

# **Development of Monte Carlo Based X-Ray Clumpy Torus Model and Its Applications to Nearby Obscured Active Galactic Nuclei**



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# Abstract

An active galactic nucleus (AGN) is essential for understanding the coevolution between the supermassive black hole (SMBH) and the host galaxy. Many studies indicated that the ubiquitous presence of an obscuring matter composed of gas and dust (so-called “clumpy torus”) around the accreting SMBH (e.g., Antonucci, 1993; Urry & Padovani, 1995; Netzer, 2015; Ramos Almeida & Ricci, 2017). This clumpy torus plays an essential role in AGN feeding that connects the SMBH and the host galaxy as a mass reservoir. However, the basic properties of the clumpy torus (e.g., the hydrogen column density and the covering factor) are still unclear.

X-ray observations are a powerful tool to investigate the nature of the surrounding material around the SMBH. This is because X-rays can trace all matter, including gas and dust at various physical conditions. The X-ray spectrum of the AGN mainly consists of two components: (1) direct component from the center and (2) reflection component from the accretion disk and the torus. This torus reflection component carries essential information on the torus structure. For instance, the relative intensity to the direct component, shape of the reflection continuum, and the fluorescent Fe  $K\alpha$  line at 6.4 keV depend strongly on the hydrogen column density and the covering factor. To investigate the torus structure from the X-ray spectrum of the AGN, Monte Carlo radiative transfer simulations from complex structures are indispensable. However, it is only recently that X-ray spectra models from clumpy torus have been developed. Hence we worked on the following two studies.

In Chapter 3, we construct an X-ray spectral model from the clumpy torus (XClumpy) using the Monte Carlo simulation for Astrophysics and Cosmology framework (MONACO: Odaka et al. 2016). The adopted geometry of the torus is the same as that in Nenkova et al. (2008a,b), who assumes the power law distribution of clumps in the radial direction and the Gaussian distribution in the elevation direction. We examine the dependence of the X-ray continuum and Fe  $K\alpha$  fluorescence line profile on the torus parameters. We compare our model with other torus models: MYTorus model (Murphy & Yaqoob, 2009), Ikeda model (Ikeda et al., 2009), and CTorus model (Liu & Li, 2014). As an example, we also present the results applied to the broadband X-ray spectra of the Circinus galaxy observed with XMM-Newton, Suzaku, and NuSTAR. Our model well reproduces the broadband X-ray spectra. We obtain a hydrogen column density along the equatorial plane  $N_{\text{H}}^{\text{Equ}} = 9.08^{+0.14}_{-0.08} \times 10^{24} \text{ cm}^{-2}$ , a torus angular width  $\sigma = 14.7^{+0.44}_{-0.39}$  degree, and a 2–10 keV luminosity  $\log L_{2-10}/\text{erg s}^{-1} = 42.5$ .

In Chapter 4, we apply XClumpy (Tanimoto et al., 2019) to the broadband X-ray spectra of 10 obscured AGNs observed with both Suzaku and NuSTAR. The infrared spectra of these AGNs were analyzed by Ichikawa et al. (2015) with the CLUMPY code (Nenkova et al., 2008a,b). Since XClumpy adopts the same clump distribution as that in the CLUMPY, we can directly compare the torus parameters obtained from the X-ray spectra and those from the infrared ones. Our model well reproduces the broadband X-ray spectra of all objects. The torus angular widths determined from the infrared spectra ( $\sigma_{\text{IR}}$ ) are systematically larger than those from the X-ray data ( $\sigma_{\text{X}}$ ); the difference ( $\sigma_{\text{IR}} - \sigma_{\text{X}}$ ) correlates with the inclination angle determined from the X-ray spectrum. These results can be explained by contribution from dusty polar outflows to the observed infrared flux, which becomes more significant at higher inclinations (more edge-on views). The ratio of the hydrogen column density and V-band extinction in the line of sight absorber shows large scatter ( $\sim 1$  dex) around the Galactic value, suggesting that a significant fraction of AGNs have dust-rich circumnuclear environments.

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# Chapter 1

## Introduction

### 1.1 Overview of Active Galactic Nucleus

#### 1.1.1 Coevolution between the SMBH and the Host Galaxy

One of the most critical questions in astronomy is to understand how a supermassive black hole (SMBH) was born and has grown in the Universe. Recent studies indicated that the SMBH ( $10^6$ – $10^9 M_\odot$ ) universally exists at the galaxy center. Remarkably, the SMBH mass is proportional to the bulge mass (e.g. Magorrian et al., 1998; Marconi & Hunt, 2003; Gültekin et al., 2009; Kormendy & Ho, 2013). Figure 1.1 shows the correlation between the SMBH mass and the bulge mass. This fact suggests that the SMBH and the host galaxy have coevolved. Nevertheless, the mechanism of the coevolution is still unclear.

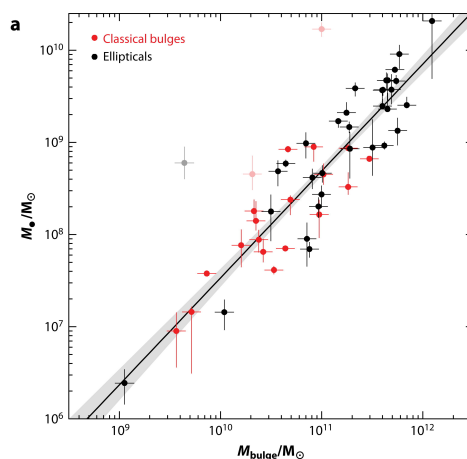


Figure 1.1: The correlation between the SMBH mass and the bulge mass (Kormendy & Ho, 2013).

### 1.1.2 Active Galactic Nucleus (AGN)

To understand the coevolution between the SMBH and the host galaxy, an active galactic nucleus (AGN) is the principal object. AGNs are the most energetic persistent objects in the Universe and their central engine is mass accretion. The mass accretion onto the SMBH leads to the conversion of the gravitational potential energy into the electromagnetic radiation. In other words, AGNs are the growth process of SMBHs. Hence we can examine the SMBH growth history by AGN observations. This Chapter 1.1.2 introduces several basic concepts related to the accretion.

#### Eddington Luminosity

The Eddington luminosity is the maximum luminosity in a spherically symmetric mass accretion. Here we briefly define the Eddington luminosity and Eddington ratio. Let us consider a gas particle around the SMBH with the mass  $M_{\text{BH}}$  and the luminosity  $L_{\text{BH}}$ . The gravity attracts this particle inward, while the radiation pressure pushes it outward. When  $L_{\text{BH}}$  is small, the radiation pressure force is smaller than the gravitational force. In this case, the SMBH can confine the particle. As  $L_{\text{BH}}$  becomes larger, the radiation pressure force also increases and eventually overcomes the gravitational force. Then, the radiation pressure blows off the gas particle. Hence the gas cannot accrete onto the SMBH. This maximum luminosity is the Eddington luminosity  $L_{\text{Edd}}$ .

Let us derive the Eddington luminosity for spherical accretion flow comprising pure hydrogen. The gravitational force  $F_{\text{G}}$  is

$$F_{\text{G}} = \frac{GM_{\text{BH}}m_{\text{H}}}{r^2} \quad (1.1)$$

where  $G$  is the gravitational constant,  $M_{\text{BH}}$  is the SMBH mass,  $m_{\text{H}}$  is the hydrogen mass, and  $r$  is the radius. The radiation pressure force  $F_{\text{R}}$  is

$$F_{\text{R}} = \frac{\sigma_{\text{T}}L_{\text{BH}}}{4\pi r^2 c} \quad (1.2)$$

where  $\sigma_{\text{T}}$  is the Thomson scattering cross section and  $c$  is the light speed. By equating these forces (Equation (1.1) and (1.2)), we obtain the Eddington luminosity,

$$L_{\text{Edd}} = \frac{4\pi GM_{\text{BH}}m_{\text{H}}c}{\sigma_{\text{T}}} \quad (1.3)$$

$$\simeq 1.25 \times 10^{38} \frac{M_{\text{BH}}}{M_{\odot}} \text{erg s}^{-1}. \quad (1.4)$$

We can also define the Eddington ratio  $\lambda_{\text{Edd}}$  by using  $L_{\text{Edd}}$ :

$$\lambda_{\text{Edd}} = \frac{L_{\text{BH}}}{L_{\text{Edd}}} \quad (1.5)$$

## Standard Disk

The accretion onto black holes is one of the most fundamental concepts for understanding various active phenomena in the Universe. In the 1970s, Shakura & Sunyaev (1973) proposed geometrically thin and optically thick accretion disk (standard disk). Kato et al. (2008) summarizes the assumptions of the standard disk model:

1. The SMBH determine the gravitational field.
2. They ignored the self-gravity of the disk.
3. The disk is steady.
4. The disk is axisymmetric.
5. The disk is geometrically thin.
6. The disk is optically thick.
7. Keplerian rotation is dominant.
8. Hydrostatic balance holds in the vertical direction.
9. They adopt a specialized viscous law.
10. They ignored the magnetic fields.

The disk luminosity  $L_{\text{disk}}$  is

$$L_{\text{disk}} = \frac{GM\dot{M}}{2r_{\text{in}}} \quad (1.6)$$

where  $r_{\text{in}}$  is the inner disk radius. This equals to half of the total potential energy difference (between infinity to the inner disk radius) multiplied by the mass accretion rate. The effective temperature of the disk has radial dependence in accretion disks. We obtain

$$T_{\text{eff}} = \left[ \frac{3GM\dot{M}}{8\pi\sigma r^3} \left( 1 - \sqrt{\frac{r_{\text{in}}}{r}} \right) \right]^{1/4}. \quad (1.7)$$

When the radius is far from the inner edge, we approximate

$$T_{\text{eff}} \propto r^{-3/4}. \quad (1.8)$$

The inner region of the disk is hotter than the outer one. Thus, the total disk spectra are composed of multi-color blackbody spectra. In other words, low energy photons mainly come from the outer region of the disk, whereas high energy photons originate from the inner one.



Table 1.1: AGN Classification

| Classification | Luminosity | Narrow line | Broad line | Radio loud | Host galaxy |
|----------------|------------|-------------|------------|------------|-------------|
| Seyfert 1      | Low        | Yes         | Yes        | No         | Spiral      |
| Seyfert 2      | Low        | Yes         | No         | No         | Spiral      |
| Quasar 1       | High       | Yes         | Yes        | Some       | ...         |
| Quasar 2       | High       | Yes         | No         | Some       | ...         |
| FR 1           | Low        | Yes         | Yes        | Yes        | Elliptical  |
| FR 2           | High       | Yes         | Yes        | Yes        | Elliptical  |
| LIRG           | High       | Yes         | No         | No         | Irregular   |

### 1.1.3 AGN Classification

AGNs are as diverse as humans. For instance, the SMBH mass range from  $10^5 M_\odot$  to  $10^9 M_\odot$  and the AGN luminosity range from  $10^{40} \text{ erg s}^{-1}$  to  $10^{48} \text{ erg s}^{-1}$ . Some AGNs show both narrow lines and broad lines, while the others exhibit only narrow lines in their optical spectra. Some AGNs have jets and emit strong radio waves. Table 1.1 lists the AGN classification. This Chapter 1.1.3 summarizes the AGN classification.

#### Seyfert Galaxies

Seyfert galaxies are the most common AGN class in the local Universe. Hence they are the best targets to study the physical processes in AGNs. Seyfert (1943) observed six galaxies with 60 and 100 inch telescopes on Mount Wilson. They discovered that the central core emits the highly ionized emission lines not found in normal galaxies. These highly ionized emission lines are due to the AGN. In this case, we classify the galaxy as the Seyfert galaxy. The difference between Seyfert galaxies and Quasars is the luminosity. Seyfert galaxies have lower luminosity ( $L \leq 10^{45} \text{ erg s}^{-1}$ ) than Quasars.

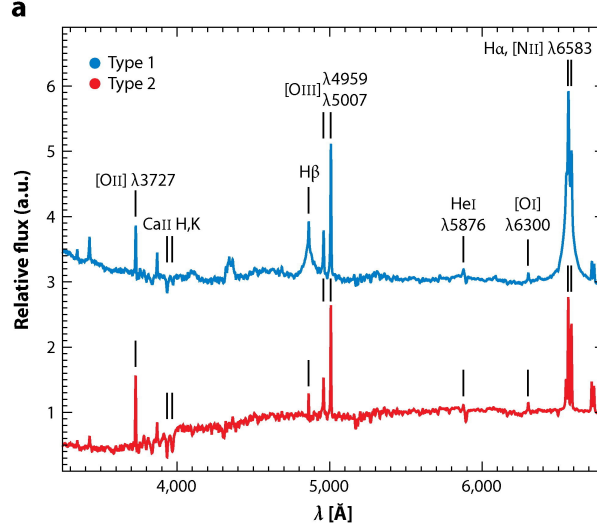


Figure 1.2: The optical spectra of Seyfert 1 and Seyfert 2 galaxies (Hickox & Alexander, 2018).

### Optical Classification

Khachikian & Weedman (1974) discovered that they were able to classify the Seyfert galaxies into two types (Seyfert 1 and Seyfert 2 galaxies). While Seyfert 1 galaxies show both narrow lines ( $100\text{--}500 \text{ km s}^{-1}$ ) and broad lines ( $1,000\text{--}10,000 \text{ km s}^{-1}$ ), Seyfert 2 galaxies have only narrow lines. Figure 1.2 shows the optical spectra of Seyfert 1 and Seyfert 2 galaxies. In the Seyfert 1 galaxies, the Balmer lines (e.g.,  $H\alpha$  and  $H\beta$ ) would appear broader than the narrow lines (e.g.,  $[OII]$ ,  $[OIII]$ ,  $[NII]$ , and  $[NeIII]$ ). In the Seyfert 2 galaxies, both the forbidden and Balmer lines show the same narrow width.

### X-ray Classification

We can also classify them based on the hydrogen column density along the line of sight ( $N_H^{LOS}$ ) obtained from the X-ray spectrum. The threshold is  $\log N_H^{LOS}/\text{cm}^{-2} = 22$ . We classify almost Seyfert galaxies with  $\log N_H^{LOS}/\text{cm}^{-2} \leq 22$  as Seyfert 1 and almost them with  $22 \leq \log N_H^{LOS}/\text{cm}^{-2}$  as Seyfert 2. Especially, we classify Seyfert galaxies with  $22 \leq \log N_H^{LOS}/\text{cm}^{-2} \leq 24$  as Compton-thin AGN and them with  $24 \leq \log N_H^{LOS}/\text{cm}^{-2}$  as Compton-thick AGN. A catalog of hard X-ray selected AGN contains about 10% of Seyfert galaxies in which the optical classification does not match the one based on the X-ray one. Hence it is important to know the classification is based on the optical classification or the X-ray one.

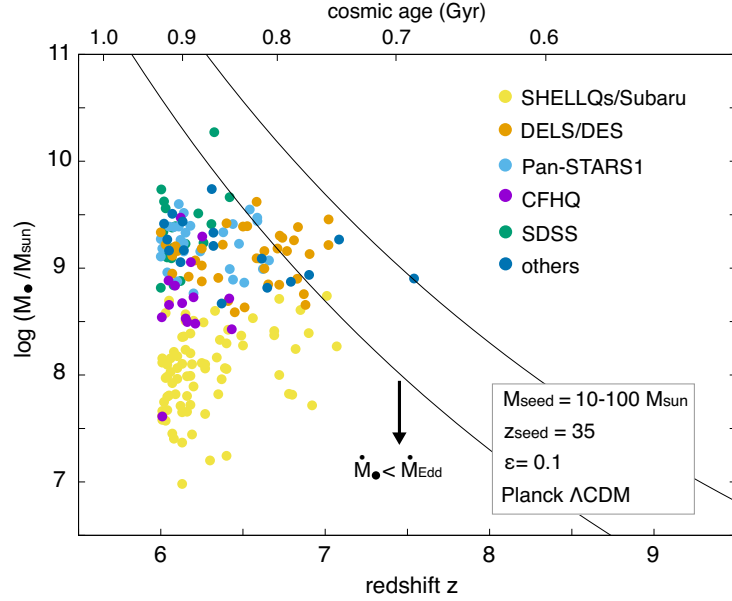


Figure 1.3: The correlation between the redshift and the SMBH mass of Quasars at  $z \geq 6$  (Inayoshi et al., 2019).

## Quasars

Quasars are the most luminous AGN class with  $L \geq 10^{45} \text{ erg s}^{-1}$ . Hence they are essential for investigating the early Universe. For instance, Bañados et al. (2018) found the highest redshift Quasar at  $z = 7.54$ . This redshift corresponding to 690 million years after the Big Bang. Figure 1.3 shows the correlation between the redshift and the SMBH mass of Quasar (Inayoshi et al., 2019). Currently, we discovered about 200 Quasars at  $z \geq 6$ .

## Optical Identification

In the 1960s, radio telescopes performed extensive surveys. One of the most important surveys is the Third Cambridge catalog (3C: Edge et al. 1959 and 3CR: Bennett 1962). The catalog discovered 471 radio sources detected at 159 MHz. Nevertheless, it is difficult to identify many of the sources because the optical images were just like blue stars. These sources were therefore called quasi-stellar radio sources (Quasars).

Schmidt (1963) revealed sharp emission lines in these sources. They found that these lines in the case of 3C 273 are indeed the Balmer lines, but redshifted by 16%. Spectroscopy of other 3C sources then led to the discovery of several quasars with significant redshift. They suspected that these sources are indeed the more distant equivalent of nearby Seyfert galaxies. Schmidt & Green (1983) introduced an arbitrary dividing line in order to separate these AGNs. They classified the Seyfert galaxies with  $L \geq 10^{45} \text{ erg s}^{-1}$  as the Quasars.

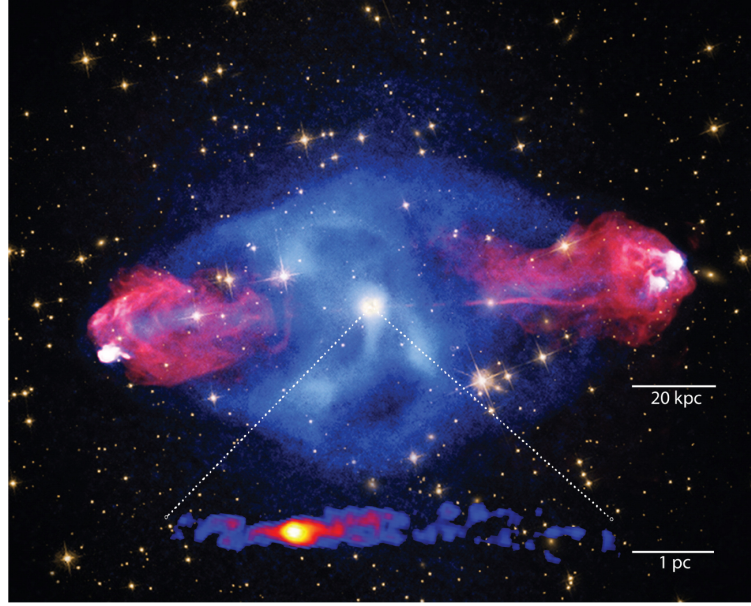


Figure 1.4: The multiwavelength images of the FR 2 radio galaxy Cygnus A. Red: radio observed with VLA. Blue: X-ray observed with Chandra (Blandford et al., 2019).

### Radio Galaxies

Radio galaxies are AGN class luminous at radio wavelength. This is because radio galaxies have AGN jets that emit radio waves by synchrotron radiation. Curtis (1918) discovered the AGN jets in the radio galaxy M87 (16.7 Mpc). Fabian (2012); Blandford et al. (2019) suggested that the AGN jets can have a significant influence on AGN environments. The host galaxy of the radio galaxy is a giant elliptical galaxy with a low star formation rate (SFR) in local Universe. Hence radio galaxies are essential for investigating the final phase of the coevolution. These radio-loud AGNs account for only 10% of all AGNs.

### Radio Classification

Fanaroff & Riley (1974) classified radio galaxies into two types (FR 1 and FR 2). FR 1 galaxies are the low luminosity ( $L \leq 10^{32} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$  at 175 MHz) that are brightest towards the center. FR 2 galaxies are the high luminosity ( $L \geq 10^{32} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$  at 175 MHz) that are brightest at the edges. Figure 1.4 shows the multiwavelength images of the FR 2 radio galaxy Cygnus A. This radio galaxy has jets with about 100 kpc. Hence we can see the radio lobes extend far outside of the host galaxy.

