Application of Clumpy Torus Model to Broadband X-Ray Spectra of Two Seyfert 1 Galaxies: IC 4329A and NGC 7469

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Abstract

We apply a new X-ray clumpy torus model, XCLUMPY, in which the clump distribution is assumed to be the same as that in the infrared clumpy torus model (CLUMPY) by Nenkova et al., to the broadband X-ray spectra of type-1 active galactic nuclei (AGNs) for the first time. We analyze the archival data of IC 4329A and NGC 7469 observed with NuSTAR/Suzaku and NuSTAR/XMM-Newton, respectively, whose infrared spectra were studied with CLUMPY by Ichikawa et al. and optical extinctions ($A_V$) of the tori were estimated. We consider two models, invoking (Model 1) a relativistic reflection component from the accretion disk and (Model 2) a partial absorber. Assuming that the narrow Fe Kα emission line at 6.4 keV originates from the torus, we separate the contribution of the torus reflection components in the total spectra. Our models yield equatorial hydrogen column densities of the tori to be $N_{HI}^{Equ} = (0.53 \pm 1.43) \times 10^{23}$ cm$^{-2}$ and $N_{HI}^{Equ} = (0.84 \pm 1.43) \times 10^{24}$ cm$^{-2}$, for IC 4329A and NGC 7469, respectively. We find that the $N_{HI}/A_V$ ratios in the tori are by factors of 25–68 (IC 4329A) and 2.4–3.9 (NGC 7469) smaller than that in the Galactic interstellar medium (ISM). These results suggest that a non-negligible fraction of AGNs are “dust-rich” compared with the Galactic ISM, as opposite to the general trend previously reported in many obscured AGNs.

Key words: galaxies: individual (IC 4329A, NGC 7469) – galaxies: Seyfert – X-rays: galaxies

1. Introduction

To reveal basic properties of obscuring material in active galactic nuclei (AGNs), often referred to as the “torus”, it is important to understand the feeding and feedback mechanisms of AGNs (see, e.g., Ramos Almeida & Ricci 2017, for a recent review). Among them, the gas-to-dust ratio is a key parameter for understanding the circumnuclear environments. It has been reported in many (but not all) AGNs that the ratios of optical extinction ($A_V$) to hydrogen column density ($N_{HI}$) toward the nuclei, as estimated from the infrared/optical and X-ray spectra, respectively, are smaller than the Galactic value (Maiolino et al. 2001; Vasudevan et al. 2009; Burtscher et al. 2016). A plausible explanation is that the gas-to-dust ratio of obscuring material is higher (i.e., more “gas-rich”) than that of the Galactic interstellar medium (ISM). It may be due to dust-free neutral gas in the broad line region (BLR), which can also cause variability in the X-ray absorption (see Burtscher et al. 2016 and references therein). However, opposite cases (i.e., a torus is more “dust-rich” than Galactic) have also been reported (e.g., Barcons et al. 2003; Huang et al. 2011; Ordovás-Pascual et al. 2017), making our understanding of AGN environments not that simple. More independent studies using a well-studied, local AGN sample are necessary to solve this issue.

The X-ray spectrum of an AGN contains a reflection component from the torus, accompanied by narrow fluorescence lines such as Fe Kα at 6.4 keV. This component carries information on all material, including gas and dust, around supermassive black holes (SMBH). In particular, even in type-1 AGNs where no line-of-sight absorption is observed, the equivalent width of the Fe Kα line can be used to infer the torus structure, such as its covering fraction and/or column density (e.g., Tazaki et al. 2013; Kawamuro et al. 2016). Complementary to the X-ray data, the infrared spectra give information on the properties of dust. Thus, comparing the X-ray and infrared spectra is quite useful to constrain the nature of AGN tori (e.g., Ricci et al. 2014; Baloković et al. 2018), including the gas-to-dust ratio. In such studies, it is desirable to apply “self-consistent” models, in terms of the torus geometry, to both X-ray and infrared data.

Recently, Tanimoto et al. (2019) constructed a new X-ray clumpy torus model, XCLUMPY, based on the Monte Carlo simulation for Astrophysics and Cosmology (MONACO; Odaka et al. 2016) framework. In this model, the geometry of the torus is the same as that in the CLUMPY model in the infrared band (Nenkova et al. 2008a, 2008b), in which clumps are distributed according to power-law and normal profiles in the radial and angular directions, respectively. It has three variable torus parameters: equatorial hydrogen column density, torus angular width, and inclination angle. The XCLUMPY model enables us to directly compare the results with those obtained from the infrared spectra with the CLUMPY code in a self-consistent way.

In this paper, we apply the XCLUMPY model to the X-ray spectra of unobscured (type-1) AGNs for the first time. Our sample is IC 4329A and NGC 7469, whose infrared spectra have been analyzed in detail with the CLUMPY model (Alonso-Herrero et al. 2011; Ichikawa et al. 2015). We utilize their best-quality broadband X-ray spectra, simultaneously observed with NuSTAR and Suzaku (for IC 4329A) and with NuSTAR and XMM-Newton (NGC 7469). This work is complementary to studies of obscured AGNs that compared the line-of-sight column densities with the $A_V$ values obtained with the CLUMPY model (González-Martín et al. 2013; A. Tanimoto et al. 2019, in preparation). The main goal of our paper is to constrain the torus properties, in particular the gas-to-dust ratios. In addition, we can also correctly estimate the contribution of the reflection component from the torus in the total spectra. Two major models have been proposed as the X-ray spectra of type-1 AGNs to explain the broad iron-K emission line feature and bump structure peaked around...
30 keV; one invoking a relativistic reflection component from the innermost accretion disk, the other assuming variable partial absorbers (see Section 3). Although discriminating between these models is not a goal of our paper (and hence we treat the two models equally), it is always crucial to properly take into account the torus reflection component in modeling the broadband X-ray spectra of AGNs.

