**Suzaku Observations of Heavily Obscured (Compton-thick) Active Galactic Nuclei Selected by the Swift/BAT Hard X-Ray Survey**

Atsushi Tanimoto¹, Yoshihiro Ueda¹, Taiki Kawamuro¹,²,³, Claudio Ricci³,⁴,⁵, Hisamitsu Awaki⁶, and Yuichi Terashima⁶

¹Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan
²National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan
³Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile
⁴Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China
⁵Chinese Academy of Sciences South America Center for Astronomy and China-Chile Joint Center for Astronomy, Camino El Observatorio 1515, Las Condes, Santiago, Chile
⁶Department of Physics, Ehime University, Matsuyama 790-8577, Japan

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**Abstract**

We present a uniform broadband X-ray (0.5–100.0 keV) spectral analysis of 12 Swift/Burst Alert Telescope selected Compton-thick (log $N_H$/cm$^{-2}$ $\gtrsim$ 24) active galactic nuclei (CTAGNs) observed with Suzaku. The Suzaku data of three objects are published here for the first time. We fit the Suzaku and Swift spectra with models utilizing an analytic reflection code and those utilizing the Monte-Carlo-based model from an AGN torus by Ikeda et al. The main results are as follows: (1) The estimated intrinsic luminosity of a CTAGN strongly depends on the model; applying Compton scattering to the transmitted component in an analytic model can largely overestimate the intrinsic luminosity at large column densities. (2) Unabsorbed reflection components are commonly observed, suggesting that the tori are clumpy. (3) Most of CTAGNs show small scattering fractions (<0.5%), implying a buried AGN nature. (4) Comparison with the results obtained for Compton-thin AGNs suggests that the properties of these CTAGNs can be understood as a smooth extension from Compton-thin AGNs with heavier obscuration; we find no evidence that the bulk of the population of hard-X-ray-selected CTAGNs are different from less obscured objects.

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

1. Introduction

To reveal the nature of heavily obscured active galactic nuclei (AGNs) whose line-of-sight hydrogen column density is log $N_H$/cm$^{-2}$ $\gtrsim$ 24, so-called Compton-thick AGNs (CTAGNs), is an important yet unresolved issue in modern astronomy (Ueda 2015). CTAGNs are thought to be key objects to understanding the origin of the coevolution of supermassive black holes (SMBHs) and their host galaxies (Kormendy & Ho 2013). According to a galaxy/SMBH evolutionary scenario (e.g., Hopkins et al. 2006), major mergers trigger violent star formation and rapid growth of SMBHs heavily obscured by gas and dust (Ricci et al. 2017a). This leads to the idea that some CTAGNs may be distinct populations (i.e., those in a different evolutionary stage) from less obscured AGNs. Due to observational difficulties in detecting CTAGNs, however, it remains an open question whether or not CTAGNs are intrinsically the same objects as the rest of AGNs in terms of their nucleus structure, host galaxy properties, and cosmological evolution.

The presence of CTAGN populations is required to explain the origin of the cosmic X-ray background (CXB; e.g., Ueda et al. 2003, 2014; Gilli et al. 2007; Treister et al. 2009; Aird et al. 2015). Their estimated number density is highly uncertain, however, depending on several parameters assumed in population synthesis models of the CXB (e.g., Akylas et al. 2012). Among them, modeling of broadband X-ray spectra of CTAGNs is a critical issue. The spectral modeling also largely affects an estimate of the intrinsic luminosity of distant CTAGNs detected in deep surveys with limited photon statistics, and hence the determination of their luminosity function. Thus, it is very important to systematically analyze high-quality broadband (0.5–100 keV) X-ray spectra of a large sample of bright CTAGNs in the local universe and thereby determine averaged spectra of CTAGNs as a function of column density.