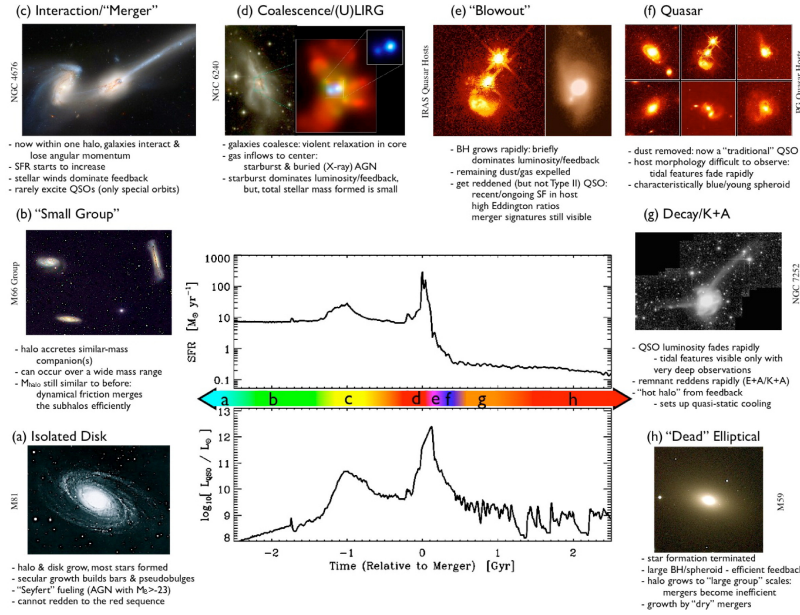


Figure 1.5: The schematic outline of the major merger (Hopkins et al., 2008a,b).

## Infrared Galaxies

Infrared galaxies are AGN class luminous at infrared wavelength. They are essential for understanding the coevolution between the SMBH and the host galaxy. This is because they accompany galaxy mergers that play an important role in the coevolution. Figure 1.5 shows the schematic outline of the major merger (Hopkins et al., 2008a,b). Initially, the AGN is like the Seyfert galaxy and the host galaxy is the spiral galaxy. Once the galaxies coalesce, they become luminous due to the starburst and the AGN. When they blow off the gas and dust around them, they behave like normal Quasars. Finally, both star formation and AGN calm down and they resemble the radio galaxies.

## Infrared Classification

In the 1980s, Infrared Astronomical Satellite (IRAS) performed the first all sky survey at infrared wavelengths and discovered the infrared galaxies that emit more energy in the infrared wavelength than at all other wavelengths combined. Sanders & Mirabel (1996) defined the Luminous Infrared Galaxies (LIRG) with  $\log L_{\text{IR}}/L_{\odot} \geq 11$  and Ultra Luminous Infrared Galaxies (ULIRG) with  $\log L_{\text{IR}}/L_{\odot} \geq 12$ . Recently, Armus et al. (2009) constructed the Great Observatories All sky LIRG Survey (GOALS) that was a first comprehensive imaging and spectroscopic survey of over 200 low redshift ( $z \leq 0.088$ ) LIRGs combined data from NASA's Spitzer Space Telescope, Chandra X-Ray Observatory, Hubble Space Telescope, and Galaxy Evolution Explorer observations.

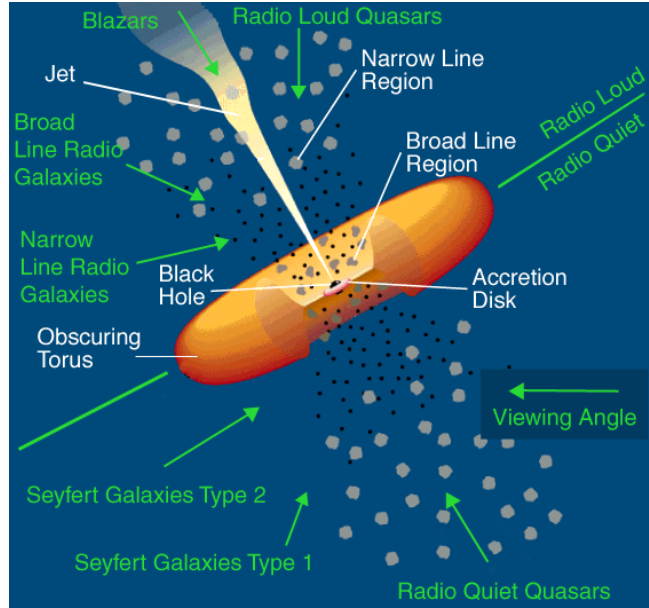


Figure 1.6: The unification model of the active galactic nucleus.

#### 1.1.4 AGN Unification

To explain the AGN diversity with a small number of physical parameters, many studies suggested the AGN unification model. Figure 1.6 shows the AGN unification model. It indicated the ubiquitous presence of an obscuring matter composed of gas and dust (so-called “torus”) around the accreting SMBH (e.g., Antonucci, 1993; Urry & Padovani, 1995; Netzer, 2015; Ramos Almeida & Ricci, 2017). Antonucci (1993) suggested that the existence of an optically thick torus surrounding the central regions on scales of 1–100 pc. In the face on (Seyfert 1), we can observe both broad lines and narrow lines. In contrast, in the edge on (Seyfert 2), we can only observe narrow lines. This is because the torus blocks the line of sight. Antonucci & Miller (1985) discovered broad Balmer lines in the Seyfert 2 galaxy NGC 1068 when they observed the optical polarization. Miller & Goodrich (1990) also observed the highly polarized Seyfert 2 galaxies and found hidden broad line regions.

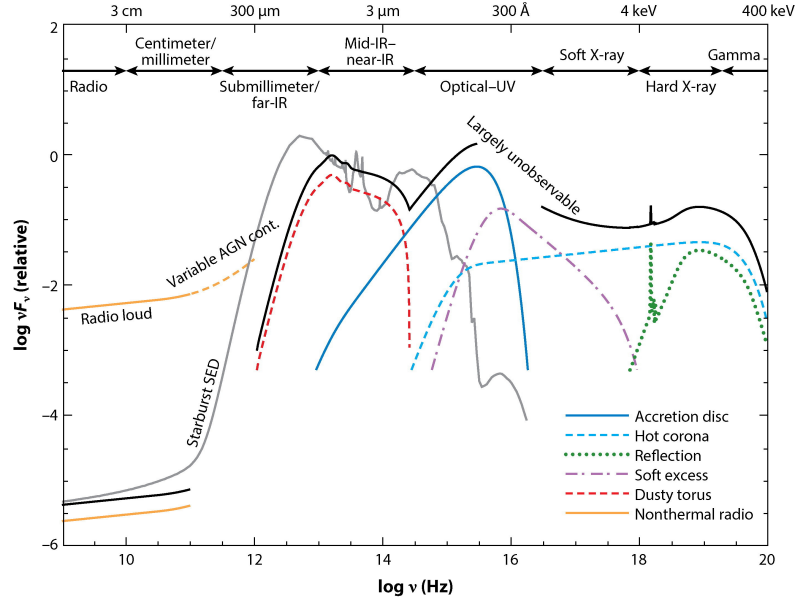


Figure 1.7: The spectral energy density (SED) of an unobscured AGN (Hickox & Alexander, 2018). Yellow line: nonthermal radio emission from the jet. Red line: thermal emission from the dusty torus. Blue line: thermal emission from the accretion disk. Light blue: non-thermal X-ray emission from the host corona. Green line: Compton scattering component from the torus.

## 1.2 Torus Structure from Multiwavelength Observations

The AGN torus is essential for understanding the coevolution between the SMBH and the host galaxy. This is because the AGN torus plays an essential role in AGN feeding that connects the SMBH and the host galaxy as a mass reservoir. Nevertheless, the basic properties of the AGN torus (e.g., the hydrogen column density and the covering factor) remain unclear.

Multiwavelength observations are indispensable for elucidating the AGN properties. The reason is that AGN components (e.g., the accretion disk, the dust torus, the broad line region, the narrow line region, and the jets) emit multiwavelength electromagnetic waves. Figure 1.7 shows the spectral energy density (SED) of an unobscured AGN (Hickox & Alexander, 2018). For instance, (1) Radio: nonthermal radio emission from the jet, (2) Infrared: thermal emission from the dusty torus. (3) Optical: thermal emission from the accretion disk, and (4) X-ray: nonthermal X-ray emission from the hot corona and its Compton scattering from the torus. This Chapter 1.2 summarizes the torus properties obtained from multiwavelength observations.

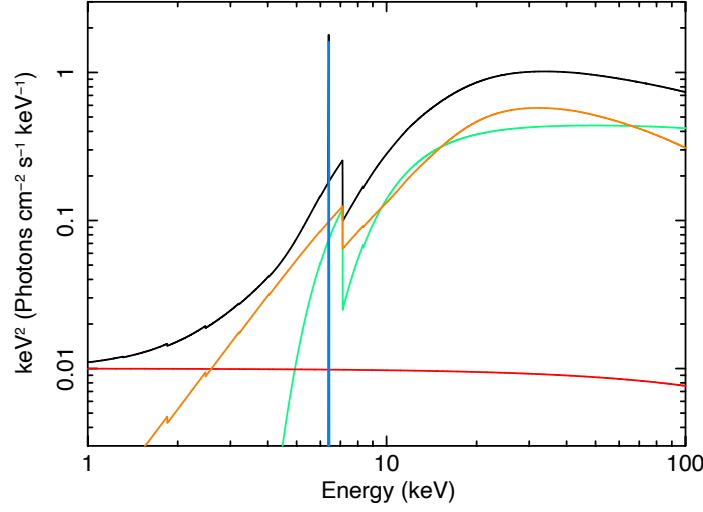


Figure 1.8: The X-ray spectrum of an obscured AGN. Black line: total. Red line: scattered component. Orange line: reflection component from the torus. Green line: direct component. Blue line: Fe  $K\alpha$  fluorescence line from the torus.

### 1.2.1 X-ray Spectrum of AGN

The X-ray spectrum of the AGN is a powerful tool to investigate the nature of surrounding material around the SMBH. This is because X-rays can trace all matter including gas and dust at various physical conditions. Figure 1.8 shows the X-ray spectrum of an obscured AGN. The X-ray spectrum of the AGN mainly consists of four components: (1) direct power law component absorbed by the torus, (2) unabsorbed scattered component, (3) reflection component from the torus, and (4) Fe  $K\alpha$  fluorescence line from the torus. This torus reflection component carries essential information on the torus structure. For instance, the relative intensity to the direct component, the shape of the reflection continuum, and those of the Fe  $K\alpha$  fluorescence line at 6.4 keV depend strongly on the hydrogen column density and the torus covering factor. To estimate the torus structure, we have to calculate the reflected X-ray spectrum from the torus.



Table 1.2: X-ray Spectral Models from Smooth Torus

| Model   | Method      | Geometry       | Distribution |
|---------|-------------|----------------|--------------|
| Pexrav  | Analytic    | Plane          | Smooth       |
| Pexmon  | Analytic    | Plane          | Smooth       |
| MYTorus | Monte Carlo | Donuts         | Smooth       |
| Ikeda   | Monte Carlo | Partial Sphere | Smooth       |
| Borus02 | Monte Carlo | Partial Sphere | Smooth       |

### 1.2.2 X-ray Spectral Model from Smooth Torus

To investigate the torus structure, many studies constructed various X-ray spectral models from the torus. Here we introduce five representative models. Table 1.2 summarizes the five models:

1. **Pexrav (Magdziarz & Zdziarski, 1995)**. They analytically calculated the reflection continuum from cold gas in an infinite plane.
2. **Pexmon (Nandra et al., 2007)**. They added some fluorescence lines (e.g., Fe  $K\alpha$ , Fe  $K\beta$ , and Ni  $K\alpha$ ) to the pexrav.

These analytic models are convenient to use but give only a rough approximation of the real data. This is because the torus geometry is more complex than a single plane. To consider more realistic torus geometry, we need to perform Monte Carlo ray-tracing simulations.

1. **MYTorus (Murphy & Yaqoob, 2009)**. They assumed a bagel like shape whose opening angle is fixed. This model have been widely used to fit the observed X-ray spectra of AGNs (e.g., Yaqoob, 2012; Yaqoob et al., 2015, 2016; Koss et al., 2013, 2015, 2016, 2017; Ricci et al., 2014a,b, 2015, 2016a,b, 2017a,b).
2. **Ikeda model (Ikeda et al., 2009)**. They assumed essentially spherical geometry with two bipolar conical holes whose opening angle is a free parameter. This model also has been applied to the observed X-ray spectra of AGNs (e.g., Awaki et al., 2009; Eguchi et al., 2011; Tazaki et al., 2011, 2013; Kawamuro et al., 2013, 2016a,b; Tanimoto et al., 2016, 2018; Oda et al., 2017, 2018; Yamada et al., 2018).
3. **Borus02 (Baloković et al., 2018)**. They also assumed a partial sphere whose opening angle is also a free parameter. This model also have been widely used to fit the observed X-ray spectra of AGNs (e.g., Baloković et al., 2018; Marchesi et al., 2018, 2019a,b).

### 1.2.3 Evidences of Clumpy Torus

Many studies indicated that the AGN torus must be composed of dusty clumps rather than of smooth gas (e.g., Krolik & Begelman, 1988; Laor & Draine, 1993; Hönig et al., 2006; Hönig & Beckert, 2007; Nenkova et al., 2008a,b). Here we summarize four major evidences:

1. **The geometrical thickness of the torus.** The velocity dispersion of matter must be as large as a typical rotation velocity of the torus ( $v = 100 \text{ km s}^{-1}$ ) to sustain a geometrically thick torus as obtained from the absorbed AGN fraction (e.g. Ricci et al., 2015). In the case of the smooth gas, this corresponds to the thermal velocity. However, the velocity of the dust gas cannot become so fast. This is because dust grains would reach a maximum sublimation temperature ( $T = 1500 \text{ K}$ ; Laor & Draine 1993).
2.  **$10 \mu\text{m}$  silicate emission features in Seyfert 2 galaxies.** Pier & Krolik (1992, 1993) constructed the infrared spectral model from the smooth torus and predicted that the  $10 \mu\text{m}$  silicate feature would only show absorption lines in the case of Seyfert 2 galaxies. By contrast, Mason et al. (2009); Nikutta et al. (2009) discovered silicate emission features in the infrared spectra of Seyfert 2 galaxies.
3. **Correlation between the infrared luminosity and X-ray luminosity.** An inner region of the torus has a higher temperature since radiation from the central accretion disk heats the dust. In smooth tori, we expected the ratio between the infrared luminosity and X-ray luminosity would be systematically higher in type 1 AGNs where inner parts of the torus are more visible. However, the correlations are very similar among type 1 and type 2 AGNs (Gandhi et al., 2009; Ichikawa et al., 2012, 2017, 2019; Asmus et al., 2015; Kawamuro et al., 2016a).
4. **X-ray spectral features of the torus reflection component.** The X-ray spectra of heavily absorbed AGNs often show unabsorbed torus-reflection components (e.g. Ueda et al., 2007). If we apply smooth torus models to such an X-ray spectrum, the inclination angle and torus half-opening angle become very close to each other (Awaki et al., 2009; Eguchi et al., 2011; Tazaki et al., 2011; Tanimoto et al., 2016, 2018). This corresponds to the geometry where the observer sees the AGN through the edge of the torus boundary. However, it seems unrealistic in a statistical sense.

Table 1.3: Infrared Spectral Models from Clumpy Torus

| Model        | Smooth | Clumpy | Outflow |
|--------------|--------|--------|---------|
| CLUMPY       | No     | Yes    | No      |
| CAT3D        | No     | Yes    | No      |
| Siebenmorgen | Yes    | Yes    | Yes     |
| Stalevski    | Yes    | Yes    | No      |
| CAT3D–WIND   | No     | Yes    | Yes     |

### 1.2.4 Infrared Spectral Models from Clumpy Torus

Many studies have constructed the infrared spectral models from the clumpy torus (e.g., Nenkova et al., 2008a,b; Hönig et al., 2010; Hönig & Kishimoto, 2010; Siebenmorgen et al., 2015; Stalevski et al., 2016; Hönig & Kishimoto, 2017). Table 1.3 summarizes the five infrared spectral models:

1. **CLUMPY (Nenkova et al., 2008a,b)**. They constructed the infrared spectral model from the clumpy torus by assuming the power law distribution in the radial direction and the normal distribution in the elevation direction for the configuration of the clumps. Many researches have applied their model to the infrared spectra of AGNs (Ramos Almeida et al., 2009, 2011a,b,c, 2014a,b; Alonso-Herrero et al., 2011, 2012a,b, 2013; Ichikawa et al., 2015; García-Bernete et al., 2015, 2019).
2. **CAT3D (Hönig et al., 2010; Hönig & Kishimoto, 2010)**. They provided a radiative transfer model of the three-dimensional clumpy dust torus assuming the optically thick dust clouds and the low torus volume filling factor.
3. **Siebenmorgen Torus Model (Siebenmorgen et al., 2015)**. They constructed the two-phase (smooth and clumpy) model. They assumed that distribution of the dust is a torus-like geometry, which can be described as a clumpy medium or a homogeneous disk, or as a combination of the two.
4. **Stalevski Torus Model (Stalevski et al., 2016)**. They also provided the two-phase model. They modeled the dust with a two-phase medium, consisting of a large number of high density clumps and a low density smooth component.
5. **CAT3D–WIND (Hönig & Kishimoto, 2017)**. They constructed the clumpy disk and outflow model. This model assumed that the dusty gas consists of an inflowing disk and an outflowing wind.

### 1.2.5 X-Ray Spectral Models from Clumpy Torus

It was only recently that X-ray spectral models from clumpy torus were developed (e.g., Liu & Li, 2014; Furui et al., 2016). Liu & Li (2014) constructed such a model with the Geant4 library (Agostinelli et al., 2003; Allison et al., 2006, 2016) for the first time. They adopted clump distribution confined in a partial sphere. Then, Furui et al. (2016) made an X-ray clumpy torus model with bagel-like geometry with the Monte Carlo simulation for Astrophysics and Cosmology code (MONACO: Odaka et al. 2016). MONACO also utilizes the Geant4 library but is optimized for astrophysical applications.

## 1.3 Thesis Structure

The thesis structure is the following. Chapter 2 presents X-ray observatories. In Chapter 3, we constructed a new X-ray spectral model from the clumpy torus (XClumpy: Tanimoto et al. 2019) with the Monte Carlo simulation for Astrophysics and Cosmology code (MONACO: Odaka et al. 2016). This Chapter 3 is based on the Tanimoto et al. (2019). In Chapter 4, we applied the XClumpy (Tanimoto et al., 2019) to the broadband X-ray spectra of 10 obscured AGNs observed with Suzaku and NuSTAR. This Chapter 4 is based on Tanimoto et al. (2020) submitted to the Astrophysical Journal. We adopt the cosmological parameters ( $H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.308$ ,  $\Omega_\lambda = 0.692$ : Planck Collaboration et al. 2016). The errors on the spectral parameters correspond to the 90% confidence limits for a single parameter.

## Chapter 2

# X-ray Observatories

### 2.1 Chandra

Chandra (1999–) is the first high spatial resolution X-ray astronomical satellite (Weisskopf et al., 2002). It carries four instruments:

1. Advanced CCD Imaging Spectrometer (ACIS: 0.20–10.0 keV) (Garmire et al., 2003).
2. High Resolution Camera (HRC: 0.10–10.0 keV).
3. High Energy Transmission Grating (HETG: 0.50–10.0 keV) (Canizares et al., 2000).
4. Low Energy Transmission Grating (LETG: 0.08–6.00 keV).

### 2.2 XMM-Newton

XMM-Newton (1999–) is the ESA's second cornerstone of the Horizon 2000 Science Program (Jansen et al., 2001). It has three instruments:

1. European Photon Imaging Camera (EPIC) MOS (0.10–12.0 keV) (Turner et al., 2001).
2. European Photon Imaging Camera PN (0.10–12.0 keV) (Strüder et al., 2001).
3. Reflection Grating Spectrometer (RGS: 0.35–2.50 keV) (den Herder et al., 2001).