This paper is organized as follows. Section 2 gives the details of our sample. In Section 3, we describe the observations and data reduction. In Section 4, we present an analysis of the broadband X-ray spectra by applying the XCLUMPY model. In Section 5, we compare our results with the previous studies and discuss their torus properties. We adopt the cosmological parameters of \((H_0, \Omega_m, \Omega_{\Lambda}) = (70 \text{ km s}^{-1} \text{ Mpc}^{-1}, 0.3, 0.7)\) and the solar abundances of Anders & Grevesse (1989) throughout the paper. Errors on spectral parameters correspond to 90% confidence limits for single parameters.

2. Sample

For our study we selected two Seyfert 1 galaxies, IC 4329A (\(z = 0.0161\); Willmer et al. 1991) and NGC 7469 (\(z = 0.0163\); Springob et al. 2005), from the sample of Ichikawa et al. (2015). To constrain the torus parameters, Ichikawa et al. (2015) applied the CLUMPY model to the high-spatial-resolution infrared spectra and photometries obtained with ground-based telescopes, using the Spitzer/IRS (30 \(\mu\)m) and Herschel/PACS (70 \(\mu\)m and 160 \(\mu\)m) photometries as the upper bounds. Among them, these are the two AGNs that show low X-ray absorptions \((N_H < 10^{23} \text{ cm}^{-2})\). We excluded NGC 4151 and NGC 1365, which are classified as Seyfert 1 galaxies, but are known to show very complex, variable absorption in the X-ray bands (see, e.g., Yaqoob & Warwick 1991 and Risaliti et al. 2005, respectively).

The X-ray data of these sources were analyzed by many authors: e.g., for IC 4329A, Done et al. (2000; ASCA+RXTE), Gondoin et al. (2001; XMM-Newton+BeppoSAX), McKernan & Yaqoob (2004; Chandra/HETGS), Steenbrugge et al. (2005; XMM-Newton), Beckmann et al. (2006; INTEGRAL), Winter et al. (2009; Swift/BAT), Patrick et al. (2012; Suzaku+Swift/BAT), Miyake et al. (2016; Suzaku), Iso et al. (2016; Suzaku), and Brenneman et al. (2014; Suzaku+NuSTAR); for NGC 7469, e.g., Guainazzi et al. (1994; ASCA), Nandra et al. (2000; RXTE) De Rosa et al. (2002; BeppoSAX), Blustin et al. (2003; XMM-Newton), Scott et al. (2005; Chandra/HETGS), Winter et al. (2009; Swift/BAT), Patrick et al. (2012; Suzaku+Swift/BAT), Iso et al. (2016; Suzaku) and Middei et al. (2018; XMM-Newton+NuSTAR). The Chandra/HETGS observations (Shu et al. 2010) confirmed the presence of a narrow \((<10,000 \text{ km s}^{-1})\) in FWHM Fe K\(\alpha\) component centered at 6.4 keV in both IC 4329A (see their Appendix) and NGC 7469; in IC 4329A, excess emission is detected at \(\approx 6.0-6.4\) keV, which can be interpreted as a modestly broadened Fe K\(\alpha\) line from the disk (Brenneman et al. 2014).

Many of these works employed the pexrav model (Magdziarz & Zdziarski 1995) with an Fe K\(\alpha\) line, the pexmon model (Nandra et al. 2007), which includes self-consistently calculated fluorescence lines, or the xillver model (García et al. 2014) whose ionization parameter is fixed at zero, to represent the reflection component from the torus, or to approximate total reflection components, including that from the accretion disk. Models of relativistic reflection from the accretion disk have been applied by Done et al. (2000) and Patrick et al. (2012) for IC 4329A, and by De Rosa et al. (2002) and Patrick et al. (2012) for NGC 7469. Iso et al. (2016) systematically applied a partial covering model to local Seyfert galaxies, including our targets.

3. Observations and Data Reduction

We analyze the best-quality simultaneous broadband X-ray spectra that cover the energy band from 0.3 keV to 70 keV with a CCD energy resolution below \(\approx 10\) keV. IC 4329A was observed simultaneously with Suzaku (Mitsuda et al. 2007) and NuSTAR (Harrison et al. 2013) in 2012, and NGC 7469 was with XMM-Newton (Jansen et al. 2001) and NuSTAR in 2015. The observation log of the X-ray data used in this paper is given in Table 1. The details of data reduction are described below.

### 3.1. IC 4329A

#### 3.1.1. Suzaku

Suzaku observed IC 4329A in 2012 August. It carried four X-ray CCD cameras (X-ray imaging spectrometer, XISs; Koyama et al. 2007) and a non-imaging instrument (the hard X-ray detector, HXD; Takahashi et al. 2007), which cover the energy band below and above \(\approx 10\) keV, respectively. XIS0, XIS2, and XIS3 are frontside-illuminated CCDs (XIS-FI) and XIS1 is the backside-illuminated one (XIS-BI). The HXD consists of the PIN (10–70 keV) and GSO (40–600 keV) detectors (Kokubun et al. 2007).

We reprocessed the unfiltered XIS event data with the AEPIPELINE script. Events were extracted from a circular region with a radius of 160 arcsec centered at the source position. The background was taken from a source-free circular region with a radius of 120 arcsec. We generated the response matrix file (RMF) with XISRMFGEN and ancillary response files (ARF) with XISSIMARFGEN (Ishisaki et al. 2007). To improve the statistics, we co-added the spectra of XIS0 and XIS3. The spectrum were binned to contain at least 1000 counts per bin. We did not utilize the data of XIS1, whose effective area in the iron-K band was smaller than those of XIS-FIs, to avoid cross-calibration uncertainties.

The unfiltered HXD data were also reprocessed using AEPIPELINE. We only analyzed the PIN data, because the source was weakly detected with the GSO (Brenneman et al. 2014). We utilized the “tuned” background event files (Fukazawa et al. 2009).
to make the spectrum of the non-X-ray background (NXB), to which a simulated spectrum of the cosmic X-ray background was added. In the spectral analysis, we only utilized the 16–40 keV range, where the source flux is brighter than 3% of the NXB level (the maximum systematic error in the 15–70 keV range; see Fukazawa et al. 2009).