Hard X-ray observations above 10 keV provide one of the least-biased AGN samples thanks to the strong penetrating power against obscuration unless the column density largely exceeds log $N_H$/cm$^{-2}$ $\gtrsim$ 24.5. All-sky hard X-ray surveys performed with Swift and INTEGRAL have produced catalogs of local AGNs including CTAGNs (Markwardt et al. 2005; Beckmann et al. 2006, 2009; Tueller et al. 2008, 2010; Burlon et al. 2011; Ajello et al. 2012; Baumgartner et al. 2013; Malizia et al. 2016), which have been extensively followed up with pointed observations (e.g., Ajello et al. 2008; Winter et al. 2009a; Vasudevan et al. 2013). From the Swift/Burst Alert Telescope (BAT) 70-month catalog (Baumgartner et al. 2013), Ricci et al. (2017b) systematically analyze X-ray data below 10 keV obtained mainly with Swift/X-Ray Telescope (XRT) and XMM-Newton, which are combined with the Swift/BAT spectra in the 14–150 keV range. As a result, Ricci et al. (2015) identify 55 CTAGN candidates (see also Akylas et al. 2016). However, since the photon statistics of the Swift/XRT spectrum is limited and the data above and below 10 keV were not simultaneously obtained (thus being affected by time variability), large uncertainties remain in the derived column density and intrinsic luminosity.

The Suzaku observatory (Mitsuda et al. 2007) has a unique capability of simultaneously observing broadband X-ray spectra covering the 0.5–40.0 keV range with high-quality
charge coupled device (CCD) data below 10 keV (Section 2).

The combination of Suzaku and Swift is proved to be very powerful for studying the broadband spectra of local AGNs (Ueda et al. 2007; Eguchi et al. 2009, 2011; Winter et al. 2009b; Tazaki et al. 2011, 2013; Gandhi et al. 2013, 2015; Kawamura et al. 2013, 2016a, 2016b). Recently, NuSTAR has started to observe nearby CTAGNs (e.g., Puccetti et al. 2014; Koss et al. 2015; Rivers et al. 2015; Guainazzi et al. 2016) covering the 4–80 keV range. However, most of them do not have simultaneous CCD spectra in the 0.5–10 keV range, which are particularly useful to observe emission-line absorption-edge features thanks to the good energy resolution.

This paper presents a summary of uniform spectral analyses of local CTAGNs observed with Suzaku and Swift, following Kawamura et al. (2016a) for Compton-thin (22 ≤ log N_H/cm^2 ≤ 24) AGNs. Section 2 describes the sample selection and data reduction of the Suzaku data. Our sample consists of 12 CTAGNs selected from the Swift/BAT 70-month catalog. The Suzaku spectra of three objects are reported here for the first time. Section 3 presents the Suzaku light curves and the analysis of the Suzaku+Swift/BAT spectra. We apply analytical models and Monte-Carlo-based torus models by Ikeda et al. (2009) to these spectra. Section 4 summarizes our results for the individual objects in comparison with earlier works. In Section 5, we discuss our overall results by comparing the Compton-thick population with the Compton-thin AGNs. The luminosities are calculated from the observed redshift with the cosmological parameters given by Verner & Ferland (1996) and Verner et al. (1996). The errors on the spectral parameters correspond to the 90% confidence limits for a single parameter.

2. Sample and Analysis

2.1. Sample

Our sample consists of 12 CTAGN candidates from Ricci et al. (2015) (i.e., a subsample of the Swift/BAT 70-month catalog; Baumgartner et al. 2013) that were observed with Suzaku during its lifetime. To ensure high spectral quality, we select data with a net exposure longer than 20 ks. We do not include NGC 1106, NGC 2788A, and UGC 03752 (Tanimoto et al. 2016), which were observed without the Hard X-ray Detector (HXD) sensitive to energies above 10 keV. We also exclude objects whose Suzaku data have already been thoroughly analyzed in individual papers, such as the Circinus galaxy (Yang et al. 2009), NGC 1068 (Bauer et al. 2015), and NGC 3079 (Konami et al. 2012), and two low-luminosity AGNs, NGC 4102 and NGC 5643 (Kawamura et al. 2016b). In particular, the Circinus galaxy and NGC 1068 are heavily Compton-thick AGNs with line-of-sight column densities larger than 10^{25} cm^2, which could be distinct populations to mildly Compton-thick ones (log N_H/cm^2 < 25) studied in this paper. Tables 1 and 2 show the information on the sample and the Suzaku observation log, respectively. The results based on Suzaku observations of three objects (NGC 1194, NGC 6552, and NGC 7130) are reported here for the first time. Although NGC 7582 is a changing-look AGN (Bianchi et al. 2009), we include this object in the sample, which was classified as a CTAGN by Ricci et al. (2015) with the spectral analysis of the long-term averaged Swift/BAT spectrum and XMM-Newton spectra.