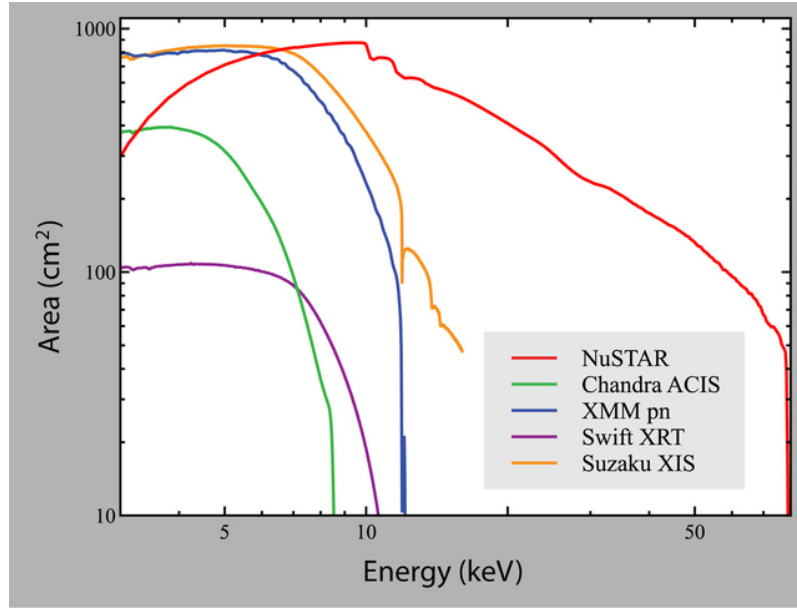


Figure 2.1: The NuSTAR’s effective area compared to other X-ray satellites <https://www.nustar.caltech.edu/page/researchers>.

## 2.3 Suzaku

Suzaku (2005–2015) was the fifth Japanese X-ray astronomical satellite (Mitsuda et al., 2007). It carried two detectors:

1. X-ray Imaging Spectrometer (XIS: Koyama et al. 2007). The XIS consisted of four X-ray CCD cameras (XIS-0, XIS-1, XIS-2, and XIS-3). XIS-0, XIS-2, and XIS-3 are Front-Side Illuminated CCDs (FIXIS: 0.4–12.0 keV) and XIS-1 is the Back Illuminated one (BIXIS: 0.2–12.0 keV).
2. Hard X-ray Detector (HXD: Takahashi et al. 2007). The HXD composed of silicon PIN diodes and Gadolinium Silicate crystal (GSO) covering the 10–70 keV and 40–600 keV (Kokubun et al., 2007), respectively.

## 2.4 NuSTAR

The Nuclear Spectroscopic Telescope Array Mission (NuSTAR: 2012–) is the first focusing high energy X-ray mission (Harrison et al., 2013). It carries two coaligned grazing incidence telescopes coupled with two focal plane modules (FPM: 3–79 keV). Figure 2.1 shows the NuSTAR’s effective area compared to other X-ray satellites.

## Chapter 3

# XClumpy: X-Ray Spectral Model from Clumpy Torus and Its Application to Circinus Galaxy

### Abstract

We construct an X-ray spectral model from the clumpy torus (XClumpy) in an active galactic nucleus (AGN), using the Monte Carlo simulation for Astrophysics and Cosmology framework (MONACO: Odaka et al. 2011, 2016). The adopted geometry of the torus is the same as that in Nenkova et al. (2008a,b), who assumes a power law distribution of clumps in the radial direction and a normal distribution in the elevation direction. We examine the dependence of the X-ray continuum and Fe  $K\alpha$  fluorescence line profile on the torus parameters. We compare our model with other torus models: MYTorus model (Murphy & Yaqoob, 2009), Ikeda model (Ikeda et al., 2009), and CTorus model (Liu & Li, 2014). As an example, we also present the results applied to the broadband X-ray spectra of the Circinus galaxy observed with XMM-Newton, Suzaku, and NuSTAR. Our model well reproduces the broadband X-ray spectra. We obtain a hydrogen column density along the equatorial plane  $N_{\text{H}}^{\text{Equ}} = 9.08^{+0.14}_{-0.08} \times 10^{24} \text{ cm}^{-2}$ , a torus angular width  $\sigma = 14.7^{+0.44}_{-0.39}$  degree, and a 2–10 keV luminosity  $\log L_{2-10}/\text{erg s}^{-1} = 42.5$ .

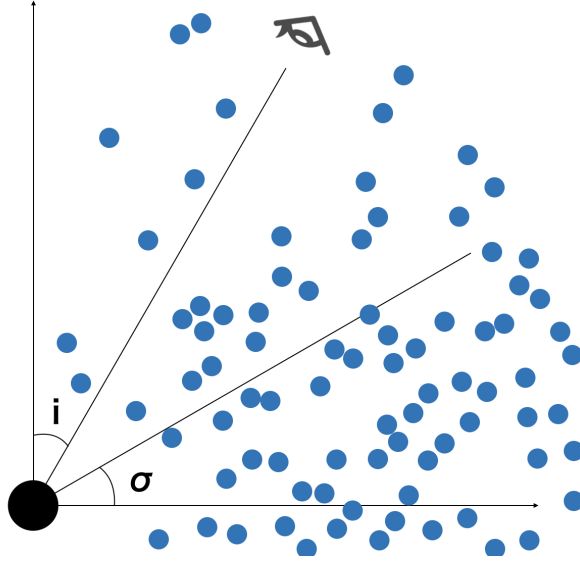


Figure 3.1: The cross section view of the torus. We assume a power law distribution of clumps in the radial direction and a normal distribution in the elevation direction.

### 3.1 Introduction

In this Chapter 3, we constructed a new X-ray clumpy torus model (XClumpy), by adopting the same geometry of clump distribution as that of the CLUMPY model in the infrared band (Nenkova et al., 2008a,b). This model enables us to directly compare the results inferred from the infrared and X-ray bands, which constrain the spatial distribution of dust and that of all matter, respectively. The structure of this Chapter 3 is the following. Chapter 3.2 describes the adopted torus geometry. Chapter 3.3 presents the details of Monte Carlo simulations. In Chapter 3.4, we present major results of our model such as dependencies of the X-ray continuum and Fe  $K\alpha$  line profile on the torus parameters. We also compare our model with other torus models: MYTorus model (Murphy & Yaqoob, 2009), Ikeda model (Ikeda et al., 2009), and CTorus model (Liu & Li, 2014). Chapter 3.5 applies our model to the broadband X-ray spectra of the Circinus galaxy observed with XMM-Newton, Suzaku, NuSTAR.

### 3.2 Torus Geometry

In our model, a torus is not continuous medium but is composed of many clumps randomly distributed following a given number density function. For simplicity, each clump is a sphere with a radius of  $R_{\text{clump}}$ , and has a uniform hydrogen number density  $n_{\text{H}}$ . We adopt



the same geometry as that in Nenkova et al. (2008a,b), who assumed a power law distribution of clumps in the radial direction between inner and outer radii, and normal distribution in the elevation direction (Figure 3.1). Specifically, the number density function  $d(r, \theta, \phi)$  (in units of  $\text{pc}^{-3}$ ) is represented in the spherical coordinate system (where  $r$  is radius,  $\theta$  is polar angle, and  $\phi$  is azimuth) as:

$$d(r, \theta, \phi) = N \left( \frac{r}{r_{\text{in}}} \right)^{-q} \exp \left( -\frac{(\theta - \pi/2)^2}{\sigma^2} \right). \quad (3.1)$$

where  $N$  is the normalization,  $q$  is the index of the radial density profile, and  $\sigma$  is the torus angular width.

The normalization  $N$  is related to the number of clumps along the equatorial plane  $N_{\text{clump}}^{\text{Equ}}$  as

$$\begin{aligned} N_{\text{clump}}^{\text{Equ}} &= \int_{r_{\text{in}}}^{r_{\text{out}}} d \left( r, \frac{\pi}{2}, 0 \right) \pi R_{\text{clump}}^2 dr. \\ N &= \frac{(1-q)N_{\text{clump}}^{\text{Equ}}}{\pi R_{\text{clump}}^2 r_{\text{in}}^q (r_{\text{out}}^{1-q} - r_{\text{in}}^{1-q})} \end{aligned} \quad (3.2)$$

By substituting Equation (2) into Equation (1), we obtain the number of clumps along the line-of-sight at a given polar angle:

$$N_{\text{clump}}^{\text{LOS}}(\theta) = N_{\text{clump}}^{\text{Equ}} \exp \left( -\frac{(\theta - \pi/2)^2}{\sigma^2} \right). \quad (3.3)$$

For instance, for  $N_{\text{clump}}^{\text{Equ}} = 10$  and  $\sigma = 60$  degree,  $N_{\text{clump}}^{\text{LOS}}(\pi/2) \approx 10$ ,  $N_{\text{clump}}^{\text{LOS}}(\pi/3) \approx 7$ , and  $N_{\text{clump}}^{\text{LOS}}(\pi/6) \approx 3$ .

The total number of clumps in the torus  $N_{\text{clump}}^{\text{Tot}}$  is obtained by integrating the number density function,

$$\begin{aligned} N_{\text{clump}}^{\text{Tot}} &= \int_{r_{\text{in}}}^{r_{\text{out}}} \int_0^\pi \int_0^{2\pi} d(r, \theta, \phi) r^2 \sin \theta dr d\theta d\phi \\ &= \frac{2N_{\text{clump}}^{\text{Equ}}(1-q)(r_{\text{out}}^{3-q} - r_{\text{in}}^{3-q})}{R_{\text{clump}}^2(3-q)(r_{\text{out}}^{1-q} - r_{\text{in}}^{1-q})} \int_0^\pi \exp \left( -\frac{(\theta - \pi/2)^2}{\sigma^2} \right) \sin \theta d\theta \end{aligned} \quad (3.4)$$

Typically  $N_{\text{clump}}^{\text{Tot}} \sim 10^6$  for the adopted parameters (Table 1).

We also define the total hydrogen column density along the equatorial plane:

$$N_{\text{H}}^{\text{Equ}} = \frac{4}{3} R_{\text{clump}} N_{\text{clump}}^{\text{Equ}} n_{\text{H}} \quad (3.5)$$

Here  $\frac{4}{3} R_{\text{clump}} (= \frac{4}{3} \pi R_{\text{clump}}^3 / (\pi R_{\text{clump}}^2))$  corresponds to the average length crossing the line-of-sight in one clump (a sphere with a radius of  $R_{\text{clump}}$ ) when the clumps are randomly

located. The parameter  $N_{\text{H}}^{\text{Equ}}$  can be directly compared with the total optical-depth along the equatorial plane introduced in Nenkova et al. (2008a,b).

To summarize, our model has 8 independent parameters that define the torus properties: (1) inner radius of the torus ( $r_{\text{in}}$ ), (2) outer radius of the torus ( $r_{\text{out}}$ ), (3) radius of each clump ( $R_{\text{clump}}$ ), (4) number of clumps along the equatorial plane ( $N_{\text{clump}}^{\text{Equ}}$ ), (5) index of the radial density profile ( $q$ ), (6) torus angular width ( $\sigma$ ), (7) hydrogen column density along the equatorial plane ( $N_{\text{H}}^{\text{Equ}}$ ), and (8) the inclination angle ( $i$ , the polar angle of the line of sight).

In our work, we fix (1)  $r_{\text{in}}$ , (2)  $r_{\text{out}}$ , (4)  $N_{\text{clump}}^{\text{Equ}}$ , and (5)  $q$  to the mean values obtained by Ichikawa et al. (2015), who applied the CLUMPY model to the infrared spectral energy distribution of nearby 21 AGNs. We note that the clump-size parameter (3)  $R_{\text{clump}}$  does not affect the calculation of the infrared spectra as long as it is sufficiently small (Nenkova et al., 2008a,b). This is not the case for the X-ray spectra, however. We therefore assume a typical value (a logarithmic average) within the torus region based on a theoretical estimate by Kawaguchi & Mori (2010, 2011). The adopted value (0.002 pc) is compatible with the observations of transient X-ray absorption events by torus clumps in nearby AGNs (Markowitz et al., 2014). Thus, our model has three free parameters related to the torus: (6)  $\sigma$ , (7)  $N_{\text{H}}^{\text{Equ}}$ , and (8)  $i$ . Table 3.1 summarizes the values of the fixed parameters and the range of the free parameters.

### 3.3 Monte Carlo Simulation

#### 3.3.1 Material Properties and Physical Processes

The MONACO framework (Odaka et al., 2011, 2016) is utilized to perform our ray-tracing simulations where a clumpy torus is irradiated by X-rays from its central position. For simplicity, we assume that all matter in the torus is neutral cold gas. Any thermal motion of the gas is ignored. As the physical processes, we take into account photoelectric absorption, fluorescence line emission after it, and Compton scattering. We assume that all Compton scattering is made by electrons bound to atoms or molecules, not by free electrons, unlike in most of previous works. Although our assumption may not hold if there are ionized plasma in the torus, the difference would be only slight energy shifts of scattered X-rays by electron binding energies (Odaka et al., 2011, 2016). This is not important except for high energy-resolution spectroscopy like that by a microcalorimeter (Hitomi Collaboration et al., 2018). We adopt the photoelectric cross sections compiled in the National Institute of Standards and Technology (NIST) database (Schoonjans et al., 2011), and Solar abundances by Anders & Grevesse (1989).

Table 3.1: Summary of Parameters

| Note | Parameter                                       | Grid        | Units  |
|------|-------------------------------------------------|-------------|--------|
| (01) | $r_{\text{in}}$                                 | 0.05        | pc     |
| (02) | $r_{\text{out}}$                                | 1.00        | pc     |
| (03) | $R_{\text{clump}}$                              | 0.002       | pc     |
| (04) | $N_{\text{clump}}^{\text{Equ}}$                 | 10.0        | ...    |
| (05) | $q$                                             | 0.50        | ...    |
| (06) | $\sigma$                                        | 10.0 – 70.0 | degree |
| (07) | $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2}$ | 22.0 – 26.0 | ...    |
| (08) | $i$                                             | 18.2 – 87.1 | degree |
| (09) | $\Gamma$                                        | 1.50 – 2.50 | ...    |
| (10) | $\log E_{\text{cut}}/\text{keV}$                | 1.00 – 3.00 | ...    |

Column (01): inner radius of the torus. Column (02): outer radius of the torus. Column (03): radius of the clump. Column (04): number of the clump along the equatorial plane. Column (05): index of the radial density profile. Column (06): torus angular width. Column (07): hydrogen column density along the equatorial plane. Column (08): inclination angle. Column (09): photon index. Column (10): cutoff energy.

### 3.3.2 Table Model

We construct an X-ray spectral table model that can be directly applied to the observed data on the XSPEC package (Arnaud, 1996). First, for each set of the torus parameters, we determine the locations of all clumps with randomization. We put clumps following Equation (1), and then randomly shift their three dimensional locations if the clumps overlap. For each geometry set, we perform Monte-Carlo simulations by generating 0.2 billion primary photons. The reflected spectra (continuum and fluorescence lines) are accumulated from all azimuth directions for each range of the inclination angle.

In each run, the photon energies are distributed according to a power law spectrum with a photon index of 2.0 in an energy range of 0.5–500 keV. The information on the initial energy of each input photon is recorded in the simulation. Hence, we are able to reproduce the spectra for various spectral parameters (photon index  $\Gamma$  and high-energy cutoff  $E_{\text{cut}}$ ) by multiplying different weights to primary photon energies in the original simulation data. Table 3.1 also summarizes the range and grid values of the spectral parameters available in our table model.

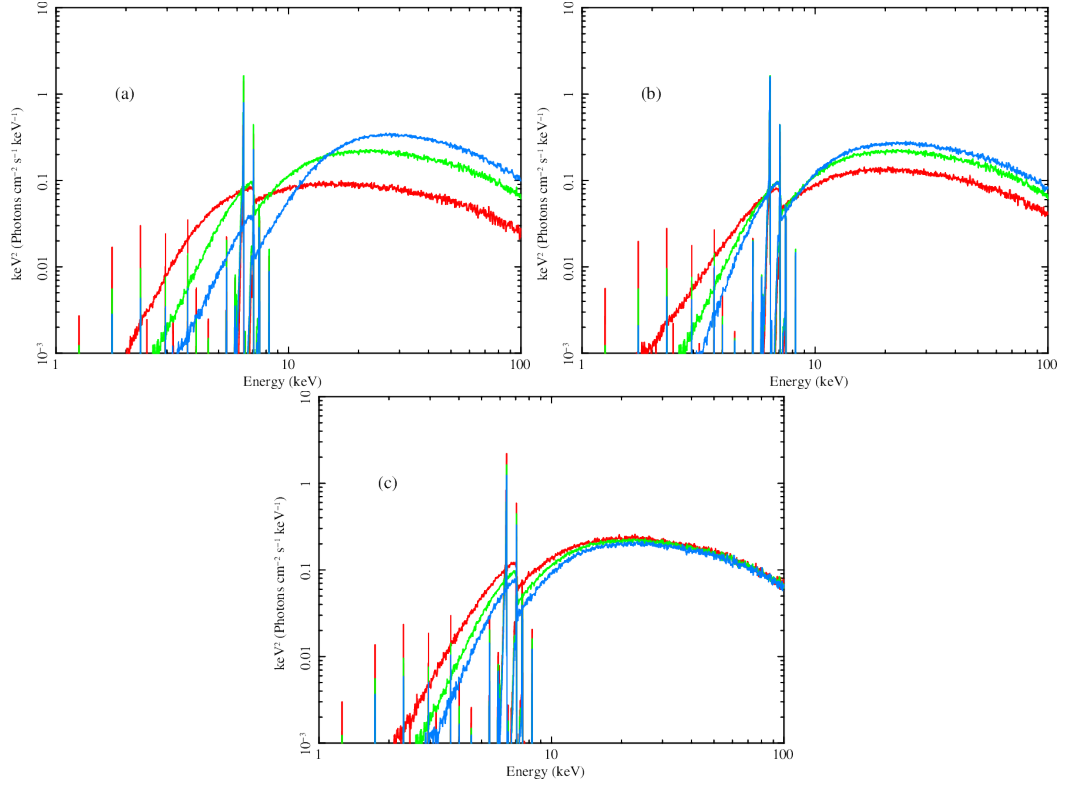


Figure 3.2: The dependence of the reflected X-ray spectrum on the (a) hydrogen column density along the equatorial plane ( $N_{\text{H}}^{\text{Equ}}$ ), (b) torus angular width ( $\sigma$ ), and (c) inclination angle ( $i$ ). We adopt the following values as default parameters:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 24.0$ ,  $\sigma = 40.0$  degree,  $i = 60.0$  degree,  $\Gamma = 2.0$ , and  $E_{\text{cut}} = 100$  keV. (a) Red line:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 23.5$ . Green line:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 24.0$ . Blue line:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 24.5$ . (b) Red line:  $\sigma = 20.0$  degree. Green line:  $\sigma = 40.0$  degree. Blue line:  $\sigma = 60.0$  degree. (c) Red line:  $i = 40.0$  degree. Green line:  $i = 60.0$  degree. Blue line:  $i = 80.0$  degree.

## 3.4 Results

### 3.4.1 Dependence of Reflected Continuum on Torus Parameters

We investigate the dependence of the reflected X-ray spectrum on the torus parameters. Here we adopt the following values as default (fixed) parameters unless otherwise stated:  $\log N_{\text{H}}/\text{cm}^{-2} = 24.0$ ,  $\sigma = 40.0$  degree,  $i = 60.0$  degree,  $\Gamma = 2.0$ , and  $E_{\text{cut}} = 100$  keV. Figure 3.2 shows the dependence of the X-ray spectrum on the (a) hydrogen column density along the equatorial plane, (b) torus angular width, and (c) inclination angle.