3.1.2. NuSTAR

NuSTAR also observed IC 4329A in 2012 August simultaneously with the Suzaku observation. NuSTAR carries two focial plane modules (FPMs: FPMA and FPMB), which cover an energy range of 3–79 keV. We analyzed the FPM data with HEAsoft v6.21 and CALDB released in 2017 December 12. We extracted the spectrum from a circular region with a 75 arcsec radius centered at the source peak, and took the background from a nearby source-free circular region with the same radius. We then combined the source spectra, background spectra, RMF, and ARF using the ADDASCASPEC script. The combined spectrum was binned to contain at least 1000 counts per bin.

3.2. NGC 7469

3.2.1. XMM-Newton

XMM-Newton observed NGC 7469 in 2015 June. It carries three X-ray CCD cameras, one EPIC/PN (Strüder et al. 2001) and MOS (Turner et al. 2001). We analyzed only the data of PN, which has a much larger effective area than the MOS detectors, using the Science Analysis Software (SAS) v17.0.0 and current calibration file released on 2018 June 22. The PN data were reprocessed with the EPPROC script. We extracted the spectrum from a circular region with a radius of 40 arcsec centered at the source peak, and took the background from a source-free circular region with a 50 arcsec radius in the same CCD chip. We generated the RMF with RMFGEN and ARF with ARFGEN. The spectrum was binned to contain at least 100 counts per bin.

3.2.2. NuSTAR

NGC 7469 was also observed with NuSTAR in 2015 June simultaneously with XMM-Newton. We extracted the FPMs spectra from a circular region with a 70 arcsec radius centered at the source peak, and took the background from a nearby source-free circular region with the same radius. We combined the spectra of FPMs, using ADDASCASPEC. The combined spectrum was binned to contain at least 100 counts per bin.

4. X-Ray Spectral Analysis and Results

It is well established from previous studies that a typical X-ray spectrum of Seyfert 1 galaxies cannot be represented by a single power law but consists of multiple components: a direct power-law component with an exponential cutoff (or thermally Comptonized component), its reflection components from the torus and/or the accretion disk, and a soft excess (see, e.g., Risaliti et al. 2004). Absorptions by ionized matter (warm absorbers) are often observed. In the iron-K band, in addition to a narrow Fe Kα emission line centered at 6.4 keV, a broad emission line feature is sometimes recognized, although its intensity and shape strongly depend on the continuum modeling. The hard X-ray continuum shows a bump structure peaked around 30 keV over a power-law component extrapolated from lower energies. The origins of these spectral features are still debated, and at least two distinct interpretations have been proposed: (1) relativistically blurred reflection from the accretion disk (e.g., Tanaka et al. 1995), and (2) partial covering by line-of-sight absorbers with multiple ionization stages (e.g., Miyakawa et al. 2012).

We perform simultaneous fit to the Suzaku/XIS (0.7–10 keV), Suzaku/HXD-PIN (16–40 keV), and NuSTAR/FPMs (3–70 keV) data for IC 4329A, and XMM-Newton/EPIC-PN (0.3–10 keV) and NuSTAR/FPMs (3–70 keV) for NGC 7469. We ignore the 1.5–2.0 keV range for IC 4329A to avoid possible calibration uncertainties in the Suzaku/XIS spectra. The observed spectra folded with the energy responses are plotted in the upper panels of Figures 1(a)–(d).

Following major previous works, here we consider two spectral models: Model 1 in which a relativistic reflection component from the accretion disk is included, for which we employ the RELXILL model (Dauser et al. 2013; García et al. 2014), and Model 2 where partial covering is applied to the direct component, for which we adopt the same model used by Iso et al. (2016). We consider the warm absorber of one layer (Model 1) or two layers (Model 2). In both models, we utilize the XCLUMPY model to represent the reflection component (with fluorescence emission lines) from the torus. Models 1 and 2 are commonly applied to the spectra of both targets.

We always consider Galactic absorption, whose column density is fixed at the value estimated from the H I map by (Kalberla et al. 2005) for each target. To correct for relative calibration differences in the effective area among the instruments, we multiply a constant factor to the spectra. For IC 4329A, it is fixed at unity for Suzaku/XIS and at 1.16 for Suzaku/HXD-PIN (based on the calibration with the Crab Nebula), and is left free for NuSTAR/FPMs. For NGC 7469, it is fixed at unity for XMM-Newton/EPIC-PN and is left free for NuSTAR/FPMs.

4.1. Model 1: Relativistic Reflection Model

Model 1 is composed of a direct power-law component, its relativistic reflection component from the inner accretion disk, and that from the torus. The first two components are subject to a warm absorber in the line of sight. In the XSPEC terminology, the model is expressed as:

\[
\text{Model 1} = \text{const} \times \text{phabs} * (\text{zxispcf} * (\text{zcutoffpl} + \text{compTT} + \text{relxill}) + \text{atable(xclumpy_R.fits}) + \text{atable(xclumpy_L.fits}} + \text{zgauss})).
\]

(1)

(1) The \text{const} and \text{phabs} terms represent the cross-calibration constant and the Galactic absorption, respectively.

(2) The \text{zcutoffpl} term represents the direct component (cutoff power law), the \text{compTT} term the soft excess (thermal Comptonization model by Titarchuk 1994), and the \text{relxill} term the reflection component from the accretion disk based on the RELXILL code.

\text{Another interpretation considering dual power-law components has been proposed by, e.g., Noda et al. (2013); see also Kawaguchi et al. (2001) for an earlier theoretical work.}
All components are subject to absorption by a warm absorber (zxipcf). The compTT term is required only in NGC 7469.

