close to $\theta_{\text{tor}}$. To further investigate the physical and geometrical properties of ESO 116-G018, we therefore try to apply MYTorus in a different configuration, which allows one to disentangle the inclination angle and column density between the direct continuum and the reprocessed component.

### 3.2.4. MYTorus in “Decoupled” Configuration

In “decoupled” configuration (Yaqoob 2012), the direct continuum and the Compton-scattered component can, in principle, have different inclination angle and column density values. Since the direct continuum is a pure “line-of-sight” quality, which is independent on observation angle, the inclination angle of the direct continuum is fixed to $\theta_{\text{obs,Z}} = 90^\circ$, such that the column density of the direct-continuum model the “line-of-sight” column density, $N_{\text{H,Z}}$. The inclination angle of the Compton-scattered continuum and fluorescent lines is instead set to be either $\theta_{\text{obs,S,L}} = 0^\circ$ (face on) or $\theta_{\text{obs,S,L}} = 90^\circ$ (edge on), modeling a “back-side” reflection-dominated scenario or a “near-side” Compton-scattered component-dominated scenario, respectively. In this configuration, the column density of the Compton-scattered component and fluorescent emission-line component parameterizes the “global averaged” column density of the torus, $N_{\text{H,S}}$, which can significantly differ from the “line-of-sight” column density in an inhomogeneous, patchy, torus (see Yaqoob 2012 for more details). Therefore, MYTorus in “decoupled” configuration can be used to model a more realistic distribution of the obscuring material. We note that the fluorescent emission-line component and Compton-scattered component are still coupled since they are expected to be originated from the same process.

The best-fit photon indices are $\Gamma_{0,0} = 1.51_{-0.11}^{+0.37}$ and $\Gamma_{0,90} = 1.74_{-0.34}^{+0.40}$ for “face-on” and “edge-on” modes, respectively. The “line-of-sight” column densities are $N_{\text{H,Z},0,0} = 1.46_{-0.57}^{+0.30} \times 10^{24}$ cm$^{-2}$ and $N_{\text{H,Z},0,90} = 2.58_{-0.83}^{+0.32} \times 10^{24}$ cm$^{-2}$. The “global average” column densities are $N_{\text{H,S},0,0} = 0.43_{-0.11}^{+0.24} \times 10^{24}$ cm$^{-2}$ and $N_{\text{H,S},0,90} = 0.38_{-0.08}^{+0.11} \times 10^{24}$ cm$^{-2}$. The “global average” column densities are $\sim 15\%$ and $29\%$ of the “line-of-sight” column densities for “edge-on” and “face-on” configurations, respectively, which suggests a patchy torus in ESO 116-G018. We present the unfolded NuSTAR and XMM-Newton spectra of ESO 116-G018 in the “decoupled” MYTorus model in “face-on” and “edge-on” configuration in Figure 4.

In conclusion, the best-fit results of the MYTorus model in both “coupled” MYTorus model and “decoupled” MYTorus model in “edge-on” configuration confirm that ESO 116-G018 is a bona fide CT AGN at $\gtrsim 3\sigma$ confidence. While MYTorus is effective in modeling the X-ray spectra of heavily obscured AGN, the “coupled” mode assumes a fixed torus opening angle ($\theta_{\text{tor}} = 60^\circ$, i.e., a covering factor $f_c = \cos \theta_{\text{tor}} = 0.5$), limiting the model to a single torus geometry and the “decoupled” mode fails to directly parameterize the geometrical properties of the obscuring material. To complement our analysis, we therefore model the ESO 116-G018 spectrum using the recently published borus02 model (Baloković et al. 2018), an updated version of the so-called BNtorus model (Brightman & Nandra 2011).