In Figure 3.2(a), we find that the continuum flux above  $\sim 20$  keV increases and the overall spectrum hardens with the hydrogen column density along the equatorial plane. This is because the intensity of the Compton-reflected continuum and the amount of self-absorption

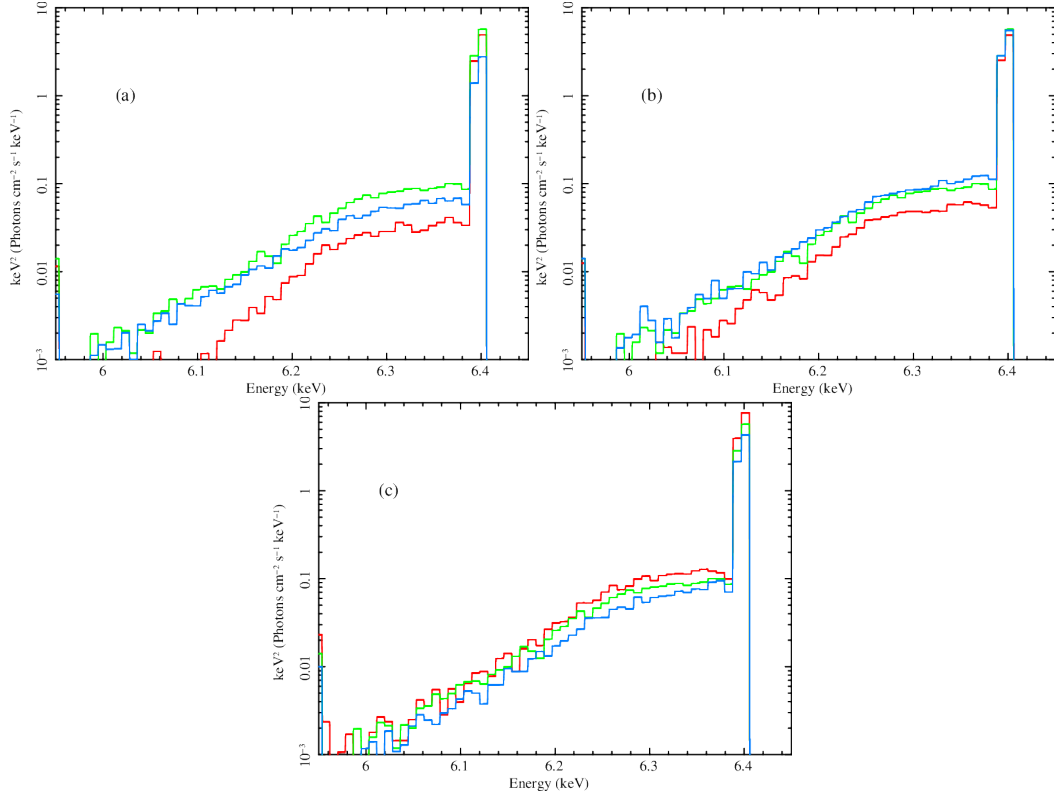


Figure 3.3: The dependence of the Fe K $\alpha$  line profile on the (a) hydrogen column density along the equatorial plane ( $N_{\text{H}}^{\text{Equ}}$ ), (b) torus angular width ( $\sigma$ ), and (c) inclination angle ( $i$ ). We adopt the following values as default parameters:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 24.0$ ,  $\sigma = 40.0$  degree,  $i = 60.0$  degree,  $\Gamma = 2.0$ , and  $E_{\text{cut}} = 100$  keV. (a) Red line:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 23.5$ . Green line:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 24.0$ . Blue line:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 24.5$ . (b) Red line:  $\sigma = 20.0$  degree. Green line:  $\sigma = 40.0$  degree. Blue line:  $\sigma = 60.0$  degree. (c) Red line:  $i = 40.0$  degree. Green line:  $i = 60.0$  degree. Blue line:  $i = 80.0$  degree.

by the torus increase with the total mass of the torus, which is proportional to  $N_{\text{H}}$  when the other parameters are fixed. Figure 3.2(b) indicates that the X-ray flux below 7.1 keV (the K-edge of cold iron) and that above 7.1 keV decreases and increases with  $\sigma$ , respectively. The total mass and covering fraction of the reflector increase with  $\sigma$  for a fixed  $N_{\text{H}}$ , leading to stronger reflection and self-absorption by the torus. In Figure 3.2(c), we find that the flux below 20.0 keV decreases with the inclination angle. This is because the line-of-sight absorption of the reflection component increases with the viewing angle.

### 3.4.2 Dependence of Fe K $\alpha$ line profile on Torus Parameters

We investigate the dependence of Fe K $\alpha$  line profile on the torus parameters. We adopt the same default parameters as in Chapter 3.4.1 ( $\log N_{\text{H}}/\text{cm}^{-2} = 24.0$ ,  $\sigma = 40.0$  degree,

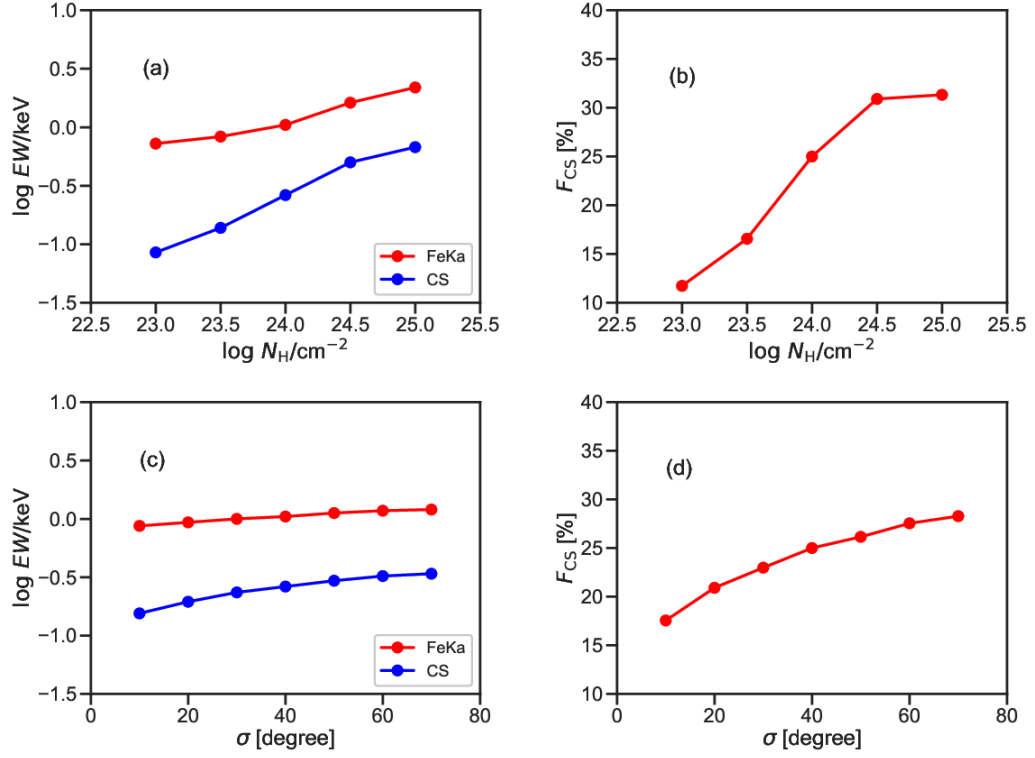


Figure 3.4: The dependence of the equivalent widths and Compton shoulder fraction on the (a)-(b) hydrogen column density along the equatorial plane ( $N_{\text{H}}^{\text{Equ}}$ ) and (c)-(d) torus angular width ( $\sigma$ ). We set basic torus parameters:  $\log N_{\text{H}}^{\text{Equ}}/\text{cm}^{-2} = 24.0$ ,  $\sigma = 40.0$  degree,  $i = 60.0$  degree,  $\Gamma = 2.0$ , and  $E_{\text{cut}} = 100$  keV. Left: Red line: equivalent width of Fe K $\alpha$ . Blue line: equivalent width of Compton shoulder. Right: Red line: Compton shoulder fraction.

$i = 60.0$  degree,  $\Gamma = 2.0$ , and  $E_{\text{cut}} = 100$  keV). Figure 3.3 shows the dependence of the Fe K $\alpha$  on the (a) hydrogen column density along the equatorial plane, (b) torus angular width, and (c) inclination angle.

We also investigate the dependence of the equivalent width of the total Fe K $\alpha$  line, that of the Compton shoulder component, and the Compton shoulder fraction relative to the total line intensity. We define these quantities as follows:

$$\text{EW}_{\text{K}\alpha} = \int_{6.086\text{keV}}^{6.404\text{keV}} \frac{L(E)}{R(E)} dE \quad (3.6)$$

$$\text{EW}_{\text{CS}} = \int_{6.086\text{keV}}^{6.390\text{keV}} \frac{L(E)}{R(E)} dE \quad (3.7)$$

$$f_{\text{CS}} = \frac{\int_{6.086\text{keV}}^{6.390\text{keV}} L(E) dE}{\int_{6.086\text{keV}}^{6.404\text{keV}} L(E) dE} \quad (3.8)$$

where  $R(E)$  and  $L(E)$  are the spectra of the reflection continuum and emission line, respectively. We set the upper boundary of the integrals to 6.404 keV for  $EW_{K\alpha}$ , which is just above the Fe  $K\alpha_1$  (6.403 keV), and to 6.390 keV for  $EW_{CS}$ , just below Fe  $K\alpha_2$  (6.390 keV). The lower boundary of the integrals are set to be 6.086 keV, corresponding to the lowest energy of the second-order Compton shoulder of Fe  $K\alpha_2$ .

Figure 3.4 plots the dependence of the equivalent widths and the Compton shoulder fraction on the (a)-(b) hydrogen column density, (c)-(d) torus angular width, and (e)-(f) inclination angle.

As noticed from Figures 3.4 (a) and (c), the equivalent width of the Fe  $K\alpha$  line increases with  $N_H$  and  $\sigma$ , confirming the same trends found with smooth torus models (Ikeda et al., 2009; Murphy & Yaqoob, 2009). Figures 3.4 (b) and (d) show that the Compton shoulder fraction also increases with  $N_H$  and  $\sigma$ . This is because the probability that a fluorescent line is further Compton reflected by surrounding matter increases with the total mass of the torus.

### 3.4.3 Comparison of Torus Models

We compare our model with other torus models: MYTorus model (Murphy & Yaqoob, 2009), Ikeda model (Ikeda et al., 2009), and CTorus model (Liu & Li, 2014). To consider similar geometry among the models as much as possible, we set the torus parameters as follows: for MYTorus model  $N_H^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree (fixed in the model); for Ikeda model  $N_H^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$ , and  $\theta_{\text{open}} = 60.0$  degree; for CTorus model  $N_H^{\text{Equ}} = 1.5 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree (fixed); for XClumpy model  $N_H^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\sigma = 30.0$  degree. We set  $N_H^{\text{Equ}} = 1.5 \times 10^{24} \text{ cm}^{-2}$  in CTorus model because Liu & Li (2014) define it as the value when all clumps are exactly aligned along the radial direction, whereas our definition refers to the case where the clumps are randomly distributed (see Equation (5)).

Figure 3.5 shows the comparison of the reflected X-ray continuum for (a)  $N_{\text{clump}}^{\text{Equ}} = 5.0$  (this parameter is relevant only for CTorus and XClumpy) and  $i = 20.0$  degree, (b)  $N_{\text{clump}}^{\text{Equ}} = 10.0$  and  $i = 20.0$  degree, (c)  $N_{\text{clump}}^{\text{Equ}} = 5.0$  and  $i = 87.0$  degree, and (d)  $N_{\text{clump}}^{\text{Equ}} = 10.0$  and  $i = 87.0$  degree. In Figures 3.5 (c) and (d) (i.e., edge-on), we find that the fluxes above 20 keV are almost the same among all the models, whereas those below 20 keV in the clumpy torus models (CTorus and XClumpy) are larger than those in the smooth torus models (MYTorus and Ikeda torus). This is mainly because a significant fraction of photons reflected by the far-side torus can reach the observer without being absorbed by the near-side torus in clumpy geometry in the case of edge-on view. This effect is more prominent in XClumpy than in CTorus. In CTorus, the clumps are confined within an elevation angle of 30

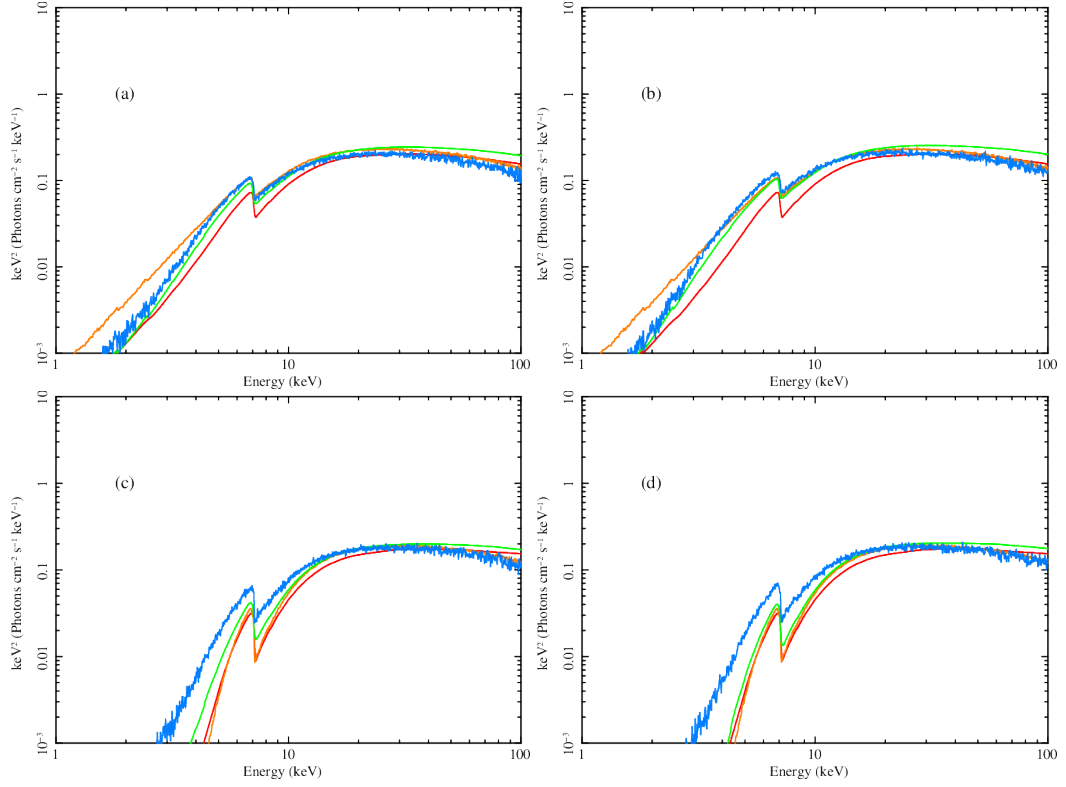


Figure 3.5: The comparison of the reflected X-ray continuum among the torus models: Left:  $N_{\text{clump}}^{\text{Equ}} = 5.0$ . Right:  $N_{\text{clump}}^{\text{Equ}} = 10.0$ . Top:  $i = 20.0$  degree. Bottom:  $i = 87.0$  degree. Red line: MYTorus model. Orange line: Ikeda model. Green line: CTorus model. Blue line: XClumpy model. Torus parameters are as follows. MYTorus model:  $N_{\text{H}}^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree (fixed). Ikeda model:  $N_{\text{H}}^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree. CTorus model:  $N_{\text{H}}^{\text{Equ}} = 1.5 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree (fixed). XClumpy:  $N_{\text{H}}^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\sigma = 30.0$  degree.

degree from the equatorial plane with a constant number density, whereas in XClumpy they are distributed to higher elevation angles with decreasing number densities. In XClumpy, photons can be reflected at higher elevation angles, which are subject to smaller line-of-sight absorption in edge-on view, thus producing larger soft X-ray fluxes, than in CTorus. As we mentioned in Chapter 3.1, smooth torus models cannot explain a large amount of the unabsorbed reflection component often seen in the X-ray spectra of heavily obscured AGNs (Tanimoto et al., 2016, 2018). This feature can be naturally explained with the clumpy torus models.

In Figures 3.5 (a) and (b) (i.e., face-on), we find that Ikeda model, which adopts a similar spherical torus geometry to those in CTorus and XClumpy, produces higher fluxes at energies below several keV than the clumpy torus models. The trend is opposite to the



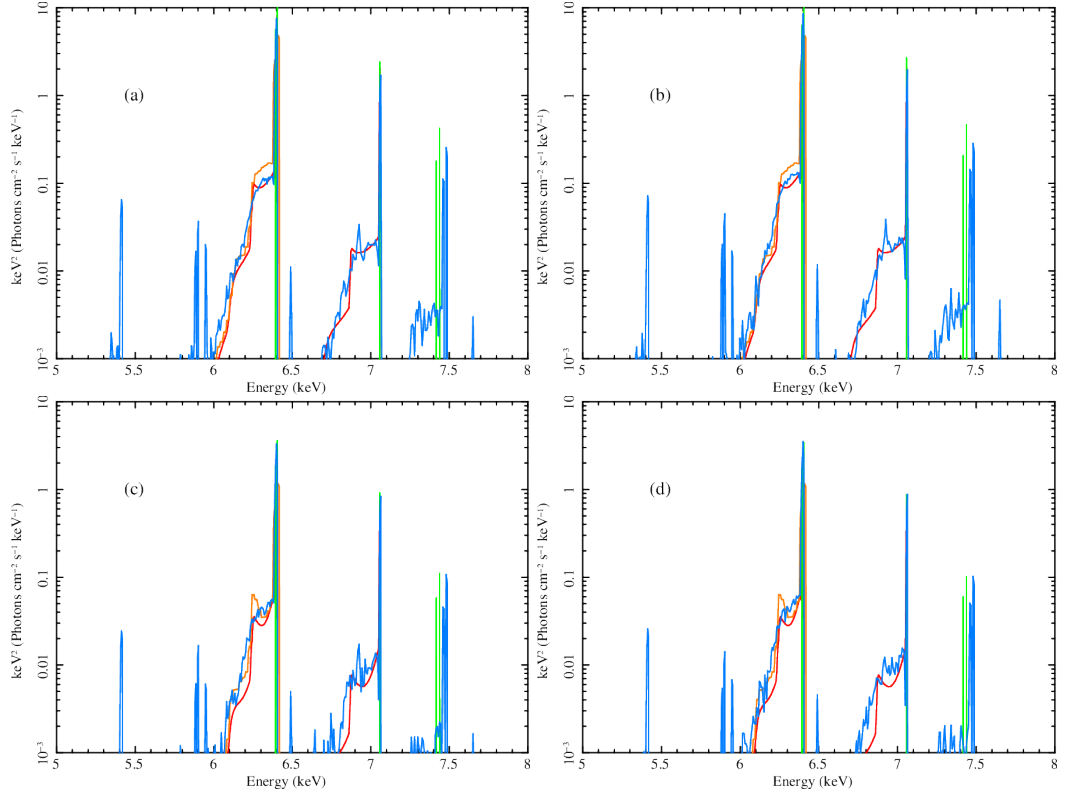


Figure 3.6: The comparison of the emission lines among the torus models: Left:  $N_{\text{clump}}^{\text{Equ}} = 5.0$ . Right:  $N_{\text{clump}}^{\text{Equ}} = 10.0$ . Top:  $i = 20.0$  degree. Bottom:  $i = 87.0$  degree. Red line: MYTorus model. Orange line: Ikeda model. Green line: CTorus model. Blue line: XClumpy model. Torus parameters are as follows. MYTorus model:  $N_{\text{H}}^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree (fixed). Ikeda model:  $N_{\text{H}}^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree. CTorus model:  $N_{\text{H}}^{\text{Equ}} = 1.5 \times 10^{24} \text{ cm}^{-2}$  and  $\theta_{\text{open}} = 60.0$  degree (fixed). XClumpy:  $N_{\text{H}}^{\text{Equ}} = 1.0 \times 10^{24} \text{ cm}^{-2}$  and  $\sigma = 30.0$  degree.

edge-on case; when viewed edge-on, in Ikeda model the soft X-ray reflection component comes from the entire surface of the smooth torus without being absorbed, whereas in the clumpy torus models it comes from clumps at various depths (as measured from the observer) and hence is subject to absorption by other clumps while traveling inside the torus. We note that CTorus and XClumpy produce almost the same fluxes below 20 keV, unlike in the edge-on case. This is because the averaged column density along the line-of-sight responsible for the self absorption is similar between the two models, even if the clump distribution in XClumpy is spread wider in elevation angles than in CTorus. In the torus geometry of MYTorus (bagel-like shape), the area of the irradiated surface is smaller and hence the soft X-ray flux of the reflection component becomes weaker than in Ikeda model.