RELXILL is a state-of-the-art relativistic reflection model, which combines the XILLVER code (García et al. 2014), a reflection model from an ionized disk, with relativistic broadening by the RELLINE code (Dauser et al. 2010, 2013). The free parameters of RELXILL are the inclination angle of the observer with respect to the accretion disk (i), the iron abundance (Z\text{Fe}), the photon index, the ionization parameter of the disk (ξ), the fraction of reflected flux (R = Ω/2π, where Ω is the solid angle of the reflector), the spin parameter of the SMBH (a), the inner (q_1) and outer (q_2) emissivity indices, the radius at which the emissivity index changes (R_m), the inner (R_{in}) and outer (R_{out}) radii of the disk, and the cutoff energy. We assume Z\text{Fe} = 1.0 (solar abundance), q_1 = q_2 = 2.4 (hence R_{br} is dummy), which is a mean value for local Seyfert 1 galaxies obtained by Patrick et al. (2012), and R_{out} = 10^3 r_G (where r_G is the gravitational radius of the SMBH). We fix a = 0, which cannot be well constrained by the data. The inclination i is fixed at the value determined from the infrared data by Ichikawa et al. (2015). The photon index, normalization, and cutoff energy are linked to those of the zcutoffpl term.

(3) The table models (atable{xclumpy_R.fits} and atable{xclumpy_L.fits}) correspond to the reflection continuum and emission lines from the torus, respectively, based on the XCLUMPY model. The parameters are the photon index, cutoff energy, equatorial hydrogen column density (N_H^\text{tor}), torus angular width (σ), and inclination angle (i). The photon index, normalization, and cutoff energy are linked to those of the zcutoffpl term. The values of σ and i are fixed at those determined from the infrared data by Ichikawa et al. (2015).

4 The other parameters, the inner and outer radii of the torus, the radius of each clump, the number of clumps along the equatorial plane, and the index of radial density profile, are fixed at 0.05, 1.00, 0.002, 10.0, and 0.50 pc, respectively (Tanimoto et al. 2019).

Figure 1. Observed broadband spectra of IC 4329A and NGC 7469 folded with the energy responses. The best-fit models are overplotted. Left: Model 1. Right: Model 2. Upper: IC 4329A. Lower: NGC 7469. In the upper panels, the folded spectra of Suzaku/XIS (black crosses), Suzaku/HXD-PIN (green crosses), and NuSTAR/FPMs (red crosses) are plotted for IC 4329A, and those of XMM-Newton/EPIC-PN (black crosses) and NuSTAR/FPMs (red crosses) are plotted for NGC 7469. The solid curves represent the best-fit models. In the lower panels, the fitting residuals in units of 1σ error are shown.
Table 2
Best-fit Parameters of IC 4329A

| Component   | No. | Parameter   | Model 1                      | Model 2                      | Units       |
|-------------|-----|-------------|------------------------------|------------------------------|-------------|
| ZXIPCF1     | (1) | \( N_{\text{H}} \) | 5.68^{+0.09}_{-0.10}       | 5.92^{+0.12}_{-0.12}        | \( 10^{21} \) cm\(^{-2} \) |
|             | (2) | \( \log \xi \) | 0.27^{+0.01}_{-0.10}       | 0.17^{+0.10}_{-0.09}       |             |
| ZXIPCF2     | (3) | \( N_{\text{H}} \) | ...                        | 1.04^{+0.06}_{-0.14}       | \( 10^{24} \) cm\(^{-2} \) |
|             | (4) | \( \log \xi \) | ...                        | 1.91^{+0.06}_{-0.14}       |             |
|             | (5) | \( C_{\text{line}} \) | ...                        | 0.23^{+0.01}_{-0.02}       |             |
| ZCUTOFFPL   | (6) | \( \Gamma \) | 1.77^{+0.01}_{-0.00}       | 1.83^{+0.01}_{-0.01}       | keV         |
|             | (7) | \( E_{\text{cut}} \) | 318^{+55}_{-46}            | 1000^{+73}_{-88}           | keV         |
|             | (8) | \( K_{p} \) | 3.05^{+0.02}_{-0.03}       | 4.21^{+0.13}_{-0.14}       | \( 10^{-2} \) photon cm\(^{-2} \) s\(^{-1} \) |
| ZGAUSS      | (9) | \( E_{\text{line}} \) | 0.77^{+0.01}_{-0.00}       | 0.77^{+0.01}_{-0.01}       | keV         |
|             | (10)| \( \sigma_{\text{line}} \) | 2.98^{+0.27}_{-0.25}       | 3.17^{+0.50}_{-0.46}       | \( 10^{-2} \) keV |
|             | (11)| \( K_{\text{L}} \) | 4.07^{+0.07}_{-0.04}       | 3.99^{+0.40}_{-0.36}       | \( 10^{-4} \) photon cm\(^{-2} \) s\(^{-1} \) |
| RELXILL     | (12)| \( \log \xi \) | 0.29^{+0.01}_{-0.00}       | ...                        |             |
|             | (13)| \( R_{\text{in}} \) | 87^{+73}_{-31}             | ...                        | \( r_{G} \) |
|             | (14)| \( R \) | 3.20^{+0.13}_{-0.25}       | ...                        | \( 10^{3} \) |
| XCLUMPY     | (15)| \( \log \frac{N_{\text{HI}}}{N_{\text{H}}} \) | 0.66^{+0.10}_{-0.13}       | 1.35^{+0.08}_{-0.09}       | \( 10^{23} \) cm\(^{-2} \) |
|             | (16)| \( \sigma \) | 40 (fixed)                | 40 (fixed)                 | degree      |
|             | (17)| \( \theta \) | 18.19 (fixed)             | 18.19 (fixed)              | degree      |
|             | (18)| \( C_{\text{NuSTAR}} \) | 0.97^{+0.01}_{-0.00}       | 0.97^{+0.01}_{-0.01}       | \( 10^{13} \) erg s\(^{-1} \) |
|             | (19)| \( L_{2-10} \) | 6.47                      | 8.14                      |             |
|             |     | \( \chi^{2}/\text{dof} \) | 1338.8/1120              | 1324.6/1120               |             |