2.2. Analysis

Suzaku (Mitsuda et al. 2007) is the fifth Japanese X-ray astronomy satellite, which operated from 2005 to 2015. It carried on board four X-ray CCD cameras called the X-ray Imaging Spectrometers (XIS-0, XIS-1, XIS-2, and XIS-3) as the focal plane instruments of four XRTs, as well as a nonimaging, collimated HXD. The XIS cameras covered the 0.3–12.0 keV range as focal plane detectors of the XRTs; XIS-0, XIS-2, and XIS-3 were front-side-illuminated CCDs (FIXISs), and XIS-1 was the back-illuminated one (BIXIS). Since 2006 November, XIS-2 became unusable most probably as a result of a micrometeoroid impact. The HXD consisted of Si PIN photodiodes and gadolinium silicon oxide scintillation counters, which covered the ranges 10–70 keV and 40–600 keV, respectively. We analyze the XIS and HXD data using HEAsoft version 6.21 with the calibration database (CALDB) released on 2016 February 15 for the XIS and the CALDB released on 2011 September 13 for the HXD.

2.2.1. Suzaku/XIS

We reprocess the unfiltered XIS data by using aepipeline. To extract the light curves and spectra, we use circular regions centered on the source peak with a radius of 90 arcsec, while the background is taken from a homocentric annular region with inner and outer radii of 120 and 240 arcsec, respectively. Since the background spectra also contain about 10% of the source photons owing to the tail of the point-spread function of the XRT, we correct for this effect in our spectral analysis. We generate the XIS response matrix with xisrmfgen and ancillary response files with xisimarfgen (Ishisaki et al. 2007). We bin each of the XIS spectra to contain at least 50 counts per bin.

2.2.2. Suzaku/HXD

In this paper, we only analyze the HXD-PIN data, because all of our targets except NGC 4945 were too faint at energies above 50 keV to be detected by HXD-GSO. We reprocess the unfiltered HXD data by using aepipeline. We utilize the “tuned” background event files (Fukazawa et al. 2009) to reproduce the spectrum of the non-X-ray background (NXB), except for ESO 565–G019,7 to which the simulated spectrum of the CXB is added. In the spectral analysis, we only utilize an energy range where the source flux is brighter than 3% of the NXB level (Fukazawa et al. 2009).

3. Light Curves and Spectra

3.1. Light Curves

Figure 1 shows the background-subtracted light curves of the FIXISs (2–10 keV) and the HXD-PIN (16–40 keV), together with their hardness ratio (16–40 keV/2–10 keV), for all targets. To minimize any systematic uncertainties caused by the orbital motion of the satellite, we set the time bin size to the orbital period (5760 s). To check possible time variability, we perform a χ^2 test to each light curve assuming a null hypothesis of a

7 We utilize the same background spectrum as used in Gandhi et al. (2013), which was produced from night Earth data, because the reproducibility of the tuned background file was found to be insufficient.
constant flux (Table 3). We find that the FIXIS light curves are consistent with being constant for all targets. On the other hand, the HXD-PIN light curves of CGCG 420–015, NGC 4945, and NGC 6552 show significant time variability at >99% confidence levels. Similar short-term variability of NGC 4945 was also reported by Yaqoob (2012) and Puccetti et al. (2014). We have confirmed that the shape of the HXD-PIN spectra of these three targets did not vary over statistical errors depending on flux. Thus, in this paper we analyze the spectra averaged over the whole observation for all targets.