Figure 3.6 shows the comparison of the emission lines for (a)  $N_{\text{clump}}^{\text{Equ}} = 5.0$  and  $i = 20.0$

Table 3.2: Torus Parameters Obtained from Infrared Spectrum

| $R_{\text{inner}}$        | $R_{\text{outer}}$  | $N_{\text{clump}}^{\text{Equ}}$ | $\tau_v$       | $\sigma$       | $i$            |
|---------------------------|---------------------|---------------------------------|----------------|----------------|----------------|
| (1)                       | (2)                 | (3)                             | (4)            | (5)            | (6)            |
| $0.071^{+0.003}_{-0.003}$ | $1.4^{+0.3}_{-0.2}$ | $7^{+1}_{-1}$                   | $37^{+3}_{-2}$ | $65^{+2}_{-5}$ | $63^{+4}_{-2}$ |

Column (1): inner radius of the torus in units of pc. Column (2): outer radius of the torus in units of pc. Column (3): number of the clump along the equatorial plane. Column (4): optical depth of each cloud. Column (5): torus angular width in units of degree. Column (6): inclination angle in units of degree.

degree, (b)  $N_{\text{clump}}^{\text{Equ}} = 10.0$  and  $i = 20.0$  degree, (c)  $N_{\text{clump}}^{\text{Equ}} = 5.0$  and  $i = 87.0$  degree, and (d)  $N_{\text{clump}}^{\text{Equ}} = 10.0$  and  $i = 87.0$  degree. We note that there are limitations in the treatment of fluorescence lines in the previous models. MYTorus model includes only Fe  $K\alpha$  and Fe  $K\beta$  (with the Compton shoulder), and Ikeda model only Fe  $K\alpha$  (with the Compton shoulder). CTorus model includes other lines than Fe  $K\alpha$  and  $K\beta$  (such as Ni  $K\alpha$ ,  $K\beta$ ), but the Compton shoulders are not taken into account. The XClumpy model includes all prominent fluorescence lines from many elements with the Compton shoulder. It should be also stressed that XClumpy accurately calculates the smeared profiles of the Compton shoulders since the MONACO framework considers atomic and molecular binding of electrons responsible for the scattering (Odaka et al., 2016).

### 3.5 Application to Circinus galaxy

We apply the XClumpy model to broadband X-ray spectra of the Circinus galaxy. The Circinus galaxy ( $z = 0.0014$ ) is one of the closest (4.2 Mpc) obscured AGNs and is an ideal target for investigating torus structure. Ichikawa et al. (2015) applied the CLUMPY model to its infrared data and derived the torus parameters (Table 2). Table 3 summarizes the X-ray observations of the Circinus galaxy analyzed in this paper. Suzaku observed this object in 2006 July. Simultaneous observations with XMM-Newton and NuSTAR were performed in 2013 February.

#### 3.5.1 Data Analysis

##### Suzaku

We analyzed the XIS and HXD data with the HEASoft 6.24 and the calibration database (CALDB) released on 2016 June 7 (XIS) and 2011 September 13 (HXD). We reprocessed

Table 3.3: Summary of Observations

| Observatory | Observation<br>ID | Start Date  | End Date    | Exposure | Reference |
|-------------|-------------------|-------------|-------------|----------|-----------|
| (1)         | (2)               | (3)         | (4)         | (5)      | (6)       |
| Suzaku      | 701036010         | 2006 Jul 21 | 2006 Jul 23 | 108      | (1)       |
| Newton      | 0701981001        | 2013 Feb 03 | 2013 Feb 03 | 59       | (2)       |
| NuSTAR      | 30002038004       | 2013 Feb 03 | 2013 Feb 03 | 40       | (2)       |

Column (1): observatory. Column (2): observation identification number. Column (3): start date in units of ymd. Column (4): end date in units of ymd. Column (5): exposure time in units of ksec. Column (6): nominal position. (7) reference of the previous work. (1) Yang et al. (2009). (2) Arévalo et al. (2014).

the unfiltered XIS and HXD data with *aepipeline*. To extract the XIS light curves and spectra, we accumulated photon events in the circle of a 1 arcmin radius centered on the source peak, by subtracting the background taken from a source-free circular region of a 1 arcmin radius. We generated the XIS redistribution matrix files (RMF) by using *xismfgen* and ancillary response files (ARF) by using *xissimarfgen* (Ishisaki et al., 2007). We combined the source spectra, background spectra, RMF, and ARF of FIXIS by using *addascaspec*. We binned the BIXIS and FIXIS spectra to contain at least 50 counts per bin. We generated the light curves and spectra of HXD-PIN by using *hxdpinxblc* and *hxdpinxbpi* and HXD-GSO by using *hxdgsoxblc* and *hxdgsoxbpi*. We utilized the tuned background files to reproduce the spectra of non X-ray background (NXB). The spectrum of the cosmic X-ray background (CXB) simulated with the energy response for diffuse emission was added to the NXB spectrum of HXD-PIN, whereas the CXB is ignored for HXD-GSO.

### XMM-Newton

We analyzed the EPN and MOS data using the science analysis software (SAS) 16.10 and current calibration file (CCF) released on 2017 December 15. We reprocessed the unfiltered EPN and MOS data by using *epproc* and *emproc*, respectively. We extracted the source spectra from the circle of a 1 arcmin radius centered on the flux peak. The background was taken from a source-free circular region of 1 arcmin radius in the same CCD chip. We generated the RMF by using *rmfgen* and ARF by using *arfgen*. We combined the source spectra, background spectra, RMF, and ARF of MOS by using *addascaspec*. We then binned the EPN and MOS spectra to contain at least 50 counts per bin.

## NuSTAR

We analyzed the FPM data, using the HEAsoft 6.24 and CALDB released on 2018 April 19. Utilizing nupipeline and nuproducts, we extracted the spectrum from the 1-arcmin radius circle centered at the source peak and subtracted the background from a source-free circular region of a 1 arcmin radius. We combined the source spectra, background spectra, RMF, and ARF by using addascaspec. The combined spectrum is then binned to contain at least 50 counts per bin.

### 3.5.2 Spectral Analysis

Since our main interest is the reflection component from the torus, here we only analyze the spectra above 2 keV, in order to avoid complexity in modelling the soft X-ray emission. To best constrain the torus parameters, we perform simultaneous fit to the Suzaku/BIXIS (2–8 keV), Suzaku/FIXIS (2–10 keV), Suzaku/PIN (16–40 keV), Suzaku/GSO (50–100 keV), XMM-Newton/EPN (2–8 keV), XMM-Newton/MOS (2–10 keV), and NuSTAR/FPM (8–60 keV). Possible time variability between the two epochs (2006 and 2013) is ignored, which is found to be not required from the data. We apply the XClumpy model to reproduce the torus reflection component. The whole model is represented as follows in the XSPEC (Arnaud, 1996) terminology:

$$\begin{aligned} & \text{const1} * \text{phabs} \\ & * (\text{zphabs} * \text{cabs} * \text{zcutoffpl} + \text{const2} * \text{zcutoffpl} \\ & + \text{atable}\{\text{XClumpy\_R.fits}\} + \text{atable}\{\text{XClumpy\_L.fits}\} \\ & + \text{phabs} * \text{powerlw} + \text{phabs} * (\text{apec} + \text{phabs} * \text{mekals})) \end{aligned} \quad (3.9)$$

Below we explain the details of each component:

1. Cross-normalization factor (const1). We multiply a constant to take into account the difference in the absolute flux calibration among the instruments. We set this value of Suzaku/FIXIS unity as a reference. The cross-normalizations of Suzaku/BIXIS ( $N_{\text{BIXIS}}$ ), XMM-Newton/EPN ( $N_{\text{EPN}}$ ), XMM-Newton/MOS ( $N_{\text{MOS}}$ ), and NuSTAR/FPM ( $N_{\text{FPM}}$ ) are left as a free parameter. The cross-normalization of Suzaku/PIN and Suzaku/GSO is set to 1.16, according to the calibration results obtained using the Crab Nebula.
2. Galactic absorption (phabs). The hydrogen column density is fixed at  $0.525 \times 10^{22} \text{ cm}^{-2}$ , a value estimated from the H<sub>I</sub> map (HI4PI Collaboration et al., 2016).

3. Transmitted component through the torus, which is subject to photoelectric absorption (zphabs) and Compton scattering (cabs). The line-of-sight column density is determined by the torus parameters (see Equation 3). We model the intrinsic continuum by a power-law with an exponential cutoff (zcutoffpl).
4. Unabsorbed scattered component. The scattering fraction  $f_{\text{scat}}$  (const2) is multiplied to the same model as the intrinsic continuum by linking the photon index, cutoff energy, and normalization.
5. Reflection continuum (XClumpy\_R.fits) from the torus, based on the XClumpy model. The photon index, cutoff energy, and normalization are linked to those of the intrinsic continuum.
6. Fluorescence lines (XClumpy\_L.fits) from the torus, based on the XClumpy model. The photon index, cutoff energy, and normalization are linked to those of the intrinsic continuum. Since we find that the XClumpy model slightly underestimates the observed line fluxes, we add additional two gaussians for Fe  $K\alpha$  and Fe  $K\beta$ .
7. Contamination from CGX1 (X-ray binary). We adopt the same model and flux as in Arévalo et al. (2014), who examined the spectrum of CGX1 with Chandra.
8. Contamination from CGX2 (supernova remnant). We also assume the same model and flux as in Arévalo et al. (2014).

### 3.5.3 Results and Discussion

Our model can well reproduce the broadband X-ray spectra observed with the three satellites. Table 3.4 summarizes the best-fit parameters. Figure 3.7 shows the (a) folded X-ray spectra and (b) best-fit models. We confirm that the torus of the Circinus galaxy is heavily Compton-thick; the column density in the line-of-sight and that along the equatorial plane are estimated to be  $4.86^{+0.07}_{-0.04} \times 10^{24} \text{ cm}^{-2}$  and  $9.08^{+0.14}_{-0.08} \times 10^{24} \text{ cm}^{-2}$ , respectively. Accordingly, the X-ray spectrum is dominated by the reflection component rather than the transmitted one.

#### Comparison to Previous Researches

Here we compare our results with the previous X-ray works using the same data (Yang et al., 2009; Arévalo et al., 2014). Yang et al. (2009) analyzed the Suzaku spectra with the pexrav model, and obtained a line-of-sight absorption of  $N_{\text{H}}^{\text{LOS}} = 4.70^{+0.50}_{-0.32} \times 10^{24} \text{ cm}^{-2}$  and a photon index of  $\Gamma = 1.58^{+0.07}_{-0.10}$ . The simultaneous XMM-Newton and NuSTAR data in 2013 were analyzed by Arévalo et al. (2014). Applying the MYTorus model, they obtained

Table 3.4: Best Fitting Parameters

| $C_{\text{BIXIS}}$     | $C_{\text{EPN}}$       | $C_{\text{MOS}}$       | $C_{\text{FPM}}$       | $N_{\text{H}}^{\text{LOS}}$ | $N_{\text{H}}^{\text{Equ}}$ |
|------------------------|------------------------|------------------------|------------------------|-----------------------------|-----------------------------|
| (01)                   | (02)                   | (03)                   | (04)                   | (05)                        | (06)                        |
| $\sigma$               | $i$                    | $\Gamma$               | $E_{\text{cut}}$       | $N_{\text{Dir}}$            | $f_{\text{scat}}$           |
| (07)                   | (08)                   | (09)                   | (10)                   | (11)                        | (12)                        |
| $E_{\text{FeK}\alpha}$ | $N_{\text{FeK}\alpha}$ | $E_{\text{FeK}\beta}$  | $N_{\text{FeK}\beta}$  | $\log L_{2-10}$             | $\chi_{\text{red}}^2$       |
| (13)                   | (14)                   | (15)                   | (16)                   | (17)                        | (18)                        |
| $1.08^{+0.01}_{-0.01}$ | $0.96^{+0.01}_{-0.01}$ | $1.02^{+0.01}_{-0.01}$ | $0.88^{+0.01}_{-0.01}$ | $4.86^{+0.07}_{-0.04}$      | $9.08^{+0.14}_{-0.08}$      |
| $14.7^{+0.44}_{-0.39}$ | $78.3^{+0.17}_{-0.15}$ | $1.80^{+0.01}_{-0.03}$ | $114^{+9.57}_{-8.91}$  | $0.41^{+0.01}_{-0.01}$      | $0.18^{+0.01}_{-0.01}$      |
| $6.43^{+0.01}_{-0.01}$ | $1.07^{+0.01}_{-0.01}$ | $7.12^{+0.01}_{-0.01}$ | $0.13^{+0.01}_{-0.01}$ | 42.5                        | 1.22                        |

Column (01): cross-calibration constant of the Suzaku/BIXIS relative to the Suzaku/FIXIS. Column (02): cross-calibration constant of the XMM-Newton/EPN relative to the Suzaku/FIXIS. Column (03): cross-calibration constant of the XMM-Newton/MOS relative to the Suzaku/FIXIS. Column (04): cross-calibration constant of the NuSTAR/FPM relative to the Suzaku/FIXIS. Column (05): hydrogen column density along the line of sight in units of  $10^{24} \text{ cm}^{-2}$ . Column (06): hydrogen column density along the equatorial plane in units of  $10^{24} \text{ cm}^{-2}$ . Column (07): torus angular width in units of degree. Column (08): inclination angle in units of degree. Column (09): photon index. Column (10): cutoff energy in units of keV. Column (11): normalization of the direct component in units of photons  $\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ . Column (12): scattering fraction in units of percent. Column (13): energy of the additional Fe  $K\alpha$  emission line. Column (14): normalization of the additional Fe  $K\alpha$  emission line in units of  $10^{-4} \text{ photons cm}^2 \text{ s}^{-1}$ .

$N_{\text{H}}^{\text{LOS}} = 6.6^{+0.9}_{-0.9} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 2.19^{+0.02}_{-0.02}$ . Our result of the line-of-sight column density ( $N_{\text{H}}^{\text{LOS}} = 4.86^{+0.07}_{-0.04} \times 10^{24} \text{ cm}^{-2}$ ) is consistent with both of them. The photon index ( $\Gamma = 1.77^{+0.06}_{-0.03}$ ) is smaller than the Arévalo et al. (2014) result, however. We infer that this is because the XClumpy model contains a larger flux of the unabsorbed reflection component, leading to a flatter intrinsic slope, compared with the MYTorus model case.

### Comparison of Torus Parameters by X-ray and infrared spectra

It is interesting to compare the torus parameters obtained from the X-ray data (Table 3.4) with those from the infrared data (Table 3.2). The total V-band optical depth in the equatorial plane obtained with the CLUMPY model is  $\tau_{\text{V}} = 173^{+26}_{-7}$ , which can be converted to  $N_{\text{H}}^{\text{Equ}} = 0.35^{+0.01}_{-0.05} \times 10^{24} \text{ cm}^{-2}$  by assuming the gas-to-dust ratio in the Galaxy (Draine

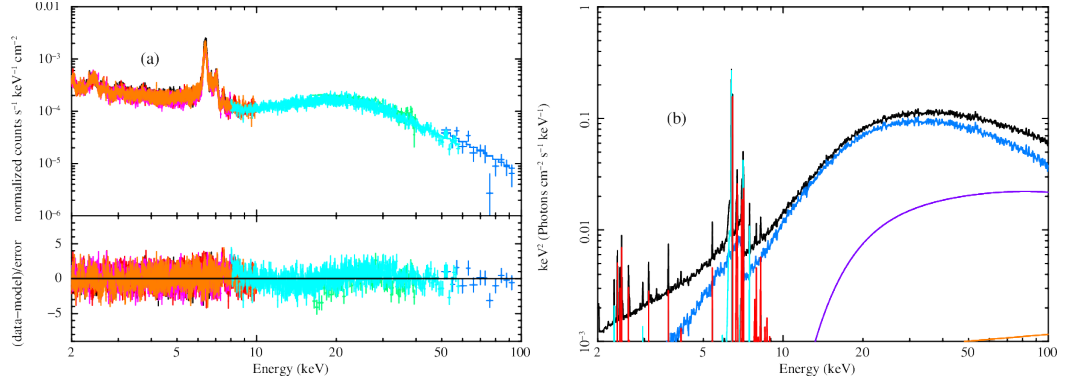


Figure 3.7: Left: folded X-ray spectrum fitted with the XClumpy model. Black crosses: Suzaku/BIXIS. Red crosses: Suzaku/FIXIS. Green crosses: Suzaku/PIN. Blue crosses: Suzaku/GSO. Pink crosses: XMM-Newton/EPN. Orange crosses: XMM-Newton/MOS. Light blue crosses: NuSTAR/FPM. Upper panel: solid curves represent the best fitting model. Lower panel: each cross represents a residual. Right: Best fitting model. Black line: total. Purple line: direct component. Blue line: reflection component from the torus. Light blue lines: emission lines from the torus. Orange line: contamination from the CGX1. Red lines: contamination from the CGX2.

2003:  $N_{\text{H}}/A_{\text{V}} = 1.87 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$ ). This value is much (by a factor of  $\sim 26$ ) smaller than the X-ray result,  $N_{\text{H}}^{\text{Equ}} = 9.08^{+0.14}_{-0.08} \times 10^{24} \text{ cm}^{-2}$ . The same conclusion holds when we compare the line-of-sight column density. This trend is consistent with the results of Bartscher et al. (2015, 2016), who estimated  $A_{\text{V}}$  from the near-to-mid infrared colors. The torus angular width obtained from the infrared data ( $\sigma = 65^{+2}_{-5}$  degree) is much larger than the X-ray results ( $\sigma = 14.7^{+0.44}_{-0.39}$  degree). These results may be explained by the presence of a dusty polar outflow observed in the infrared interfere-metric observations (Tristram et al., 2014; Stalevski et al., 2017), which apparently makes the distribution of dust wider than that of gas. Since the extended outflow is subject to smaller extinction than that toward the very center of the nucleus, it works to reduce the observed (averaged)  $A_{\text{V}}$  value.

## 3.6 Conclusion

1. We have constructed the XClumpy model, a spectral model of X-ray reflection from the clumpy torus in an AGN, where the same torus geometry as in the infrared CLUMPY model is adopted. This enables us to directly compare the X-ray and infrared results, which trace the distribution of all matter and dust, respectively.
2. We found that the equivalent width of Fe  $K\alpha$  line and the Compton shoulder fraction both increase with the hydrogen column density along the equatorial plane and torus angular width.
3. Compared with smooth torus models, our model predicts a higher fraction of unabsorbed reflection components as observed in many obscured AGNs.
4. Our model well reproduces the broadband X-ray spectra of the Circinus galaxy observed with XMM-Newton, Suzaku, and NuSTAR. We confirm that the torus is heavily Compton thick and the spectrum is dominated by the reflection component from the torus.
5. In the Circinus galaxy, the column density obtained from the X-ray data is  $\geq 20$  times larger than that from the infrared data by assuming a Galactic gas-to-dust ratio. The torus angular width derived from X-rays is much smaller than that in the infrared band. This may be explained by the presence of a dusty polar outflow.



## Chapter 4

# Application of X-Ray Clumpy Torus Model (XClumpy) to 10 Obscured AGNs Observed with Suzaku and NuSTAR

### Abstract

We apply the XClumpy (Tanimoto et al., 2019), an X-ray spectral model from a clumpy torus in an active galactic nucleus (AGN), to the broadband X-ray spectra of 10 obscured AGNs observed with Suzaku and NuSTAR. The infrared spectra of these AGNs were analyzed by Ichikawa et al. (2015) with the CLUMPY (Nenkova et al., 2008a,b). Since the XClumpy adopts the same clump distribution as that in the CLUMPY, we are able to directly compare the torus parameters obtained from the X-ray spectrum and those from the infrared one. Our model well reproduces the broadband X-ray spectra of all objects. The main results are as follows: (1) some AGNs are dust rich compared with the Galactic interstellar medium, as opposite to the general trend previously reported in many obscured AGNs. (2) the torus angular width obtained from the infrared spectrum ( $\sigma_{\text{IR}}$ ) is systematically larger than that from the X-ray one ( $\sigma_{\text{X}}$ ). This can be explained by the polar dust outflow observed in the infrared interferometric observations.