Notes. (1) Hydrogen column density of a full absorber. (2) Its logarithmic ionization parameter, \( \xi \) (erg cm s\(^{-1} \)). (3) Hydrogen column density of a partial absorber. (4) Its logarithmic ionization parameter. (5) Its covering fraction. (6) Photon index. (7) Cutoff energy. (8) Power-law normalization of the direct component. (9) Energy of the emission line. (10) Line width of the emission line. (11) Normalization of the emission line. (12) Logarithmic ionization parameter of the accretion disk. (13) The inner radius of the disk. (14) Reflection strength. (15) Torus hydrogen column density along the equatorial plane. (16) Torus angular width. (17) Inclination angle. (18) Cross-calibration constant of NuSTAR relative to Suzaku/XIS. (19) Intrinsic luminosity in the 2–10 keV.

\( ^{a} \) The upper limit is pegged at the upper boundary value in the table model.

\( ^{b} \) Because the infrared result (\( i = 4^{+3}_{-2} \) degrees) is out of the allowed range of XCLUMPY, we fix it at its lower limit (18°); differences from \( i = 4 \) are expected to be negligible (Tanimoto et al. 2019).

(4) The \texttt{zgauss} term represents an emission line feature at 0.77 keV in IC 4329A (Brenneman et al. 2014).

We find that this model reproduces the broadband spectra of both IC 4329A (\( \chi^{2}/\text{dof} = 1338.8/1120 \)) and NGC 7469 (\( \chi^{2}/\text{dof} = 1668.7/1574 \)). The best-fit parameters are summarized in the second columns of Tables 2 and 3, and the best-fit models folded with the responses and the fitting residuals are plotted in Figures 1(a) and (c) for IC 4329A and NGC 7469, respectively. The best-fit models in units of \( E(\xi) \), where \( I \) is the energy flux at the energy \( \xi \), are plotted in Figures 2(a) and (c) for IC 4329A and NGC 7469, respectively.

4.2. Model 2: Partial Covering Model

As an alternative interpretation of X-ray spectra of Seyfert 1 galaxies to relativistic reflection models, Miyakawa et al. (2012) proposed the “variable partial covering” model and applied it for the spectral and timing analysis of MCG–6–30–15 (see also Miller et al. 2008 for an earlier work). In this model, the broad iron-K emission line feature is produced mainly by a deep iron K-edge structure due to the partial absorber in the line of sight. Iso et al. (2016) applied the same model to the Suzaku data of 20 nearby AGNs and found that it can reproduce the observations, including time variability. Our Model 2, which is based on the model in Iso et al. (2016), is expressed in XSPEC terminology as follows:

\[
\text{Model2} = \text{const} \times \text{phabs} \\
* (\text{zxipcf} \times \text{zxipcf} \times \text{zcutoffpl} + \text{compTT}) \\
+ \text{atable}(\text{xclumpy_Rfits}) + \text{atable}(\text{xclumpy_Lfits}) \\
+ \text{zgauss}.
\]

(2)

(1) Same as Model 1-(1).

(2) The \texttt{zcutoffpl} term represents the direct component and the \texttt{compTT} term represents the soft excess. Two layers of absorption by ionized matter (\texttt{zxipcf}) are multiplied, one of which is a partial absorber with a large column density (\( N_{\text{H}} \sim 1 \times 10^{24} \) cm\(^{-2} \)). Note that Miyakawa et al. (2012) considered three warm absorbers for MCG–6–30–15, whereas two are sufficient to explain our spectra of IC 4329A and NGC 7469.

(3) Same as Model 1-(3).

(4) Same as Model 1-(4).

We also find that Model 2 gives a fairly good description of the broadband spectra for both targets (\( \chi^{2}/\text{dof} = 1324.6/1120 \) for IC 4329A and 1683.6/1574 for NGC 7469). Tables 2 and 3 (third columns) summarize the best-fit parameters, Figures 1(b) and (d) plot the best-fit folded models and the residuals, and
**Table 3**

Best-fit Parameters of NGC 7469

| Component | No. | Parameter | Model 1 | Model 2 | Units |
|-----------|-----|-----------|---------|---------|-------|
| ZXIPCF1   | (1) | $N_H$     | 1.30$^{+0.15}_{-0.20}$ | 1.56$^{+0.13}_{-0.14}$ | $10^{21}$ cm$^{-2}$ |
|           | (2) | log $\xi$ | 2.49 ± 0.06 | 2.40 ± 0.05 | |
| ZXIPCF2   | (3) | $N_H$     | ...        | 1.80$^{+0.22}_{-0.21}$ | $10^{24}$ cm$^{-2}$ |
|           | (4) | log $\xi$ | ...        | 3.18$^{+0.22}_{-0.14}$ | |
|           | (5) | $C_{\text{dust}}$ | ... | 0.15 ± 0.04 | |
| ZCUTOFFPL | (6) | $\Gamma$  | 1.92$^{+0.06}_{-0.04}$ | 1.84$^{+0.04}_{-0.02}$ | keV |
|           | (7) | $E_{\text{cut}}$ | 322$^{+678}_{-122}$ | 321$^{+679}_{-139}$ | |
|           | (8) | $K_P$     | 9.22$^{+0.96}_{-0.80}$ | 8.90$^{+1.04}_{-0.43}$ | $10^{-3}$ photon cm$^{-2}$ s$^{-1}$ |
| COMPTT    | (9) | $T_{\text{bb}}$ | 8.10$^{+0.74}_{-0.35}$ | 8.61$^{+0.18}_{-0.12}$ | $10^{-2}$ keV |
|           | (10)| $T_P$     | 2.40$^{+1.20}_{-1.20}$ | 9.60$^{+7.28}_{-7.09}$ | keV |
|           | (11)| $\tau$   | 3.21$^{+0.56}_{-0.46}$ | 1.04$^{+0.18}_{-0.14}$ | |
|           | (12)| $K_S$     | 1.68$^{+0.57}_{-0.61}$ | 5.11$^{+0.95}_{-0.81}$ | $10^{-2}$ photon cm$^{-2}$ s$^{-1}$ |
| RELXILL   | (13)| log $\xi$ | 0.99$^{+0.75}_{-0.28}$ | ... | |
|           | (14)| $R_{\text{in}}$ | 9.4$^{+26}_{-24}$ | ... | $R_G$ |
|           | (15)| $R$       | 2.64$^{+0.22}_{-0.50}$ | ... | $10^{-3}$ |
| XCLUMPY   | (16)| $N_H^{\text{Eq}}$ | 1.00$^{+0.32}_{-0.17}$ | 1.00$^{+0.41}_{-0.16}$ | $10^{24}$ cm$^{-2}$ |
|           | (17)| $\sigma$  | 21 (fixed) | 21 (fixed) | degree |
|           | (18)| $i$       | 59 (fixed) | 59 (fixed) | degree |
|           | (19)| $C_{\text{Nstar}}$ | 1.13 ± 0.01 | 1.13 ± 0.01 | $10^{43}$ erg s$^{-1}$ |
|           | (20)| $L_{2-10}$ | 1.68 | 1.83 | |
|           |     | $\chi^2$/dof | 1668.7/1576 | 1683.6/1576 | |