### 3.2.5. BORUS02

The model is composed of a reprocessed component (including the Compton-scattered component and fluorescent lines) and an absorbed intrinsic continuum, described by a cutoff power law, multiplied by a “line-of-sight” absorbing component, $\text{zphabs} \times \text{cabs}$. Although the cabs model simply assumes a constant Compton scattering cross section equal to the Thomson cross section, which, in principle,
energy dependent and only valid below $\sim10 \text{ keV}$, the difference between such a model and MYTZ is insignificant below 100 keV in our case, where $N_{\text{HZ}} \sim 2.6 \times 10^{24} \text{ cm}^{-2}$ (more details are available in the MYTorus manual\(^1\)). In 

\texttt{borus02}, the torus covering factor can vary in the range of $f_c = [0.1–1]$, corresponding to a torus opening angle $\theta_{\text{Tor}} = [0–84]^\circ$. The observing angle ranges from $\theta_{\text{Tor}} \sim [18–87]^\circ$.

The 

\texttt{borus02} model is used in the following XSPEC configuration:

$$\text{ModelD} = \text{const}t_1 \ast \text{phabs} \ast (\text{borus} + \text{zphabs} \ast \text{cabs} \ast \text{cutoffpl} + \text{const}t_2 \ast \text{cutoffpl}),$$

where \texttt{borus} is the reprocessed component in \texttt{borus02}.

The best-fit photon index is $\Gamma = 1.80^{+0.06}_{-0.06}$, the “line-of-sight” column density is $N_{\text{HZ}} = 2.60^{+0.16}_{-0.14} \times 10^{24} \text{ cm}^{-2}$; the column density of the torus is $N_{\text{HLS}} = 0.52^{+0.10}_{-0.06} \times 10^{24} \text{ cm}^{-2}$; in good agreement with the “decoupled” MYTorus model in “edge-on” configuration. The half-opening angle of the torus is $\theta_{\text{Tor}} = 81.69^{+0.88}_{-0.30}$°, thus the torus covering factor is $f_c = \cos(\theta_{\text{obs}}) = 0.14^{+0.01}_{-0.01}$. The inclination angle between the observer and the torus axis is $\theta_{\text{obs}} = 84.78^{+0.86}_{-0.86}$°. The unfolded \textit{NuSTAR} and \textit{XMM-Newton} spectra of ESO 116-G018 fitted with \texttt{borus02} model is presented in Figure 5.

To conclude, the self-consistent, physically motivated models of MYTorus and \texttt{borus02} give a better characterization of the X-ray spectrum than the phenomenological model and the \texttt{pexrav} model, and confirm ESO 116-G018 to be a CT AGN at $>3\sigma$ confidence. In addition, both the MYTorus model in “decoupled” configuration and \texttt{borus02} display a significant difference between the “line-of-sight” column density and the column density of the torus, suggesting a patchy distribution of the obscuring matter. The other physical properties of interest will be discussed in Section 4.

\(^{1}\) http://mytorus.com/mytorus-instructions.html

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**Figure 4.** Unfolded \textit{XMM-Newton} and \textit{NuSTAR} spectra of ESO 116-G018 fitted with “decoupled” MYTorus “face-on” model (left panel) and “decoupled” MYTorus “edge-on” model (right panel). The \textit{XMM-Newton} data are plotted in blue, while the \textit{NuSTAR} data are plotted in red. The best-fit model prediction is plotted as a cyan solid line. The single components of the model are plotted in black with different line styles, i.e., the absorbed intrinsic continuum as a solid line, the reprocessed component and Fe K line as a dashed line, and the scattered component as a dotted line.

**Figure 5.** Unfolded \textit{XMM-Newton} and \textit{NuSTAR} spectra of ESO 116-G018 fitted with the \texttt{borus02} model. The \textit{XMM-Newton} data are plotted in blue, while the \textit{NuSTAR} data are plotted in red. The best-fit models prediction is plotted as a cyan solid line. The single components of the model are plotted in black with different line styles, i.e., “line-of-sight” continuum as a solid line, reprocessed component as a dashed line, and the scattered component as a dotted line.