Table 4.1: Information on Objects

| Object<br>(1) | Classification<br>(2) | RA<br>(3) | Dec<br>(4) | Redshift<br>(5) | Distance<br>(6) |
|---------------|-----------------------|-----------|------------|-----------------|-----------------|
| IC 5063       | Sy2                   | 20h52m02s | -57d04m07s | 0.01135         | 48.32           |
| NGC 2110      | Sy2                   | 05h52m11s | -07d27m22s | 0.00779         | 35.47           |
| NGC 3227      | Sy1.5                 | 10h23m30s | +19d51m54s | 0.00386         | 21.83           |
| NGC 3281      | Sy2                   | 10h31m52s | -34d51m13s | 0.01067         | 51.97           |
| NGC 5506      | Sy1.9                 | 14h13m14s | -03d12m27s | 0.00618         | 31.18           |
| NGC 5643      | Sy2                   | 14h32m40s | -44d10m27s | 0.00400         | 20.64           |
| NGC 5728      | Sy2                   | 14h42m23s | -17d15m11s | 0.00935         | 44.70           |
| NGC 7172      | Sy2                   | 22h02m01s | -31d52m10s | 0.00868         | 34.35           |
| NGC 7582      | Sy2                   | 23h18m23s | -42d22m14s | 0.00525         | 19.67           |
| NGC 7674      | Sy2                   | 23h27m56s | +08d46m44s | 0.02892         | 122.44          |

Column (1): galaxy name. Column (2): optical classification from the NASA/IPAC Extragalactic Database (NED). Column (3): right ascension from the NED. Column (4): declination from the NED. (5) redshift from the NED. Column (6): distance from NED in units of Mpc.

## 4.1 Introduction

This Chapter 4 presents the results of applying the XClumpy to the broadband X-ray spectra of 10 obscured AGNs observed with both Suzaku and NuSTAR. The structure of this Chapter 4 is the following: Chapter 4.2 describes our sample and data analysis. Chapter 4.3 presents the X-ray spectral model and the broadband X-ray spectral analysis. Chapter 4.4 summarizes our results. Chapter 4.5 compares the torus parameters obtained from the X-ray spectrum and those from the infrared one.

## 4.2 Sample and Analysis

Our sample is taken from that of Ichikawa et al. (2015), who examined the torus properties by applying the CLUMPY to the infrared spectra of 21 nearby AGNs. Among them, we selected 10 obscured AGNs observed with both Suzaku and NuSTAR. This is because (1) the line of sight absorption can be directly measured in obscured AGNs, giving a tight constraint on the torus column density, and (2) high quality broadband X-ray spectra are essential for separating and characterizing the torus-reflection component. We exclude two objects analyzed in other papers: Circinus galaxy (Tanimoto et al., 2019) and NGC 5135

Table 4.2: Summary of Observations<sup>1</sup>

| Object<br>(1) | Observatory<br>(2) | ID<br>(3)   | Exposure<br>(4) | Binning<br>(5) | Reference<br>(6) |
|---------------|--------------------|-------------|-----------------|----------------|------------------|
| IC 5063       | Suzaku             | 704010010   | 45160           | 50             | (01)             |
|               | NuSTAR             | 60061302002 | 18447           | 50             | (02)             |
| NGC 2110      | Suzaku             | 707034010   | 103259          | 100            | (03) (04)        |
|               | NuSTAR             | 60061061002 | 15537           | 100            | (02) (05)        |
| NGC 3227      | Suzaku             | 703022050   | 79429           | 50             | (06)             |
|               | NuSTAR             | 60202002002 | 49800           | 50             | ...              |
| NGC 3281      | Suzaku             | 703033010   | 46234           | 50             | ...              |
|               | NuSTAR             | 60061201002 | 22986           | 50             | ...              |
| NGC 5506      | Suzaku             | 701030030   | 57406           | 100            | (04)             |
|               | NuSTAR             | 60061323002 | 56585           | 100            | (07)             |

Column (1): galaxy name. Column (2): observatory. Column (3): ID. Column (4): exposure in units of second. Column (5): binning. Column (6): references.

Reference (01): Tazaki et al. (2011). Reference (02): Baloković et al. (2018). Reference (03): Rivers et al. (2014). Reference (04): Kawamuro et al. (2016a). Reference (05): Marinucci et al. (2015). Reference (06): Noda et al. (2014). Reference (07): Matt et al. (2015). Reference (08): Kawamuro et al. (2016b). Reference (09): Marchesi et al. (2019b). Reference (10): Tanimoto et al. (2018). Reference (11): Bianchi et al. (2009). Reference (12): Gandhi et al. (2017).

(Yamada et al., 2020, in prep). Table 4.1–4.3 summarize our sample and the observations.

## Suzaku

We analyze the XIS and HXD-PIN data with the HEAsoft 6.25 and the calibration database (CALDB) released on 2018 October 10 (XIS) and 2011 September 13 (HXD). XIS and HXD data are reprocessed by using *aepipeline*. XIS: We extract the source spectrum from the 1 arcmin radius circular region centered on the source peak and the background from a 1 arcmin radius source-free region. We generate the redistribution matrix files (RMF) with *xismfgen* and the ancillary response files (ARF) with *xissimarfgen* (Ishisaki et al., 2007). The source spectrum, the background spectrum, the RMF, and the ARF of FIXIS are combined with *addascaspec*. HXD: We generate the PIN spectrum with *hxdpinxbpi*. We utilize the tuned background files to reproduce the non X-ray background (NXB), to which the simulated the cosmic X-ray background (CXB) is added.

Table 4.3: Summary of Observations2

| Object<br>(1) | Observatory<br>(2) | ID<br>(3)   | Exposure<br>(4) | Binning<br>(5) | Reference<br>(6) |
|---------------|--------------------|-------------|-----------------|----------------|------------------|
| NGC 5643      | Suzaku             | 702010010   | 42882           | 50             | (08)             |
|               | NuSTAR             | 60061362002 | 22456           | 50             | (09)             |
| NGC 5728      | Suzaku             | 701079010   | 41307           | 50             | (10)             |
|               | NuSTAR             | 60061256002 | 24358           | 50             | (09)             |
| NGC 7172      | Suzaku             | 703030010   | 82279           | 100            | (04)             |
|               | NuSTAR             | 60061308002 | 32001           | 100            | ...              |
| NGC 7582      | Suzaku             | 702052040   | 31895           | 50             | (10) (11)        |
|               | NuSTAR             | 60201003002 | 48495           | 50             | (02) (09)        |
| NGC 7674      | Suzaku             | 708023010   | 52194           | 50             | (12)             |
|               | NuSTAR             | 60001151002 | 51998           | 50             | (12)             |

Column (1): galaxy name. Column (2): observatory. Column (3): ID. Column (4): exposure in units of second. Column (5): binning. Column (6): references.

Reference (01): Tazaki et al. (2011). Reference (02): Baloković et al. (2018). Reference (03): Rivers et al. (2014). Reference (04): Kawamuro et al. (2016a). Reference (05): Marinucci et al. (2015). Reference (06): Noda et al. (2014). Reference (07): Matt et al. (2015). Reference (08): Kawamuro et al. (2016b). Reference (09): Marchesi et al. (2019b). Reference (10): Tanimoto et al. (2018). Reference (11): Bianchi et al. (2009). Reference (12): Gandhi et al. (2017).

## NuSTAR

We analyze the FPM data with the HEAsoft 6.25 and the CALDB released on 2019 April 10. FPM data are reprocessed by using nupipeline. We extract the source spectrum from the 1 arcmin radius circular region centered on the source peak and the background from a 1 arcmin radius source free region with nuproducts. The source spectrum, the background spectrum, the RMF, and the ARF are combined with addascaspec.

## 4.3 Spectral Analysis

We employ the XClumpy model to reproduce the reflection spectra from the torus. The torus geometry of the clump distribution is the same as that of the CLUMPY (Nenkova et al., 2008a,b) i.e., a power law distribution in the radial direction and a normal distribution in the elevation direction. The number density function  $d(r, \theta, \phi)$  (in units of  $\text{pc}^{-3}$ ) is represented

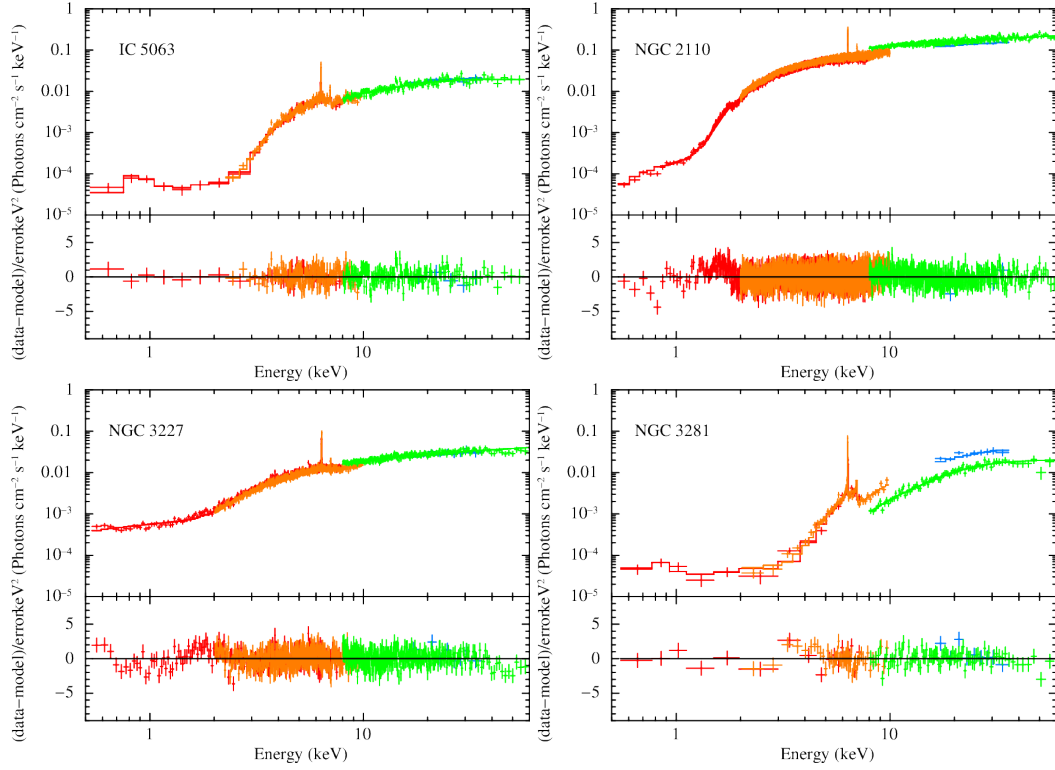


Figure 4.1: The unfolded X-ray spectrum fitted with the XClumpy. Red crosses: Suzaku/BIXIS. Orange crosses: Suzaku/FIXIS. Blue crosses: Suzaku/PIN. Green crosses: NuSTAR/FPM. Solid curves: best fitting model. Lower panel: residuals.

in the spherical coordinate system (where  $r$  is radius,  $i$  is inclination angle measured from the rotation axis, and  $\phi$  is azimuth) as:

$$d(r, \theta, \phi) = N \left( \frac{r}{r_{\text{in}}} \right)^{-1/2} \exp \left( -\frac{(i - \pi/2)^2}{\sigma^2} \right). \quad (4.1)$$

where  $N$  is the normalization,  $r_{\text{in}}$  is the inner radius of the torus, and  $\sigma$  is the torus angular width around the mid-plane (Tanimoto et al., 2019). The inner and outer radii of the torus and the radius of each clump is set to be 0.05 pc, 1.00 pc, and 0.002 pc, respectively. This model has five free parameters: (1) hydrogen column density along the equatorial plane ( $N_{\text{H}}^{\text{Equ}}$ :  $10^{23}$ – $10^{26}$  cm $^{-2}$ ), (2) torus angular width ( $\sigma$ : 10–70 degree), (3) inclination angle ( $i$ : 20–87 degree), (4) photon index ( $\Gamma$ : 1.5–2.5), and (5) cutoff energy ( $E_{\text{cut}}$ :  $10^1$ – $10^3$  keV).

For each object, we perform simultaneous fitting to the Suzaku/BIXIS (0.5–8.0 keV), Suzaku/FIXIS (2–10 keV), Suzaku/HXD (16–40 keV: the widest case), and NuSTAR/FPM (8–60 keV: the widest case) spectra. Our model is represented as follows in the XSPEC

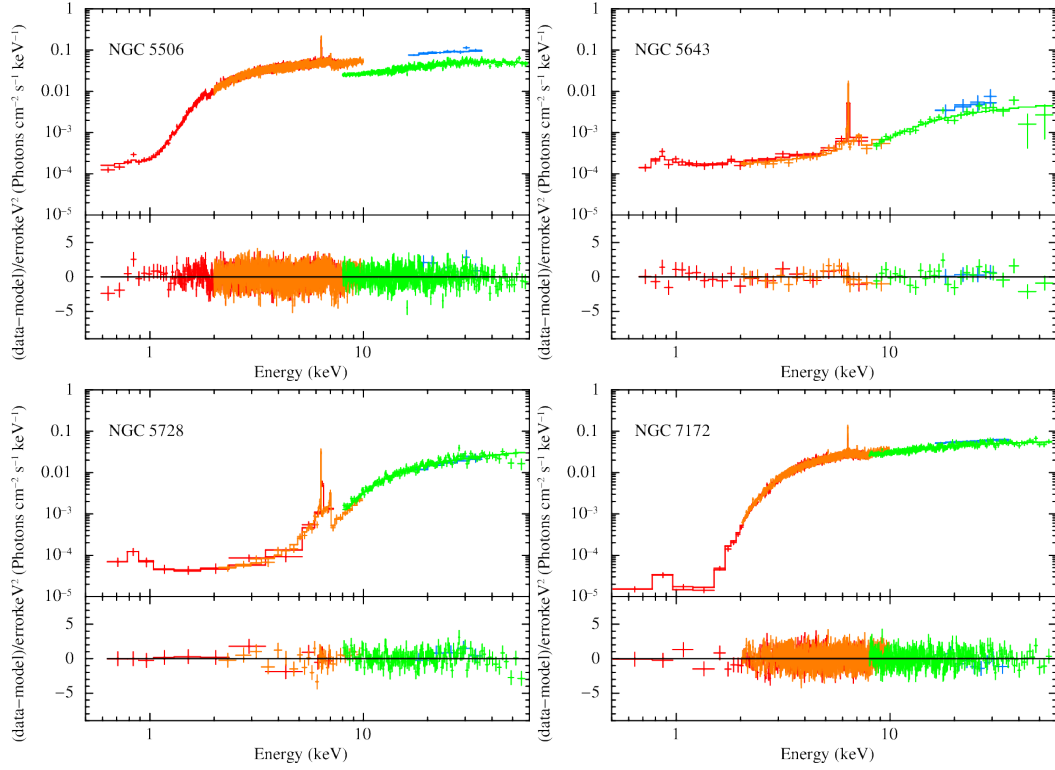


Figure 4.2: The unfolded X-ray spectrum fitted with the XClumpy. Red crosses: Suzaku/BIXIS. Orange crosses: Suzaku/FIXIS. Blue crosses: Suzaku/PIN. Green crosses: NuSTAR/FPM. Solid curves: best fitting model. Lower panel: residuals.

(Arnaud, 1996) terminology:

$$\begin{aligned}
 & \text{const1} * \text{phabs} \\
 & * (\text{const2} * \text{zphabs} * \text{cabs} * \text{zcutoffpl} \\
 & + \text{const3} * \text{zcutoffpl} + \text{atable}\{\text{XClumpy\_R.fits}\} \\
 & + \text{const4} * \text{atable}\{\text{XClumpy\_L.fits}\} + \text{apec}
 \end{aligned} \tag{4.2}$$

This model consists of six components:

1. **(const1\*phabs)** The **const1** term is a cross-normalization constant to adjust small differences in the absolute flux calibration among different instruments. We set those of Suzaku/FIXIS and NuSTAR/FPM to unity as references. That of Suzaku/HXD is set to 1.16 (for the XIS-nominal pointing position) or 1.18 (HXD nominal). We leave that of Suzaku/BIXIS ( $C_{\text{BIXIS}}$ ) as a free parameter. The **phabs** term represents the Galactic absorption. We set the hydrogen column density to a value estimated from the HI4PI survey (HI4PI Collaboration et al., 2016) with the nh tool.

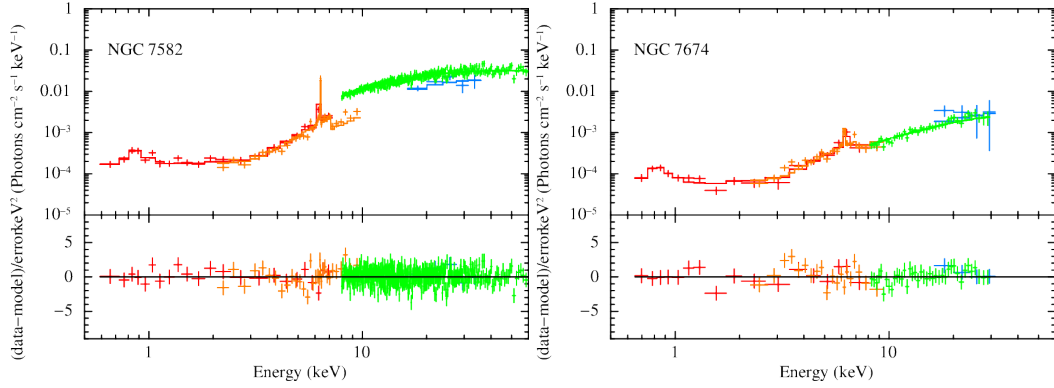


Figure 4.3: The unfolded X-ray spectrum fitted with the XClumpy. Red crosses: Suzaku/BIXIS. Orange crosses: Suzaku/FIXIS. Blue crosses: Suzaku/PIN. Green crosses: NuSTAR/FPM. Solid curves: best fitting model. Lower panel: residuals.

2. **(const2\*zphabs\*cabs\*zcutoffpl)** This component represents the transmitted continuum through the torus. The **const2** term ( $C_{\text{Time}}$ ) is a constant to account for time variability between the Suzaku and NuSTAR observations. We do not multiply this constant to the scattered component and the reflection component. This is because the size of the scatterer and reflector is most likely a parsec scale and hence little time variability is expected. We limit  $C_{\text{Time}}$  value within a range of 0.1–10.0 to avoid unrealistic results (e.g. Kawamuro et al., 2016a; Tanimoto et al., 2018). The **zphabs** and **cabs** terms represent the photoelectric absorption and Compton scattering by the torus, respectively. Here the hydrogen column density along the line of sight ( $N_{\text{H}}^{\text{LOS}}$ ) is linked to the XClumpy parameters as

$$N_{\text{H}}^{\text{LOS}} = N_{\text{H}}^{\text{Equ}} \exp\left(-\frac{(i - \pi/2)^2}{\sigma^2}\right). \quad (4.3)$$

The **zcutoffpl** is the intrinsic continuum modeled by a power law with an exponential cutoff. Since it is difficult to determine the cutoff energy, we fix this value at a typical value ( $E_{\text{cut}} = 370$  keV: Ricci et al. 2018).

3. **(const3\*zcutoffpl)** This represents the scattered component, where **const3** is the scattering fraction ( $f_{\text{scat}}$ ). We link the photon index ( $\Gamma$ ), the cutoff energy ( $E_{\text{cut}}$ ), and the normalization ( $N_{\text{Dir}}$ ) to those of the intrinsic continuum.
4. **(XClumpy\_R.fits)** This component represents the reflection continuum from the torus based on XClumpy. We link  $\Gamma$ ,  $E_{\text{cut}}$ , and  $N_{\text{Dir}}$  to those of the intrinsic continuum. When it is difficult to constrain the inclination angle, we fix it to the value obtained from the infrared data (for NGC 2110, NGC 5643, NGC 5728, and NGC 7674).