### 3.2. Spectra

We perform a simultaneous fit to the 

Suzaku/BIXIS (0.5–8.0 keV), 

Suzaku/FIXISs (2–10 keV), 

Suzaku/HXD (16–40 keV; widest case), 

and 70-month averaged 

Swift/BAT (14–100 keV) spectra. Because our targets are very faint at soft energy bands, we only utilize the BIXIS below 2 keV, which has much superior sensitivity with respect to the FIXISs. The 1.7–1.9 keV of the BIXIS spectra is excluded to avoid systematic uncertainties in the energy response around the Si K edge. We conservatively decide not to use the 

Swift/BAT spectra above 100 keV, where the signal-to-noise ratios are low for most of the targets. In the following, we uniformly apply analytic models (Section 3.2.1) and numerical torus models by Ikeda et al. (2009) (Section 3.2.2) to these spectra.

#### 3.2.1. Baseline Models

First, we apply two analytic models (Baseline1 and Baseline2) often adopted to represent the broadband spectra of obscured AGNs (e.g., Schurch et al. 2002; Matt et al. 2004; Bianchi et al. 2005; Piconcelli et al. 2007; Ueda et al. 2007; Comastri et al. 2010; Kawamuro et al. 2016a; Tanimoto et al. 2016). The models are basically composed of an absorbed direct component, an unabsorbed scattered component, a reflection component, and narrow Fe K emission lines. Other emission lines and/or optically thin thermal components are added when required from the data. The difference between the Baseline1 and Baseline2 models is that Compton scattering for the direct components is ignored in the former but is taken into account in the latter. Note that it is not trivial which of the two models is more physically reasonable, depending on the geometry considered (Section 5.2).

In the XSPEC terminology, the Baseline1 and Baseline2 models are expressed as

Baseline1 = const1 * phabs

* (const2 * zphabs * zpowerlw * zhighect

+ const3 * zpowerlw * zhighect

+ zphabs * pexrav + zgausses + apec(s)),

Baseline2 = const1 * phabs

* (const2 * zphabs * cabs * zpowerlw * zhighect

+ const3 * zpowerlw * zhighect

+ zphabs * pexrav + zgausses + apec(s)).

0. We multiply a cross-normalization factor (const1) to reflect differences in the absolute flux calibration among the instruments. We adopt the Swift/BAT data as a reference, whose const1 value is set to unity. We also fix that of Suzaku/FIXISs at unity, by assuming that there is no relative calibration error between Suzaku/FIXISs and Swift/BAT. The cross-normalization of Suzaku/BIXIS is left as a free parameter ($N_{\text{BIXIS}}$), whereas that of the Suzaku/HXD is set to 1.16 (1.18) for XIS (HXD) nominal position observations according to the calibration results obtained using the Crab Nebula. We consider Galactic absorption (phabs) whose column density is fixed at a value estimated from the HI map for each target (Kalberla et al. 2005).

1. The first term represents the absorbed direct component. The intrinsic continuum is modeled by a power law (zpowerlw) with an exponential cutoff (zhighect). In the Baseline1, we only consider photoelectric absorption