### 3.3. Summary of the Spectral Analyzing Results

In Section 3.1, we first fitted the combined high-quality \textit{XMM-Newton-NuSTAR} spectra of ESO 116-G018 using the phenomenological model A, finding that only an absorbed power law is difficult to use to characterize the Compton hump in $\sim10–40 \text{ keV}$. We thus added a reflection component \texttt{pexrav} to model B to characterize the Compton hump: we obtained a significantly improved statistic, but the lack of self-consistency motivated us to explore more realistic models, i.e., MYTorus and \texttt{borus02}, where the structure of the obscuring matter is a torus rather than a slab, like in \texttt{pexrav}. In Section 3.2.2, we first tested the “coupled” MYTorus model, which gave an unlikely geometrical scenario, i.e., the accreting SMBH would be observed through the brink of the torus.
Therefore, we adopted the MYTorus model configuration, which assumes a more general geometry, by disentangling the direct continuum and the reprocessed component, and we then fitted the spectrum with the so-called “decoupled” MYTorus model. This model gave a more reasonable result; however, the obscuring material geometrical properties, i.e., the covering factor $f_c$ and observing angle $\theta_{\text{obs}}$, cannot be directly derived using MYTorus in “decoupled” configuration. Thus, we finally tested the recently published borus02 model, which gives the best statistics and allows one to measure $f_c$ and $\theta_{\text{obs}}$.

Based on both the fit statistics and the reliability of the best-fit parameters, we believe that borus02 provides the best-fit model for ESO 116-G018 in the 2–70 keV band. In fact, while all the models used in our analysis have good fit statistics ($\chi^2_{\text{red}} \sim 0.87$–1.02), models other than borus02 are limited by the assumptions required to use them or they have notably different physical interpretations. For example, the pexrav model and “coupled” MYTorus model indicate that the spectrum is dominated by the reprocessed component, while the “decoupled” MYTorus model and borus02 model suggest that the direct continuum dominate the spectrum, especially at energy $E > 10$ keV. Such a discrepancy is also observed in other parameters, e.g., the intrinsic luminosity, which will be further discussed in Section 4.4. However, it is worth noting that in reprocessing-dominated models, such as pexrav, the reprocessed component is not obscured, while in the “coupled” MYTorus model, the reprocessed component is obscured by the dust and gas with the same column density as the “line-of-sight” one: both scenarios are unlikely to exactly characterize the real distribution of the obscuring material, which has been shown to be clumpy, rather than uniformly distributed (see, e.g., Krolik & Begelman 1988; Jaffe et al. 2004; Tristram et al. 2007; Nenkova et al. 2008; Höning & Kishimoto 2010; Stalevski et al. 2012). Indeed, the significant difference between the “line-of-sight” column density and the “global average” column density of the torus observed in the “decoupled” MYTorus model and in the borus02 model best fits support a clumpy, patchy torus scenario for ESO 116-G018.

Regardless of the geometrical configuration of the obscuring material, both self-consistent, physically motivated models, MYTorus and borus02, confirm the Compton thickness of ESO 116-G018 at a >3σ confidence level. Furthermore, the borus02 model provides excellent constraints on the geometrical properties of the obscuring torus: the covering factor is $f_c = [0.13$–0.15] and we observe the source “edge on.”

4. Discussion and Conclusions

In this work, we report the results of the 2–70 keV spectral analysis of ESO 116-G018, a nearby Seyfert 2 galaxy, observed quasi-simultaneously by NuSTAR (45 ks) and XMM-Newton (58 ks), and we establish for the first time that the source is a bona fide CT AGN. As discussed in Section 3.3, the best-fit model for ESO 116-G018 is borus02 (Baloković et al. 2018), which gives a “line-of-sight” column density of $N_{\text{HZ}} = [2.46$–2.76] $\times 10^{24}$ cm$^{-2}$. We also find that the best-fit results of “decoupled” MYTorus model in “edge-on” configuration (Murphy & Yaqoob 2009) are in excellent agreement with those of borus02 model. In the rest of the paper, we will use the borus02 model best-fit results.