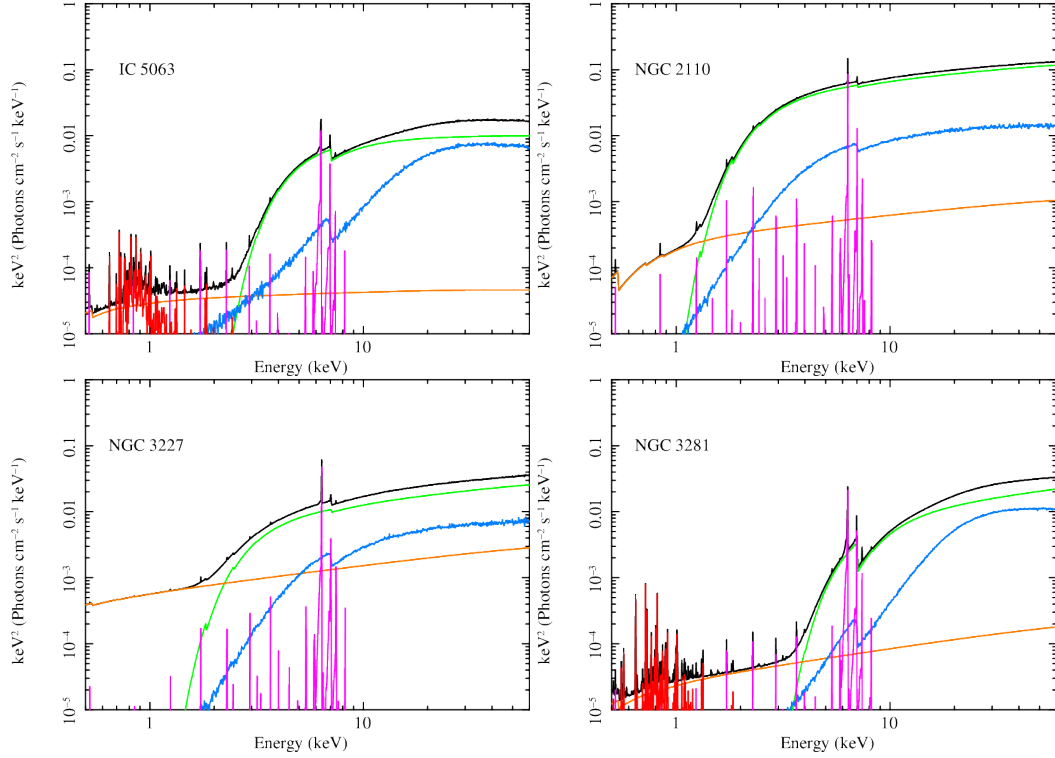


Figure 4.4: The best fitting model. Black line: total. Green line: direct component. Orange line: scattered component. Blue line: reflection continuum from the torus. Magenta line: emission lines from the torus. Red line: emission from optically thin thermal plasma.

5. (**const4\*XClumpy\_L.fits**) This component represents fluorescence lines from the torus based on XClumpy. The **const4** term is a relative normalization ( $N_{\text{Line}}$ ) to account for possible systematic uncertainties in the model (e.g., metal abundances). We link  $N_{\text{H}}^{\text{Equ}}$ ,  $\sigma$ ,  $i$ ,  $\Gamma$ , and  $E_{\text{cut}}$  to those of the reflection continuum.
6. (**aptec**) This component represents emission from an optically thin thermal plasma in the host galaxy. We adopt it when the improvement of the fit by adding this component is significant at a  $\geq 99\%$  confidence level.

## 4.4 Results

Our model well reproduces the broadband X-ray spectra of all objects. Figure 4.1–4.3 show the unfolded X-ray spectra and Figure 4.4–4.6 show the best fitting models. Table 4.4 and 4.5 summarize the best fitting parameters. Table 4.6 gives the observed fluxes, the intrinsic luminosities, and the Eddington ratios. Here we estimate the bolometric luminosity as  $L_{\text{Bol}} = 20L_{2-10\text{keV}}$  where  $L_{2-10\text{keV}}$  is the intrinsic 2–10 keV luminosity, and define the



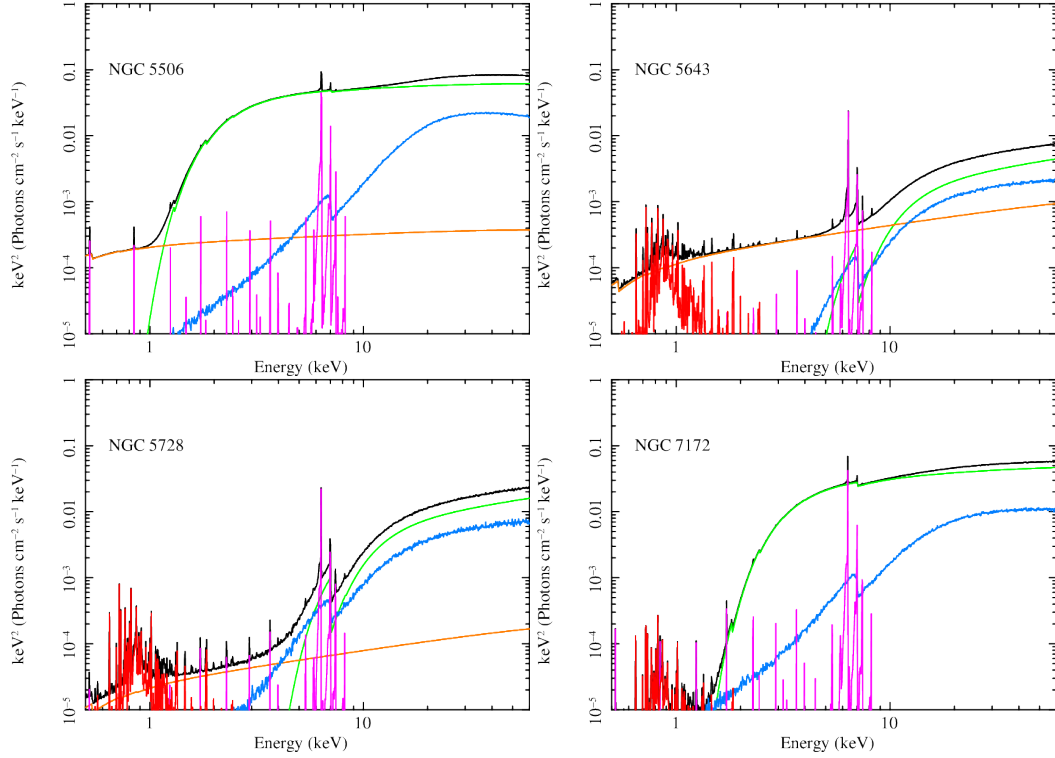


Figure 4.5: The best fitting model. Black line: total. Green line: direct component. Orange line: scattered component. Blue line: reflection continuum from the torus. Magenta line: emission lines from the torus. Red line: emission from optically thin thermal plasma.

Eddington luminosity as  $L_{\text{Edd}} = 1.25 \times 10^{38} M_{\text{BH}}/M_{\odot}$  where  $M_{\text{BH}}$  is the black hole mass. Below, we compare our results with previous studies where different reflection models were adopted. To focus on differences in the spectral models, not in the data, here we only refer to previous works that utilized Suzaku or NuSTAR data.

#### 4.4.1 IC 5063

The model with an apec component well reproduces the broadband X-ray spectrum (0.50–60.0 keV). We obtain  $N_{\text{H}}^{\text{LOS}} = 0.26^{+0.19}_{-0.14} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.88^{+0.11}_{-0.10}$  ( $\chi^2_{\text{red}} = 0.97$ ). Our best fitting parameters are consistent with the Suzaku results (Tazaki et al., 2011) and NuSTAR results (Baloković et al., 2018). Tazaki et al. (2011) estimated  $N_{\text{H}}^{\text{LOS}} = 0.25^{+0.10}_{-0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.82^{+0.08}_{-0.11}$  with the Ikeda model. Baloković et al. (2018) obtained  $N_{\text{H}}^{\text{LOS}} = 0.21 \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.75$  with the borus02 model.

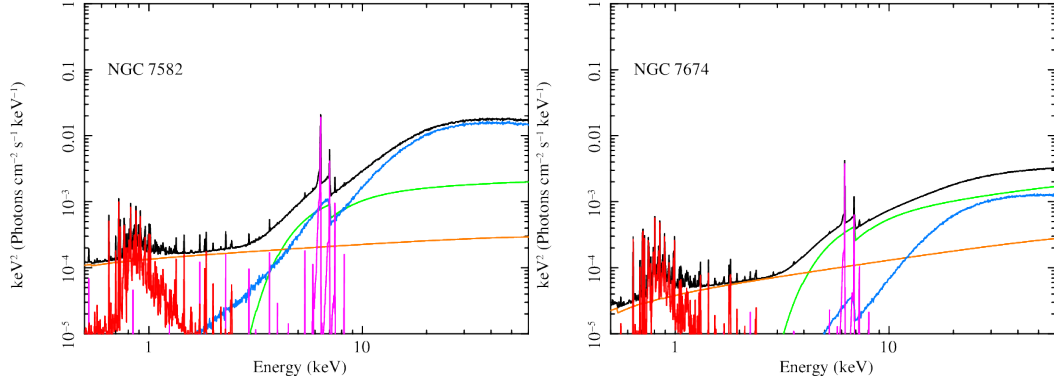


Figure 4.6: The best fitting model. Black line: total. Green line: direct component. Orange line: scattered component. Blue line: reflection continuum from the torus. Magenta line: emission lines from the torus. Red line: emission from optically thin thermal plasma.

#### 4.4.2 NGC 2110

The model without an apec component is able to reproduce the broadband X-ray spectrum (0.50–60.0 keV). Our best fitting parameters are  $N_{\text{H}}^{\text{LOS}} = 0.04^{+0.01}_{-0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.63^{+0.01}_{-0.01}$  ( $\chi^2_{\text{red}} = 1.05$ ). Our results agree with the Suzaku results (Rivers et al., 2014; Kawamuro et al., 2016a) and NuSTAR results (Marinucci et al., 2015; Baloković et al., 2018). Utilizing the pexrav model (Magdziarz & Zdziarski, 1995) for the reflection component, Rivers et al. (2014) obtained  $N_{\text{H}}^{\text{LOS}} = 0.05^{+0.01}_{-0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.66^{+0.01}_{-0.01}$ , and Kawamuro et al. (2016a) obtained  $N_{\text{H}}^{\text{LOS}} = 0.02^{+0.01}_{-0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.65^{+0.01}_{-0.01}$ . Marinucci et al. (2015) obtained  $N_{\text{H}}^{\text{LOS}} = 0.04^{+0.01}_{-0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.64^{+0.03}_{-0.03}$  with the MYTorus model, and Baloković et al. (2018) obtained  $N_{\text{H}}^{\text{LOS}} = 0.04 \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.63$  with the borus02 model.

#### 4.4.3 NGC 3227

The NuSTAR data are reported for the first time. The model without an apec component well reproduces the broadband X-ray spectrum (0.50–60.0 keV). We obtain  $N_{\text{H}}^{\text{LOS}} = 0.07^{+0.01}_{-0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.58^{+0.03}_{-0.03}$  ( $\chi^2_{\text{red}} = 1.22$ ). These are consistent with the Suzaku results by Noda et al. (2014) ( $N_{\text{H}}^{\text{LOS}} = 0.10^{+0.01}_{-0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.67^{+0.06}_{-0.06}$ ) utilizing the pexrav model.

#### 4.4.4 NGC 3281

The NuSTAR data are reported for the first time. The model with an apec component well reproduces the broadband X-ray spectrum (0.50–55.0 keV). Our best fitting parameters are

Table 4.4: Best Fitting Parameters1

| Object   | $C_{\text{BIXIS}}$          | $C_{\text{Time}}$      | $\Gamma$               | $N_{\text{Dir}}$       | $f_{\text{scat}}$      |
|----------|-----------------------------|------------------------|------------------------|------------------------|------------------------|
| (01)     | (02)                        | (03)                   | (04)                   | (05)                   | (06)                   |
|          | $N_{\text{H}}^{\text{Equ}}$ | $\sigma$               | $i$                    | $N_{\text{Line}}$      | $\chi_{\text{red}}^2$  |
|          | (07)                        | (08)                   | (09)                   | (10)                   | (11)                   |
| IC 5061  | $0.97^{+0.04}_{-0.04}$      | $0.87^{+0.04}_{-0.04}$ | $1.88^{+0.11}_{-0.10}$ | $1.04^{+0.31}_{-0.20}$ | $0.34^{+0.14}_{-0.12}$ |
|          | $10.2^{+7.27}_{-5.43}$      | $21.1^{+9.23}_{-6.61}$ | $49.5^{+9.23}_{-6.61}$ | $1.17^{+0.77}_{-0.18}$ | 0.97                   |
| NGC 2110 | $0.90^{+0.01}_{-0.01}$      | $0.64^{+0.01}_{-0.01}$ | $1.63^{+0.02}_{-0.02}$ | $5.51^{+0.15}_{-0.14}$ | $0.57^{+0.04}_{-0.04}$ |
|          | $0.22^{+0.04}_{-0.04}$      | $50.0^{+9.98}_{-4.01}$ | $25.5^{+4.43}_{-4.01}$ | $0.36^{+0.06}_{-0.06}$ | 1.05                   |
| NGC 3227 | $1.13^{+0.02}_{-0.02}$      | $0.73^{+0.02}_{-0.02}$ | $1.58^{+0.03}_{-0.03}$ | $0.68^{+0.03}_{-0.03}$ | $7.74^{+0.42}_{-0.42}$ |
|          | $0.56^{+0.07}_{-0.07}$      | $48.3^{+1.68}_{-4.54}$ | $20.0^{+6.62}_{-4.54}$ | $0.67^{+0.07}_{-0.06}$ | 1.22                   |
| NGC 3281 | $0.92^{+0.07}_{-0.07}$      | $2.97^{+0.26}_{-0.21}$ | $1.50^{+0.05}_{-0.05}$ | $0.19^{+0.03}_{-0.01}$ | $1.56^{+0.30}_{-0.30}$ |
|          | $8.96^{+7.93}_{-3.00}$      | $43.3^{+4.14}_{-9.36}$ | $20.0^{+9.60}_{-9.36}$ | $2.86^{+0.64}_{-0.44}$ | 1.23                   |
| NGC 5506 | $1.02^{+0.01}_{-0.01}$      | $2.02^{+0.04}_{-0.03}$ | $1.84^{+0.02}_{-0.01}$ | $1.88^{+0.06}_{-0.06}$ | $1.20^{+0.12}_{-0.12}$ |
|          | $12.8^{+3.50}_{-4.04}$      | $24.0^{+2.62}_{-1.54}$ | $31.1^{+3.26}_{-4.09}$ | $1.76^{+0.29}_{-0.34}$ | 1.08                   |

Column (01): galaxy name. Column (02): relative normalization of Suzaku/BIXIS to Suzaku/FIXIS. Column (03): time variability constant. Column (04): photon index. Column (05): normalization of the direct component in units of  $10^{-2}$  photons  $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ . Column (06): scattering fraction in units of percent. Column (07): hydrogen column density along the equatorial plane in units of  $10^{24} \text{cm}^{-2}$ . Column (08): torus angular width in units of degree. Column (09): inclination angle in units of degree. Column (10): relative normalization of the emission lines to the reflection component.

$$N_{\text{H}}^{\text{LOS}} = 0.66^{+0.58}_{-0.22} \times 10^{24} \text{cm}^{-2} \text{ and } \Gamma = 1.50^{+0.05}_{-0.05} (\chi_{\text{red}}^2 = 1.23).$$

#### 4.4.5 NGC 5506

The model with an apec component well reproduces the broadband X-ray spectrum (0.60–60.0 keV). We obtain  $N_{\text{H}}^{\text{LOS}} = 0.03^{+0.01}_{-0.01} \times 10^{24} \text{cm}^{-2}$  and  $\Gamma = 1.84^{+0.02}_{-0.01}$  ( $\chi_{\text{red}}^2 = 1.08$ ). Our photon index is slightly smaller from those of Suzaku (Kawamuro et al., 2016a) and NuSTAR (Matt et al., 2015), while the column density is consistent with their results. Kawamuro et al. (2016a) estimated  $N_{\text{H}}^{\text{LOS}} = 0.03^{+0.01}_{-0.01} \times 10^{24} \text{cm}^{-2}$  and  $\Gamma = 1.95^{+0.01}_{-0.01}$  by applying the pexrav model for the reflection continuum. Matt et al. (2015) obtained  $N_{\text{H}}^{\text{LOS}} = 0.03^{+0.01}_{-0.01} \times 10^{24} \text{cm}^{-2}$  and  $\Gamma = 1.91^{+0.03}_{-0.03}$  with the xillver model, which represents a reflection component from an illuminated accretion disk. We interpret that this is because XClumpy contains more unabsorbed (hence softer) reflected continuum than the pexrav

Table 4.5: Best Fitting Parameters2

| Object   | $C_{\text{BIXIS}}$          | $C_{\text{Time}}$      | $\Gamma$               | $N_{\text{Dir}}$       | $f_{\text{scat}}$      |
|----------|-----------------------------|------------------------|------------------------|------------------------|------------------------|
| (01)     | (02)                        | (03)                   | (04)                   | (05)                   | (06)                   |
|          | $N_{\text{H}}^{\text{Equ}}$ | $\sigma$               | $i$                    | $N_{\text{Line}}$      | $\chi_{\text{red}}^2$  |
|          | (07)                        | (08)                   | (09)                   | (10)                   | (11)                   |
| NGC 5643 | $1.17^{+0.12}_{-0.12}$      | $1.10^{+1.04}_{-0.45}$ | $1.58^{+0.18}$         | $0.05^{+0.07}_{-0.02}$ | $24.0^{+10.2}_{-11.7}$ |
|          | $5.22_{-3.97}$              | $49.9_{-20.0}$         | $20.0$                 | $7.20^{+2.10}_{-2.48}$ | $0.88$                 |
| NGC 5728 | $0.99^{+0.11}_{-0.11}$      | $0.42^{+0.09}_{-0.09}$ | $1.59^{+0.10}$         | $0.49^{+0.19}_{-0.13}$ | $0.75^{+0.24}_{-0.19}$ |
|          | $2.62^{+1.16}_{-0.91}$      | $70.0_{-11.9}$         | $20.0^{+29.6}$         | $0.94^{+0.11}_{-0.17}$ | $1.01$                 |
| NGC 7172 | $0.98^{+0.01}_{-0.01}$      | $1.08^{+0.02}_{-0.02}$ | $1.75^{+0.02}_{-0.02}$ | $2.05^{+0.08}_{-0.10}$ | $0.00^{+0.01}$         |
|          | $7.64^{+7.58}_{-3.05}$      | $11.0^{+0.67}_{-0.67}$ | $66.9^{+2.74}_{-4.76}$ | $1.26^{+0.36}_{-0.22}$ | $1.02$                 |
| NGC 7582 | $1.10^{+0.09}_{-0.09}$      | $0.10^{+0.01}$         | $1.78^{+0.08}_{-0.07}$ | $1.06^{+0.26}_{-0.22}$ | $1.20^{+0.28}_{-0.25}$ |
|          | $7.02^{+2.86}_{-1.93}$      | $27.4^{+2.30}_{-3.50}$ | $41.6^{+5.67}_{-4.31}$ | $0.65^{+0.17}_{-0.13}$ | $1.10$                 |
| NGC 7674 | $1.01^{+0.13}_{-0.12}$      | $1.00^{+0.19}_{-0.19}$ | $1.50^{+0.07}$         | $0.03^{+0.01}_{-0.01}$ | $15.3^{+2.87}_{-3.16}$ |
|          | $10.0^{+12.7}_{-3.87}$      | $36.5^{+3.00}_{-5.42}$ | $20.0^{+8.15}$         | $2.45^{+1.35}_{-0.77}$ | $1.18$                 |

Column (01): galaxy name. Column (02): relative normalization of Suzaku/BIXIS to Suzaku/FIXIS. Column (03): time variability constant. Column (04): photon index. Column (05): normalization of the direct component in units of  $10^{-2}$  photons  $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ . Column (06): scattering fraction in units of percent. Column (07): hydrogen column density along the equatorial plane in units of  $10^{24} \text{cm}^{-2}$ . Column (08): torus angular width in units of degree. Column (09): inclination angle in units of degree. Column (10): relative normalization of the emission lines to the reflection component. Column (11): reduced  $\chi^2$ .

model (see Tanimoto et al. 2019), resulting in a harder intrinsic continuum.

#### 4.4.6 NGC 5643

The model with an apec component well fit the broadband X-ray spectrum (0.70–55.0 keV). Our best fitting parameters are  $N_{\text{H}}^{\text{LOS}} = 0.73^{+0.75}_{-0.20} \times 10^{24} \text{cm}^{-2}$  and  $\Gamma = 1.50^{+0.12}$  ( $\chi_{\text{red}}^2 = 0.90$ ). Our results agree with the Suzaku results (Kawamuro et al., 2016b), who  $N_{\text{H}}^{\text{LOS}} = 0.94^{+0.61}_{-0.32} \times 10^{24} \text{cm}^{-2}$  and  $\Gamma = 1.57^{+0.37}_{-0.31}$  by employing the pexrav model. Analyzing the NuSTAR data, Marchesi et al. (2019b) obtained  $N_{\text{H}}^{\text{LOS}} = 2.69^{+1.88}_{-0.65} \times 10^{24} \text{cm}^{-2}$  and  $\Gamma = 1.55^{+0.13}_{-0.15}$  with the borus02 model. Their column density is slightly larger than our best fitting value probably because of coupling with the photon index.