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**Note:**

Galaxy Name | Swift ID | R.A. | Decl. | Redshift | $N_{\text{H}}$ | log $M_{\text{BH}}$/$M_{\odot}$ | References
---|---|---|---|---|---|---|---|
CGCG 420–015 | J0453.4+0940 | 04°53′25″ | +04°03′42″ | 0.2924 | 0.0654 | 8.31 | (1)
ESO 137–G034 | J1635.5–5804 | 16°35′14″ | −58°04′48″ | 0.0090 | 0.2250 | 8.02 | (2)
ESO 323–G032 | J1253.5–4137 | 12°53′20″ | −41°38′08″ | 0.0160 | 0.0844 | 7.56 | (1)
ESO 565–G019 | J0934.7–2156 | 09°34′44″ | −21°55′40″ | 0.0163 | 0.0416 | ... | ...
Mrk 3 | J0615.8+7101 | 06°15′36″ | +71°02′15″ | 0.0135 | 0.0998 | 7.96 | (2)
NGC 1194 | J0304.1–0108 | 03°04′49″ | −01°06′13″ | 0.0136 | 0.0597 | 8.12 | (1)
NGC 3393 | J1048.4–2511 | 10°48′23″ | −25°09′43″ | 0.0125 | 0.0605 | 7.20 | (3)
NGC 4945 | J1305.4–4928 | 13°05′28″ | −49°28′06″ | 0.0019 | 0.1350 | 6.14 | (3)
NGC 5728 | J1442.5–1715 | 14°42′24″ | −17°15′11″ | 0.0093 | 0.0774 | 8.07 | (1)
NGC 6552 | J1800.3–6637 | 18°00′07″ | +55°36′54″ | 0.0265 | 0.0381 | ... | ...
NGC 7130 | J2148.3–3454 | 21°48′20″ | −34°57′04″ | 0.0162 | 0.0185 | 7.61 | (1)
NGC 7582 | J2318.4–4223 | 23°18′24″ | −42°22′14″ | 0.0052 | 0.0121 | 7.56 | (4)

**References:** (1) Koss et al. 2017; (2) Khoronzhev et al. 2012; (3) van den Bosch 2016; (4) Izumi et al. 2016.
Table 2

| Galaxy Name | Suzaku ID | Start Date | End Date | Exposure | Nominal Position | Suzaku References |
|-------------|-----------|------------|----------|-----------|------------------|-------------------|
| CGCG 420-015 | 704058010 | 2009 Sep 01 | 2009 Sep 04 | 109.1 | HXD | (1) |
| ESO 137-G034 | 403075010 | 2008 Oct 05 | 2008 Oct 07 | 92.1 | HXD | (2) |
| ESO 323-G032 | 702119010 | 2007 Dec 22 | 2007 Dec 24 | 79.2 | HXD | (2) |
| ESO 565-G019 | 707013010 | 2012 May 20 | 2012 May 22 | 78.9 | XIS | (3) |
| Mrk 3 | 100040010 | 2009 Oct 22 | 2009 Oct 24 | 50.3 | XIS | … |
| NGC 1194 | 704046010 | 2009 Aug 01 | 2009 Aug 02 | 55.2 | XIS | … |
| NGC 3393 | 702300410 | 2007 May 23 | 2007 May 25 | 95.0 | HXD | … |
| NGC 9495 | 100040010 | 2006 Jan 15 | 2006 Jan 17 | 105.8 | XIS | … |
| NGC 5728 | 701079010 | 2006 Jul 19 | 2006 Jul 20 | 41.3 | HXD | (2) |
| NGC 6552 | 708140100 | 2013 Nov 14 | 2013 Nov 17 | 44.5 | HXD | … |
| NGC 7130 | 703012010 | 2008 May 11 | 2008 May 12 | 31.9 | HXD | … |
| NGC 7582 | 702052040 | 2007 Nov 16 | 2007 Nov 16 | 31.9 | HXD | … |

Note. Column (1): galaxy name. Column (2): Suzaku observation ID. Column (3): start date in units of ymd. Column (4): end date in units of ymd. Column (5): exposure in units of ks. Column (6): XIS nominal or HXD nominal. Column (7): reference of the previous work using the Suzaku data.

References. (1) Severgnini et al. 2011; (2) Comastri et al. 2010; (3) Gandhi et al. 2013; (4) Awaki et al. 2008; (5) Itoh et al. 2008.