Notes. (1) Hydrogen column density of a full absorber. (2) Its logaritmic ionization parameter, $\xi$ (erg cm s$^{-1}$). (3) Hydrogen column density of a partial absorber. (4) Its logarithmic ionization parameter. (5) Its covering fraction. (6) Photon index. (7) Cutoff energy. (8) Power-law normalization of the direct component. (9) Input soft photon temperature. (10) Plasma temperature. (11) Plasma optical depth. (12) Normalization. (13) Logarithmic ionization parameter of the accretion disk. (14) The inner radius of the disk. (15) Reflection strength. (16) Torus hydrogen column density along the equatorial plane. (17) Torus angular width. (18) Inclination angle. (19) Cross-calibration constant of $\text{Nstar}$ relative to $\text{XMM-Newton}/\text{EPIC-PN}$. (20) Intrinsic luminosity in the 2–10 keV.

The upper limit is pegged at the upper boundary value in the table model.

Figures 2(b) and (d) plot the best-fit models in units of $E_l(E)$ for IC 4329A and NGC 7469, respectively.

5. Discussion

We have presented the results of our application of the X-ray clumpy torus model (XCLUMPY) to the broadband (0.3–70 keV) spectra of two Seyfert 1 galaxies, IC 4329A and NGC 7469. This is the first work that utilizes the XCLUMPY model for type-1 AGNs. We find that both Model 1 (relativistic reflection model) and Model 2 (partial covering model) are able to reproduce the observed spectra almost equally well. This confirms the degeneracy in interpreting the physical origins of the X-ray spectra of type-1 AGNs just by utilizing the time-averaged spectroscopy. As mentioned in Section 1, we do not aim to favor or disfavor of either of the two interpretations in this paper. Below, we compare the results of the two models with previous works that adopted similar models (Section 5.1). Then, we discuss the torus properties of these AGNs by comparing our XCLUMPY results with the infrared results (Section 5.2), which is the main purpose of our work.

5.1. Comparison with Previous Studies

We have estimated the realistic contribution of the reflection component from the torus in the broadband X-ray spectrum. The contribution to the total flux in the 10–50 keV band is found to be 1.8% (Model 1) and 4.5% (Model 2) for IC 4329A, and 11% (Model 1) and 14% (Model 2) for NGC 7469. In IC 4329A, we obtain a smaller $N_H^{\text{Eq}}$ value (hence a weaker intensity) with Model 1 than with Model 2. This is probably because a part of the narrow emission-line flux can also be accounted for by the emission line component in the RELXILL model under limited energy resolution. Future high-energy-resolution spectroscopy, by instruments such as X-Ray Imaging and Spectroscopy Mission and Athena, will help us separate the two components. In the case of NGC 7469, almost similar values are obtained with Models 1 and 2. In NGC 7469, the best-fit RELXILL model produces a much broader Fe Kα line than that in the XCLUMPY model, hence such degeneracy can be ignored.

Previous works often utilized either pexrav or pexmon (Gondoin et al. 2001; Iso et al. 2016, and Miyake et al. 2016 for IC 4329A; Nandra et al. 2000 and Iso et al. 2016 for NGC 7469), or (unblurred) xillver with $\xi = 0$ (Brenneman et al. 2014 for IC 4329A; Middei et al. 2018 for NGC 7469) to represent the reflection component from distant matter or to approximate total reflection components, including that from the accretion disk. A notable difference is that XCLUMPY with $N_H^{\text{Eq}} \leq 10^{24}$ cm$^{-2}$ produces a much weaker reflection hump at $\sim$30 keV because the reflector is not as optically thick as assumed in pexrav or xillver. In fact, when we replace XCLUMPY with pexmon in our models, the flux of the torus reflection component at 30 keV is increased by a factor of 5.0.
for IC 4329A and by 2.0 for NGC 7469 compared with the case of XCLUMPY. This inevitably affects estimates of the other spectral parameters. Thus, it is very important to adopt a realistic model for the torus reflection for correctly interpreting the broadband X-ray spectra of AGNs.