Table 4.6: Fluxes and Luminosities

| Galaxy<br>Name | $\log L_{2-10}$ | $\log L_{10-50}$ | $\log \lambda_{\text{Edd}}$ | $\log M_{\text{BH}}/M_{\odot}$ | Reference |
|----------------|-----------------|------------------|-----------------------------|--------------------------------|-----------|
| (1)            | (2)             | (3)              | (4)                         | (5)                            | (6)       |
| IC 5063        | 43.0            | 43.0             | -2.27                       | 8.45                           | (1)       |
| NGC 2110       | 43.5            | 43.8             | -2.50                       | 9.25                           | (2)       |
| NGC 3227       | 42.1            | 42.3             | -1.91                       | 7.18                           | (2)       |
| NGC 3281       | 42.5            | 42.8             | -2.35                       | 8.00                           | (3)       |
| NGC 5506       | 42.7            | 42.8             | -1.93                       | 7.87                           | (4)       |
| NGC 5643       | 41.0            | 41.3             | -2.86                       | 7.05                           | (1)       |
| NGC 5728       | 42.7            | 42.9             | -2.19                       | 8.07                           | (2)       |
| NGC 7172       | 43.1            | 43.3             | -2.12                       | 8.45                           | (2)       |
| NGC 7582       | 42.4            | 42.5             | -2.15                       | 7.74                           | (2)       |
| NGC 7674       | 42.5            | 42.9             | -2.77                       | 8.50                           | (5)       |

Column (1): galaxy name. Column (2): logarithmic intrinsic luminosity in the 2–10 keV. Column (3): logarithmic intrinsic luminosity in the 10–50 keV. Column (4): logarithmic Eddington ratio ( $\lambda_{\text{Edd}} = L_{\text{Bol}}/L_{\text{Edd}}$ ). Here, we obtained the bolometric luminosity as  $L_{\text{bol}} = 20L_{2-10}$  and defined the Eddington luminosity as  $L_{\text{Edd}} = 1.26 \times 10^{38} M_{\text{BH}}/M_{\odot}$ . Column (5): logarithmic black hole mass. Column (6): reference of the black hole mass.

Reference (1): van den Bosch (2016). Reference (2): Koss et al. (2017). Reference (3): Panessa et al. (2015). Reference (4): Izumi et al. (2016). Reference (5): Haan et al. (2011).

#### 4.4.7 NGC 5728

The model with an apec component well reproduces the broadband X-ray spectrum (0.60–55.0 keV). We obtain  $N_{\text{H}}^{\text{LOS}} = 0.96^{+0.06}_{-0.13} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.50^{+0.06}$  ( $\chi^2_{\text{red}} = 1.05$ ). The photon index is slightly lower than the Suzaku (Tanimoto et al., 2018) and NuSTAR (Marchesi et al., 2019b) results, while the column density is consistent with their results; Tanimoto et al. (2018) obtained  $N_{\text{H}}^{\text{LOS}} = 1.69^{+1.45}_{-0.53} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.69^{+0.14}_{-0.14}$  by applying the Ikeda model and Marchesi et al. (2019b) obtained  $N_{\text{H}}^{\text{LOS}} = 0.96^{+0.05}_{-0.03} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.81^{+0.07}_{-0.04}$  with the borus02 model. This trend is the same as the case of NGC 5506. It can be explained by a large unabsorbed reflection-continuum flux in the XClumpy model.

#### 4.4.8 NGC 7172

The NuSTAR data are reported for the first time. The model with an apec component well replicate the broadband X-ray spectrum (0.50–60.0 keV). Our best fitting parameters are  $N_{\text{H}}^{\text{LOS}} = 0.09_{-0.04}^{+0.09} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.75_{-0.02}^{+0.02}$  ( $\chi_{\text{red}}^2 = 1.02$ ). Our results agree with the Suzaku results by Kawamuro et al. (2016a), who obtained  $N_{\text{H}}^{\text{LOS}} = 0.09_{-0.01}^{+0.01} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.74_{-0.02}^{+0.01}$  by applying the pexrav model for the reflection continuum.

#### 4.4.9 NGC 7582

The model with an apec component well fit the broadband X-ray spectrum (0.60–60.0 keV). We obtain  $N_{\text{H}}^{\text{LOS}} = 0.31_{-0.09}^{+0.13} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.78_{-0.07}^{+0.08}$  ( $\chi_{\text{red}}^2 = 1.10$ ). Analyzing the same Suzaku data with the Ikeda model, Tanimoto et al. (2018) obtained  $N_{\text{H}}^{\text{LOS}} = 0.71_{-0.15}^{+0.67} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.80_{-0.10}^{+0.09}$  (“Ikeda1” model) or  $N_{\text{H}}^{\text{LOS}} = 3.23_{-1.78}^{+1.33} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.88_{-0.12}^{+0.11}$  (“Ikeda2” model). Our XClumpy results prefer the former model for this object (i.e., a Compton thin AGN). Baloković et al. (2018) derived  $N_{\text{H}}^{\text{LOS}} = 0.44 \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.67$  with the NuSTAR data by applying the borus02 model, which are similar to our results.

#### 4.4.10 NGC 7674

The model with an apec component well replicates the broadband X-ray spectrum (0.70–30.0 keV). The best fitting parameters are  $N_{\text{H}}^{\text{LOS}} = 0.25_{-0.08}^{+0.51} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.50_{-0.05}^{+0.05}$  ( $\chi_{\text{red}}^2 = 1.33$ ). Our results are consistent with the NuSTAR results by Gandhi et al. (2017), who obtained  $N_{\text{H}}^{\text{LOS}} = 0.13_{-0.03}^{+0.03} \times 10^{24} \text{ cm}^{-2}$  and  $\Gamma = 1.40_{-0.08}^{+0.08}$  with the decoupled MYTorus model.

### 4.5 Discussion

#### 4.5.1 Comparison of Torus Parameters Obtained from X-Ray and Infrared

We compare the torus parameters obtained from the X-ray spectra and those from the infrared ones. To increase the sample, we include Circinus galaxy (Tanimoto et al., 2019) and NGC 5135 (Yamada et al., 2020, in prep) in the following discussions (i.e., total 12 objects). Figure 4.7 plots the relations between (a) the torus angular width obtained from the X-ray spectrum ( $\sigma_{\text{X}}$ ) and that from the infrared one ( $\sigma_{\text{IR}}$ ), and (b) the inclination angle obtained from the X-ray spectrum ( $i_{\text{X}}$ ) and that from the infrared one ( $i_{\text{IR}}$ ). Figure 4.8

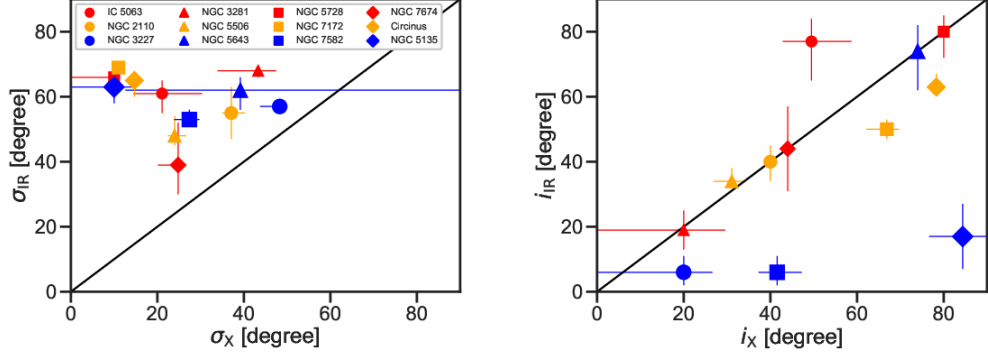


Figure 4.7: (a) Correlation between the torus angular width obtained from the X-ray spectrum ( $\sigma_X$ ) and that from the infrared one ( $\sigma_{IR}$ ). (b) Correlation between the inclination angle obtained from the X-ray spectrum ( $i_X$ ) and that from the infrared one ( $i_{IR}$ ).

(a) the hydrogen column density along the line of sight obtained from the X-ray spectrum ( $N_H^{LOS}$ ) and the V-band extinction along the line of sight from the infrared one ( $A_V^{LOS}$ ), and (b) the hydrogen column density along the equatorial plane obtained from the X-ray spectrum ( $N_H^{Equ}$ ) and the V-band extinction along the equatorial plane obtained from the infrared one ( $A_V^{Equ}$ ).

Here we recall that the X-ray spectra trace all material including gas and dust in a rather unbiased manner, while the infrared data trace only dust in a temperature dependent way. Figure 4.7(a) indicates that  $\sigma_{IR}$  is systematically larger than  $\sigma_X$ . This means that the apparent dust distribution as seen in the infrared band is more extended in the vertical direction to the equatorial plane than the gas distribution. We infer that this can be explained by contribution to the observed infrared flux from dusty polar outflows, which are commonly observed in nearby AGNs by infrared interferometric observations (e.g. Tristram et al., 2014; Lyu & Rieke, 2018). Since polar dust is not included in the CLUMPY model, it may lead to overestimate the actual angular width of the torus.

This effect becomes more significant when the infrared flux from the torus is reduced due to extinction by dust in outer cooler regions (such as circumnuclear disks) compared with the prediction by CLUMPY. In fact, such flux reduction is predicted by radiative hydrodynamical simulations, which show a “shadow” region around the equatorial plane in the mid infrared image (Wada et al., 2016). By contrast, the X-ray results are less affected by the polar outflows. This is because the mass carried by the polar outflows is much smaller than that contained in the torus itself (Wada et al., 2016) and because hard X-rays emitted at the central engine can penetrate through the torus. Liu et al. (2019) examined X-ray signatures of the polar outflows with ray-tracing simulations and found that it only contributed to the X-ray spectrum below 2 keV such as Si  $K\alpha$  emission lines, not to Fe

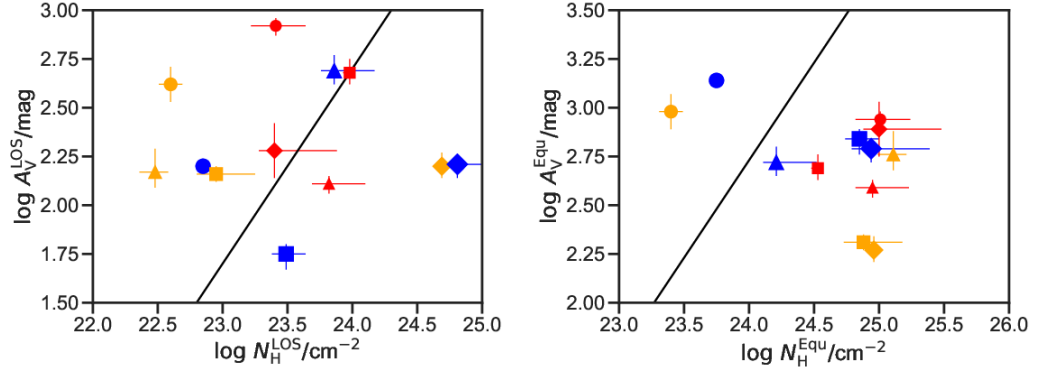


Figure 4.8: (a) Correlation between the hydrogen column density along the line of sight obtained from the X-ray spectrum ( $N_{\text{H}}^{\text{LOS}}$ ) and the V-band extinction along the line of sight from the infrared one ( $A_{\text{V}}^{\text{LOS}}$ ). (b) Correlation between the hydrogen column density along the equatorial plane obtained from the X-ray spectrum ( $N_{\text{H}}^{\text{Equ}}$ ) and the V-band extinction along the equatorial plane from the infrared one ( $A_{\text{V}}^{\text{Equ}}$ ). The black line corresponds to the Galactic value:  $N_{\text{H}}/A_{\text{V}} = 1.87 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$  (Draine, 2003).

$\text{K}\alpha$  emission lines and hard X-ray continuum above 10 keV. Hence we expect that X-ray results mainly trace the equatorial dusty torus distribution, while infrared ones might be the combinations of the equatorial dusty torus and the polar dust.

Figure 4.7(b) shows a general trend that  $i_{\text{X}} \geq i_{\text{IR}}$ , by excluding the objects for which we have assumed  $i_{\text{X}} = i_{\text{IR}}$  in the X-ray spectral analysis. We infer that this is caused by coupling with the torus angular width: dusty polar outflows work to increase  $\sigma_{\text{IR}}$ , and accordingly  $i_{\text{IR}}$  is decreased in order not to overproduce the line of sight extinction. In the following discussion, we refer to  $i_{\text{X}}$  as a more reliable estimator of the true inclination.

Figures 4.8(a) and (b) indicate large scatter ( $\sim 1$  dex) in the ratio between the hydrogen column density and the V-band extinction, both along the the line of sight and along the equatorial plane. Since the line of sight extinction is more directly determined from the X-ray and infrared data through photoelectric absorption and silicate absorption, respectively, here we focus on the former result. The mean value of  $N_{\text{H}}^{\text{LOS}}/A_{\text{V}}^{\text{LOS}}$  is close to that of the Galactic ISM:  $N_{\text{H}}/A_{\text{V}} = 1.87 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$  (Draine, 2003). This is consistent with the results of Burtscher et al. (2016), who investigated  $N_{\text{H}}^{\text{LOS}}/A_{\text{V}}^{\text{LOS}}$  utilizing colors of dust.

Under the presence of dusty polar outflows, the obtained value of  $A_{\text{V}}$  should be an flux-weighted average from two different regions, the polar outflows and the torus. Since the polar outflows are located above the torus, the extinction for them is smaller than that for the torus itself. As discussed in Chapter 4.5.2 (see also Tanimoto et al. 2019), the relative contribution from dusty polar outflows to the total infrared flux increases with the inclination. Hence, at high inclination systems, the  $A_{\text{V}}$  value may be largely underestimated



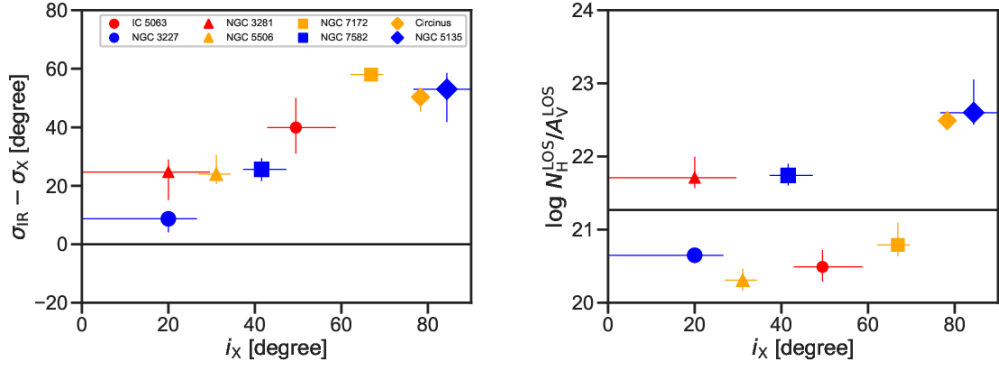


Figure 4.9: (a)  $\sigma_{\text{IR}} - \sigma_{\text{X}}$  against  $i_{\text{X}}$ . The black line shows  $\sigma_{\text{X}} = \sigma_{\text{IR}}$ . (b)  $\log N_{\text{H}}^{\text{LOS}}/A_{\text{V}}^{\text{LOS}}$  against the inclination angle obtained from the X-ray spectrum ( $i_{\text{X}}$ ). The black line corresponds to the Galactic value:  $N_{\text{H}}/A_{\text{V}} = 1.87 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$  (Draine, 2003).

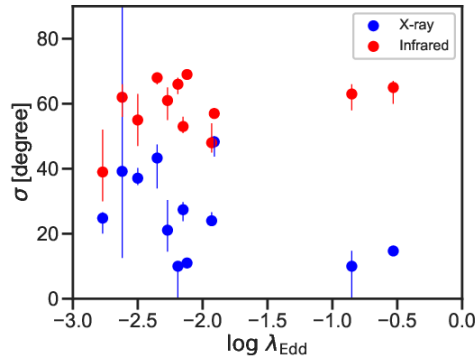


Figure 4.10: The correlation between Eddington ratio and torus angular width.

than that toward the torus, leading to large  $N_{\text{H}}^{\text{LOS}}/A_{\text{V}}^{\text{LOS}}$  values, even without invoking a significant amount of dust-free gas inside the dust sublimation radius (see e.g., Ichikawa et al., 2019).

If we exclude the two highest inclination objects (Circinus galaxy and NGC 5135) as exceptions, more than half of our sample seem to have “dust-rich” circumnuclear environment compared with the Galactic ISM; this conclusion is even strengthened if we correct for the contribution from the polar outflows. In fact, Ogawa et al. (2019) found such dust-rich AGNs by applying the XClumpy to the broadband X-ray spectra of two Seyfert 1 galaxies. This trend is opposite to that reported for some AGNs that show cold absorption in X-rays and optical broad emission lines (e.g. Maiolino et al., 2001a,b).

## 4.5.2 Origin of Torus Parameter Differences between X-ray and Infrared

To reinforce our interpretation on the torus-parameter differences between X-ray and infrared, Figure 4.9 plots  $\sigma_{\text{IR}} - \sigma_{\text{X}}$  and  $N_{\text{H}}^{\text{LOS}}/A_{\text{V}}^{\text{LOS}}$  as a function of inclination ( $i_{\text{X}}$ ). Here we exclude the four targets whose  $i_{\text{X}}$  cannot be well determined from the X-ray spectra (NGC 2110, NGC 5643, NGC 5728, and NGC 7674; see Chapter 4.3). Figure 4.9(a) indicates that  $\sigma_{\text{IR}} - \sigma_{\text{X}}$  correlates with  $i_{\text{X}}$ . This is expected from radiative hydrodynamics simulations, which showed that relative contribution from the dusty polar outflow to the total observed infrared flux increases with the inclination (Wada et al., 2016, Figure 5b). Thus, at higher inclination systems, the torus angular width is more largely overestimated in the infrared data. Figure 4.9(b) shows that the two highest inclination objects (Circinus Galaxy and NGC 5135) have particularly large  $N_{\text{H}}^{\text{LOS}}/A_{\text{V}}^{\text{LOS}}$  values.

## 4.5.3 Correlation between Eddington Ratio and Torus Angular Width

Figure 4.10 shows the correlation between the Eddington ratio ( $\lambda_{\text{Edd}}$ ) and the torus angular width ( $\sigma$ ). Figure 4.10 suggests that  $\sigma_{\text{X}}$  decreases with  $\lambda_{\text{Edd}}$ , whereas  $\sigma_{\text{IR}}$  is almost constant. The former trend is consistent with (Ricci et al., 2017b), who found that the torus covering factor decreases at  $\log \lambda_{\text{Edd}} \geq -1.5$  based on hard X-ray survey results. As noted above, we infer that  $\sigma_{\text{IR}}$  are generally overestimated due to the dusty polar outflows, and hence they cannot be used as a reliable estimator for the torus angular width.

## 4.6 Conclusion

1. We apply our X-ray spectral model from a clumpy torus (XClumpy: Tanimoto et al. 2019) to the X-ray spectra of 10 obscured AGNs observed with both Suzaku and NuSTAR. Our model well reproduces the broadband X-ray spectra of all objects.
2. The torus angular widths obtained from the infrared spectra ( $\sigma_{\text{IR}}$ ) are systematically larger than those from the X-ray ones ( $\sigma_{\text{X}}$ ). Their difference is larger in higher inclination objects. These results can be explained by significant contribution from dusty polar outflows to the infrared flux, as observed in infrared interferometric observations and predicted by theoretical simulations.
3. The ratios between the line of sight hydrogen column density and V-band extinction ( $N_{\text{H}}^{\text{LOS}}/A_{\text{V}}^{\text{LOS}}$ ) show large scatter ( $\sim 1$  dex) around the Galactic ISM value, suggesting that a large fraction of AGNs have dust-rich circumnuclear environments.

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