(zphabs), as is the case in Kawamuro et al. (2016a) for Compton-thin AGNs. In the Baseline2 model, we also consider Compton scattering out of the line of sight (cabs), whose hydrogen column density (N_H) is linked to that of zphabs. Since we cannot constrain the cutoff energy\(^{10}\) with our data, we fix it at 360 keV, the value adopted in the Ikeda torus model (Ikeda et al. 2009). We have confirmed that the choice of this value within a typical range observed in local AGNs (100–500 keV) does not affect significantly our spectral parameters. The factor N_{Suzaku}(const2) is multiplied to take into account possible time variation of the direct-component flux during the Suzaku observation with respect to 70-month averaged Swift/BAT flux. Note that this constant factor is not multiplied to the scattered and reflection components (the second and third terms), assuming that they did not vary between the Suzaku and Swift/BAT observations, as the size of the reflector has most likely a parsec scale (Kawamuro et al. 2016a). To avoid unrealistic results, we limit the N_{Suzaku} value within a range of 0.2–5.0, according to the results obtained by Kawamuro et al. (2016a) for Compton-thin AGNs.

2. The second term represents the unabsorbed scattered component. We multiply the scattering fraction f_{scat} (const3) by a cutoff power law with the same photon index and normalization as the first term.

3. The third term represents the reflection component. We adopt the analytic code (pexrav) by Magdziarz & Zdziarski (1995), which calculates a reflected continuum from cold, optically thick matter. The reflection strength relative to the direct component is defined by R = \Omega / 2\pi (\Omega is the solid angle of the reflector).\(^{11}\) To avoid unphysical parameters, we impose an upper limit of R = 2, corresponding to the extreme case where the nucleus is covered by the reflector in all directions. The inclination angle to the reflector is fixed at 60°. The photon index and normalization of the incident cutoff power law are linked to those of the first term. We consider photoelectric absorption to this component with a hydrogen column density of N_H, independently of N_{Dir} if it is found to be significantly required (i.e., N_H > 0) over a 99% confidence limit.

4. The fourth term represents emission lines of Fe Kα around 6.40 keV and Kβ around 7.06 keV (zgauss). We fix these line widths at 10 eV for both lines. We set the central energy E_{FeKα} as a free parameter, while we fix the central energy E_{FeKβ} at 7.06 keV. In the case of Mrk 3 and NGC 4945, we also include other emission lines that are significantly detected in previous Suzaku papers (Sections 4.4 and 4.7).

5. The fifth term represents emission from optically thin thermal plasmas (apec) in the host galaxy (Smith et al. 2001). We test whether inclusion of an apec component to the above model improves the fit. We adopt it if the improvement is found to be significant at a 99% confidence limit (i.e., \Delta \chi^2 \leq -9.21, which corresponds to the 99% limit of the \chi^2 distribution with a degree of freedom of 2). At maximum two apec components with different temperatures are found to be required from the data.

These analytic models reproduce the Suzaku and Swift/BAT spectra of all targets reasonably well (\chi^2/dof \leq 1.3). Tables 4 and 5 summarize the best-fit parameters of the Baseline1 and Baseline2 models, respectively. In general, we obtain slightly larger best-fit photon indices with the Baseline2 model than with the Baseline1 model because of the Klein–Nishina decline of the Compton scattering cross section. The Baseline2 model gives a larger best-fit intrinsic luminosity (Section 5.2) and accordingly a smaller scattering fraction than the Baseline1 model. The comparison of intrinsic luminosity between the two models is discussed in Section 5.2. In most cases, the spectral parameters obtained with the two models are consistent, except for the brightest sources (Mrk 3 and NGC 4945). Figures 2 and 3 (left column) plot the unfolded spectra and best-fit Baseline2 model, respectively, in units of E_{Fe} (E_F is the energy flux density at an energy of E). Figure 4 plots the folded spectra in the energy range around Fe Kα lines. Table 6 lists the observed fluxes in the 0.5–2.0 keV, 2–10 keV, and 10–50 keV ranges; the intrinsic luminosities (i.e., de-absorbed luminosities not including reflection component) in the 0.5–2.0 keV, 2–10 keV, and 10–50 keV

\(^{10}\) This corresponds to an e-folding energy (E_\text{f}) in the zhighect model when E_\text{f} is set to be zero.