In Model 1 we consider two reflection components, one from the torus and the other from the inner accretion disk utilizing the RELXILL code. Our model yields $R_{in} = 87^{+73}_{-33} r_G$ for IC 4329A, and $R_{in} = 9.4^{+26}_{-5.4} r_G$ for NGC 7469, by assuming the emissivity index $q = 2.4$, the spin parameter $a = 0$, and the inclination angle ($i$) determined by the infrared data. This would suggest that the accretion disk in IC 4329A is truncated before reaching the innermost stable orbit (ISCO), supporting the argument by Done et al. (2000). In contrast, our result is consistent with the disk in NGC 7469 extending to the ISCO ($R_{in} = R_{ISCO}$, $a = 0.78^{+0.18}_{-0.17}$, $q = 1.7^{+0.1}_{-0.08}$, and $i = 80^{+3}_{-3}$ degrees, where $R_{ISCO}$ is the radius of the ISCO).

In Model 2, we confirm the claim by Iso et al. (2016) that a partial covering model with a large column density of $N_H \sim 10^{24} \text{ cm}^{-2}$ can reproduce the data without invoking a relativistic reflection from the accretion disk. The best-fit column density and ionization parameter of the absorbers are not exactly the same as those in Iso et al. (2016): they obtained $N_H = 1.62^{+0.27}_{-0.27} \times 10^{24} \text{ cm}^{-2}$ and $\log \xi_2 = 1.49^{+0.23}_{-0.32}$ for IC 4329A and $N_H = 1.64^{+1.06}_{-0.25} \times 10^{24} \text{ cm}^{-2}$ and $\log \xi_2 = 1.42^{+0.58}_{-0.44}$ for NGC 7469 (their Table 2) and a full absorber (ZXIPCF1) is not required in both targets. The discrepancy probably occurred because we utilized a simplified zxipcf model, whereas Iso et al. (2016) utilized their own XSTAR-based warm absorber model. Also, the difference between XCLUMPY and pexrav, which is utilized by

![Figure 2. Best-fit models in units of $E_{iE}$ (where $E_i$ is the energy flux at the energy $E$). Left: Model 1. Right: Model 2. Upper: IC 4329A. Lower: NGC 7469. Black line: total. Red line: direct component. Green line: reflection component from the accretion disk. Blue line: reflection continuum from the torus. Light blue line: emission lines from the torus. Orange line: soft excess. Purple line: emission line at 0.77 keV.](image-url)
Iso et al. (2016), could have affected the fit. Application of more sophisticated absorption models utilizing XSTAR is beyond the scope of this paper.

5.2. Comparison with the Infrared Results

In a type-1 AGN that shows no line-of-sight absorption, the equivalent width of a narrow iron Kα line carries key information on the torus parameters, assuming that the contributions to the line flux from the outer accretion disk and/or BLR are unimportant. There is, however, degeneracy among the parameters, $N_{\text{H}}^\text{equiv}$, $\sigma$, and $i$ (see the Appendix). To avoid it, we have fixed $\sigma$ and $i$ at the values obtained from the infrared observations by Ichikawa et al. (2015). This enables us to make a direct comparison of $N_{\text{H}}^\text{equiv}$ with the infrared results. While X-rays measure all material (gas and dust) among which gas is dominant in mass, infrared data are only sensitive to the amount of dust. Thus, we can constrain the gas-to-dust ratio (in terms of the ratio between the optical extinction and the X-ray column density) in the torus. In this analysis, it is implicitly assumed that the gas and dust have the same spatial distribution.

Ichikawa et al. (2015) determined the V-band extinction along the equatorial plane to be $A_V = (1.93 \pm 0.17) \times 10^3$ mag for IC 4329A and $A_V = 1.75^{+0.33}_{-0.33} \times 10^3$ mag for NGC 7469. Combining the X-ray results with these $A_V$ values, we derive the $N_{\text{H}}/A_V$ ratios to be $(2.8-7.4) \times 10^{19}$ cm$^{-2}$ mag$^{-1}$ (IC 4329A) and $(4.7-8.2) \times 10^{20}$ cm$^{-2}$ mag$^{-1}$ (NGC 7469), which are smaller than the canonical value of Galactic ISM, $1.87 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$ (Draine 2003), by factors of 25–68 and 2.3–3.9 for IC 4329A and NGC 7469, respectively; when we compare our results with those obtained by Maiolino et al. (2001), the differences are further enhanced by factors of $5-10$. This result suggests that their tori are more “dusty” than, or have different dust properties (e.g., size distribution) from, Galactic ISM.

To confirm this trend in an alternative way, we also perform spectral analysis by fixing $N_{\text{H}}^\text{equiv}$ at the infrared results (converted with the Galactic $N_{\text{H}}/A_V$ ratio) and leaving $\sigma$ free. Then, we obtain $\sigma \leq 10^{\pm1}$ (Model 1, 2)$^6$ for IC 4329A, and $\sigma = 17.8^{+1.0}_{-0.2}$ degrees (Model 1) and $\sigma = 20.0^{+0.8}_{-1.0}$ degrees (Model 2) for NGC 7469. These $\sigma$ values are smaller than the infrared results, $40^\circ \pm 1^\circ$ (IC 4329A) and $21^\circ \pm 2^\circ$ (NGC 7469). In this picture, the gas-to-dust ratio is the same as the Galactic ISM at the equatorial plane but rapidly decreases with the elevation angle (i.e., the dust is vertically more extended than the gas), making the “averaged” gas-to-dust ratio in the torus smaller than the Galactic value.

On the basis of the X-ray results on $\sigma$, it is possible to infer the covering fraction of the torus (with $N_{\text{H}} > 10^{22}$ cm$^{-2}$), $C_T$. In XCLUMPY, the mean hydrogen column density at the elevation angle $\theta = (\theta_2 - \theta_1) / 2$ is given by

$$N_{\text{H}}(\theta) = N_{\text{H}}^\text{equiv} \exp\left(-\left(\frac{\theta}{\sigma}\right)^2\right).$$

Defining $\theta_1$ such that $N_{\text{H}}(\theta_1) = 10^{22}$ cm$^{-2}$, we find $\theta_1 \leq 24^\circ5$ and $\theta_2 = 27^\circ9 - 50^\circ0$, which correspond to $C_T \leq 0.41$ and $C_T = 0.47-0.77$ for IC 4329A and NGC 7469, respectively.