4.1. Comparison with Previous Results

ESO 116-G018 was found to be a CT AGN candidate by Marchesi et al. (2017a), using a joint Chandra–Swift/BAT spectra fitted with the MYTorus model in “coupled” configuration where the inclination angle is fixed to be $\theta_{\text{obs}} = 90^\circ$; they found a best-fit photon index, $\Gamma = 1.86^{+0.51}_{-0.44}$, in good agreement with the one measured in this work and a best-fit column density of $N_{\text{H}} = 9.52^{+0.46}_{-0.40} \times 10^{24}$ cm$^{-2}$, with $\chi^2$/dof = 17/14. Such a large uncertainty has been significantly improved by the high-quality data of the combined NuSTAR–XMM-Newton observations, which is potentially the best combination of observatories to study the CT AGNs in X-ray band.

4.2. EW of the Iron Kα Line

We are able to place strong constraints on the Fe Kα line EW of ESO 116-G018 due to the excellent count statistics provided by NuSTAR and XMM-Newton in the 5–8 keV band, with a significant improvement with respect to Marchesi et al. (2017a). We use the task eqwidth in XSPEC to measure EW $\text{EW}_{\text{FeK}\alpha} = 0.93^{+0.15}_{-0.10} \text{keV}$ and $\text{EW}_{\text{px}} = 0.85^{+0.13}_{-0.15} \text{keV}$ in models A and B, respectively.

To measure the Fe Kα line EW with MYTorus we use the approach described in Yaqoob et al. (2015). We therefore first measure the continuum flux, without including the emission line, at $E_{\text{Ko}} = 6.4$ keV. We then compute the flux of the fluorescent lines component in the energy range $E = [0.95 E_{\text{Ko}}, 1.05 E_{\text{Ko}}]$, i.e., between 6.08 and 6.72 keV, rest frame. EW is then computed by multiplying by $(1 + z)$ the ratio between the fluorescent line flux and the monochromatic continuum flux. We obtain $\text{EW}_{\text{coup}} = 0.78^{+0.09}_{-0.13} \text{keV}$, $\text{EW}_{\text{decoul}, \theta=0} = 0.90^{+0.12}_{-0.10} \text{keV}$, and $\text{EW}_{\text{decoul}, \theta=90} = 0.85^{+0.15}_{-0.12} \text{keV}$. All MYTorus EW values are in good agreement with the ones obtained by the phenomenological model and the pexrav model; furthermore, in all the models, the measured Iron line EW value is typical of a CT AGN ($\sim 1 \text{keV}$; see, e.g., Figure 8 in Murphy & Yaqoob 2009).

4.3. Intrinsic Luminosity

We report the 2–10 keV and 10–40 keV intrinsic luminosity in Table 2. Notably, the intrinsic luminosities derived from model B and the “coupled” MYTorus model are $\sim 12$–25 times smaller than those derived using borus02 model the “decoupled” MYTorus “edge-on” model. As discussed in Section 3.3, this is due to the fact that model B and “coupled” MYTorus model are reprocessed-component-dominated, while borus02 and the “decoupled” MYTorus “edge-on” model are direct-continuum-dominated (at least at energies $E > 10$ keV). As already discussed in the previous sections, based on the statistics and reliability of parameters, we favor the borus02 and MYTorus decoupled “edge-on” solutions. The 2–10 keV and 10–40 keV intrinsic luminosity from the best-fit model are $\text{L}_{\text{int},2-10} = 1.68^{+0.18}_{-0.15} \times 10^{43}$ erg s$^{-1}$ and $\text{L}_{\text{int},10-40} = 1.86^{+0.21}_{-0.20} \times 10^{43}$ erg s$^{-1}$, respectively. This luminosity is compatible with the knee of the luminosity function of AGN in the local universe (Ajello et al. 2012), showing that ESO 116-G018 is an average-luminosity AGN.