We can compare these values with the predictions from Ricci et al. (2017), who showed that the Eddington ratio $\lambda_{\text{Ed}}$ is the key parameter that determines the torus geometry. At $\lambda_{\text{Ed}} = 0.13-0.16$ (for IC 4329A) and $\lambda_{\text{Ed}} = 0.36-0.40$ (for NGC 7469), the mean torus covering fractions are predicted to be $\sim 0.22-0.44$ and $\sim 0.22-0.42$, respectively (Ricci et al. 2017). Our result for IC 4329A is consistent with this prediction, whereas for NGC 7469 is larger than it. We might be overestimating the torus reflection component in NGC 7469 because of possible contributions from the outer accretion disk and/or BLR in the observed iron-K line flux. Even if it is the case, it strengthens our conclusion that the torus is dusty.

Our results suggest that at least a non-negligible fraction of AGNs have more “dusty” torus than Galactic ISM. This argument may seem to be the opposite of the well-known previous results reporting larger $N_{\text{H}}/A_V$ values than in Galactic ISM in some AGNs (e.g., Maiolino et al. 2001). However, we note that the sample of Maiolino et al. (2001) is not an unbiased one but is consists of AGNs that show cold absorption in X-rays and optical broad emission lines. On the basis of the “dust color” method to measure optical extinction, Burtscher et al. (2016) showed that $N_{\text{H}}/A_V$ values were on average consistent with the Galactic value when variability in $N_{\text{H}}$ due to dust-free gas in the BLR is considered, except for heavily obscured AGNs. In fact, by applying the XCLUMPY model to 12 obscured AGNs in the Ichikawa et al. (2015) sample, A. Tanimoto et al. (2019, in preparation) reported that the mean value of $N_{\text{H}}/A_V$ in the line-of-sight material is similar to the Galactic ISM value, although there is a large scatter ($\sim$1 dex) among the sample. The reason behind the variation in $N_{\text{H}}/A_V$ among individual objects is unclear. The mid-infrared to X-ray luminosity ratios of IC 4329A and NGC 7469 are located close to the standard correlation (Ichikawa et al. 2019), apparently implying that the total amounts of dust are not largely different from other AGNs. Further systematic studies using a larger sample are required to solve this issue.

6. Conclusion

In this paper, we have reported the application of the X-ray clumpy torus model XCLUMPY to the broadband spectra of two Seyfert 1 galaxies, IC 4329A and NGC 7469, whose torus parameters were obtained from the infrared spectra (Ichikawa et al. 2015). This is the first work that utilizes XCLUMPY for unobscured AGNs. We have shown that the intensity of the narrow Fe Kα fluorescence line can be used to infer the torus geometry, even in type-1 AGNs that show no line-of-sight absorption. The main conclusions are summarized below.

1. We are able to well produce the simultaneously observed broadband (0.3–70 keV) spectra of both targets with two different models containing XCLUMPY: (Model 1) a relativistic reflection model and (Model 2) partial covering model. By fixing the angular width and inclination at the values determined by the infrared spectra, we constrain the column density along the equatorial plane for each object.

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$^6$ The lower limit is pegged at 10$^2$ (the lower boundary value in the table model).

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$^7$ Here, we adopt the black hole masses $M_{\text{BH}} = 1.2 \times 10^6 M_\odot$ for IC 4329A (de La Calle Pérez et al. 2010) and $M_{\text{BH}} = 1.1 \times 10^7 M_\odot$ for NGC 7469 (Peterson et al. 2014), and convert the 2–10 keV luminosities to bolometric ones with a correction factor of 30.
2. The XCLUMPY component (i.e., the torus reflection component) produces a weaker hump structure at \( \sim 30 \) keV compared with other reflection models such as pexmon and xillver. This fact must be correctly taken into account when interpreting AGN broadband spectra.

3. By comparing with the infrared results, the \( N_H/A_V \) ratios are found to be factors of 25–68 and 2.3–3.9 smaller than the Galactic ISM value for IC 4329A and NGC 7469, respectively. This is the opposite of the trend reported for some AGNs (e.g., Maiolino et al. 2001). Our results suggest that a non-negligible fraction of AGNs have more “dusty” tori than Galactic ISM.

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**Facilities:** XMM-Newton, Suzaku, NuSTAR.

**Software:** HEAsoft (HEASARC 2014), SAS (v17.0.0; Gabriel et al. 2004), NUSTARDAS, XSPEC (Arnaud et al. 1996), RELXILL (Dauser et al. 2013; García et al. 2014), XCLUMPY (Tanimoto et al. 2019).

**Appendix**

Predicted Fe K\( \alpha \) Equivalent Width from XCLUMPY for Unobscured AGNs

Using XCLUMPY, we investigate dependences of predicted iron-K equivalent width on torus parameters: hydrogen column density along the equatorial plane (\( N_H^{\text{Equ}} \)), torus angular width (\( \sigma \)), and inclination angle (\( i \)). Figure 3 plots the predicted iron-K equivalent width for type-1 AGNs as a function of the torus parameters.

**Figure 3.** Predicted iron-K equivalent width for type-1 AGNs plotted as a function of torus parameter: (a) hydrogen column density along the equatorial plane, (b) torus angular width, and (c) inclination angle. The blue, orange, green, red, and violet lines correspond to photon indices of \( \Gamma = 1.5, 1.75, 2.0, 2.25, 2.5 \), respectively. We adopt \( \log N_H^{\text{Equ}}/\text{cm}^{-2} = 24.0, \sigma = 30^\circ, i = 30^\circ \), and \( E_{\text{Cut}} = 100 \) keV. We note that the line-of-sight absorption is \( \log N_H \sim 24 \) in the case of \( \log N_H^{\text{Equ}} \sim 26 \).