The intrinsic X-ray luminosity can be derived indirectly from the luminosities measured at other wavelengths, such as the mid-infrared (MIR, 3–20 µm; see, e.g., Elvis et al. 1978). The MIR flux of ESO 116-G018 is $F_{\text{2.2μm}} = 0.175^{+0.002}_{-0.003}$ Jy.
(Wright et al. 2010) and the corresponding luminosity is 
$L_{2-10\,\text{keV}} = 3.34^{+0.04}_{-0.05} \times 10^{43} \text{erg s}^{-1}$. Applying the MIR-X-ray correlation in Asmus et al. (2015) to the MIR luminosity, we obtain the 2–10 keV luminosity to be $L_{\text{int},2-10\,\text{keV,MIR}} = 0.42^{+0.15}_{-0.10} \times 10^{43} \text{erg s}^{-1}$. The 2–10 keV intrinsic luminosity derived from MIR luminosity is slightly less than our best-fit one. This may be due to the fact that the covering factor of ESO 116-G018 is indeed small (see Section 4.5), which leads to a relatively small infrared luminosity.

4.4. Bolometric Luminosity and Mass of SMBH

The AGN bolometric luminosity is the measurement of the total AGN emission over the whole electromagnetic spectrum, and several bolometric corrections measurements to infer the bolometric luminosity from the X-ray one have been reported in the literature (see, e.g., Elvis et al. 1994; Marconi et al. 2004; Lusso et al. 2012; Brightman et al. 2017). In Section 3.3.2.5, we measured the intrinsic luminosity of ESO 116-G018 between 2–10 keV which is $L_{\text{int},2-10\,\text{keV}} = 1.68^{+0.10}_{-0.09} \times 10^{43} \text{erg s}^{-1}$ using our best-fit borus02 model. Applying the bolometric correction of Marconi et al. (2004, Equation (21)), we obtain the bolometric luminosity of ESO 116-G018, which is $L_{\text{bol}} = 2.92^{+0.42}_{-0.42} \times 10^{44} \text{erg s}^{-1}$.

Recently, Brightman et al. (2017) measured the X-ray bolometric correction factors, $n_{\text{bol}} = L_{\text{bol}}/L_{\text{obs,8-24}}$, where $L_{\text{obs,8-24}}$ is the observed luminosity in 8–24 keV, for CT AGNs. ESO 116-G018 8–24 keV observed luminosity is $L_{\text{obs,8-24}} = 1.23^{+0.14}_{-0.12} \times 10^{42} \text{erg s}^{-1}$, such that the bolometric luminosity from the prediction of Brightman et al. (2017) is $L_{\text{bol}} = 3.22^{+0.11}_{-0.11} \times 10^{44} \text{erg s}^{-1}$, in excellent agreement with our results measured using the Marconi et al. (2004) bolometric correction.

The Eddington ratio is a measurement of the SMBH accretion efficiency, and is defined as $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$, i.e., the ratio of bolometric luminosity, $L_{\text{bol}}$, to the so-called Eddington luminosity, $L_{\text{Edd}} = 4\pi GM_{\text{BH}}M_{\text{p}}c/\sigma_{T}$, where $M_{\text{BH}}$ is the SMBH mass and $M_{\text{p}}$ is the mass of proton. Combining the bolometric luminosity, $L_{\text{bol}}$, and the typical Eddington ratio of AGNs in local universe ($\lambda \sim 0.1$; see, e.g., Marconi et al. 2004), one can estimate the mass of the center engine in ESO 116-G018, which is $M_{\text{BH}} = L_{\text{bol}}/(4\pi GM_{\text{BH}}c\lambda_{\text{Edd}}/\sigma_{T})$ and we obtain $\log(M_{\text{BH}}/M_{\odot}) \sim 7.4$, which is in agreement with the typical mass of SMBH: $\log(M_{\text{BH}}/M_{\odot}) \sim 6.0–9.8$ (see, e.g., Woo & Urry 2002).

4.5. Covering Factor

The self-consistency of the reprocessed components in the borus02 model provides the possibility of directly deriving the geometrical properties of the obscuring material. In Section 3.3.2.5, we measured the covering factor of the torus in ESO 116-G018 using borus02 and found that a low covering factor solution ($f_{c} = 0.14^{+0.01}_{-0.01}$) is preferred. It is worth noting that this low covering factor could be explained both with a geometrically thin torus or with the fact that the torus is patchy, which is supported by the observed discrepancy between the “line-of-sight” column density and the “global average” column density of the torus.

The optical/UV disk emission reprocessed by the torus in the infrared (IR) can also provide interesting constraints on the source geometry. The ratio of the torus luminosity to the AGN luminosity can be thus be interpreted as the fraction of the sky obscured by the “torus-like” material. The covering factor can be measured with the equation $f_{c} = L_{\text{bol}}/L_{\text{AGN}} = L_{\text{IR}}/L_{\text{bol}}$ (Stalevski et al. 2016). Yamada et al. (2013) measured the IR (8–1000 $\mu$m) luminosity of ESO 116-G018, which is $L_{\text{IR}} = 1.3 \times 10^{44} \text{erg s}^{-1}$, using the IRSA (Neugebauer et al. 1984) 12, 25, 60, and 100 $\mu$m observations. Based on their measurement and using the bolometric luminosity estimated from our best-fit model discussed in Section 4.4, the IR covering factor of the torus is $f_{c} \sim [0.38–0.51]$. However, ESO 116-G018 is classified as a composite galaxy (Yamada et al. 2013), i.e., the galaxy has both star-forming and AGN activity signatures, thus the IR luminosity is constituted of not only the AGN contribution but also a significant fraction of the polycyclic aromatic hydrocarbon emission in the star-forming process, suggesting that the covering factor of the torus of ESO 116-G018 should be smaller than that derived with the technique discussed above; the constraints on the geometrical property of the torus from the infrared study are thus in line with those obtained from our measurement in X-ray.

4.6. Conclusion

We found a significant difference between the best-fit results of the phenomenological model and pxextrav model and the best-fit results of the self-consistent, physically motivated models. Such a difference is also found in NGC 1358 (Zhao et al. 2019). In addition, Marchesi et al. (2018) re-examined the distribution of the column density of sampled AGNs in the local universe accompanied with NuSTAR data, and found an overestimation of the column density from the one measured with Swift-BAT data, probably due to the low quality of the spectra. Since most of the AGNs are modeled with the phenomenological model and non-self-consistent, physically motivated model in the previous analysis, the observed distribution of AGNs will vary if self-consistent, physically motivated models are widely adopted. However, it is worth noting that the self-consistent, physically motivated models, i.e., MyTorus and borus02, require high-quality data in broadband, therefore, as we show in this work and the work discussed above, the physically motivated model complemented with the combined NuSTAR and XMM-Newton analysis will be an ideal method to study the physics of heavily obscured AGNs.

The authors would like to thank L. Marcotulli for the help with the data reduction and C. Vignali for the helpful suggestions. X.Z., S.M., and M.A. acknowledge NASA funding under contract 80NSSC17K0635. NuSTAR is a project led by the California Institute of Technology (Caltech), managed by the Jet Propulsion Laboratory (JPL), and funded by the National Aeronautics and Space Administration (NASA). We thank the NuSTAR Operations, Software, and Calibrations teams for support with these observations. This research has made use of the NuSTAR Data Analysis Software (NuSTARDAS) jointly developed by the ASI Science Data Center (ASDC, Italy) and the California Institute of Technology (USA). This research has made use of data and/or software provided by the High Energy Astrophysics Science Archive Research Center (HEASARC), which is a service of the Astrophysics Science Division at NASA/GSFC and the High
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