\(^{11}\) We set R < 0 to reproduce only the reflection component without the direct component.
ranges; the Fe Kα luminosity; and the Eddington ratio, based on the best-fit Baseline2 model. We define the Eddington luminosity as $L_{\text{Edd}} = 1.26 \times 10^{38} \frac{M_{\text{BH}}}{M_{\odot}}$ erg s$^{-1}$ and adopt a bolometric correction factor of 20 (Vasudevan & Fabian 2009) from the 2–10 keV luminosity averaged over 70 months (i.e., based on the Swift/BAT normalization).

Figure 1. Background-subtracted light curves in units of counts s$^{-1}$. Top panel: Suzaku/FIXISs (2–10 keV). Middle panel: Suzaku/HXD-PIN (16–40 keV). Bottom panel: hardness ratio between them.
3.2.2. Torus Models

Next, we apply Monte-Carlo-based numerical spectral models from uniform-density tori developed by Ikeda et al. (2009) (which we call Ikeda1 and Ikeda2). Since this model is available only above 1 keV, we limit the energy range to 1–100 keV in the spectral fit. The Ikeda torus model assumes a nearly spherical geometry with two conical holes along the polar axis and has three parameters that can be set free: the hydrogen column density along the equatorial plane $N_{\text{H}}^{\text{Eq}}$ (within a range of $10^{22}$–$10^{25}$ cm$^{-2}$), the inclination angle $\theta_{\text{incl}}$ ($1^\circ$–$89^\circ$), and the half-opening angle of the torus $\theta_{\text{open}}$ ($10^\circ$–$70^\circ$). The ratio between the inner radius $R_{\text{in}}$ and the outer radius $R_{\text{out}}$ is fixed at 0.01. As the incident spectrum, a power law with an exponential cutoff of 360 keV is assumed, whose photon index is a free parameter within a range of 1.5–2.5.

In the XSPEC terminology, these models\textsuperscript{12} are represented as follows:

\begin{align*}
\text{Ikeda1} &= \text{const1} \ast \text{phabs} \\
&\ast (\text{const2} \ast \text{torusabs} \ast \text{zpowerlw} \ast \text{zhighect} \\
&+ \text{const3} \ast \text{zpowerlw} \ast \text{zhighect} \\
&+ \text{mtable} \{\text{refl\_all\_torus.fits}\} \ast \text{zpowerlw} \ast \text{zhighect} \\
&+ \text{const4} \ast \text{atable} \{\text{refl\_fe\_torus.fits}\} \\
&+ \text{zgausses} \ast \text{apec(s)}),
\end{align*}

\text{(3)}

\begin{align*}
\text{Ikeda2} &= \text{const1} \ast \text{phabs} \\
&\ast (\text{const2} \ast \text{zphabs} \ast \text{cabs} \ast \text{zpowerlw} \ast \text{zhighect} \\
&+ \text{const3} \ast \text{zpowerlw} \ast \text{zhighect} \\
&+ \text{mtable} \{\text{refl\_all\_torus.fits}\} \ast \text{zpowerlw} \ast \text{zhighect} \\
&+ \text{const4} \ast \text{atable} \{\text{refl\_fe\_torus.fits}\} \\
&+ \text{zgausses} \ast \text{apec(s)}),
\end{align*}

\text{(4)}

These models are composed of five components similar to the case of the baseline models. (0) Same as the baseline models. (1) The absorbed direct component. (2) The scattered

\textsuperscript{12} Recently an “mtable” model to reproduce the reflected continuum has been released, which replaces old “atable” models used in previous works.
| Galaxy Name | $N_{\text{H}}$ (2) | $N_{\text{FeK}\alpha}$ (3) | $N_{\text{FeK}\beta}$ (4) | $\Gamma$ (5) | $N_{\text{H}}$ (6) | $f_{\text{FeK}\alpha}$ (7) | $f_{\text{FeK}\beta}$ (8) | $N_{\text{H}}^\text{def}$ (9) | $R_{\text{def}}$ (9) | $\chi^2$/dof |
|-------------|-----------------|-----------------|-----------------|-------------|--------------------|-----------------|-----------------|-----------------|-----------------|-----------|
| CGCG 420-015 | 1.04±0.05 | 0.59±0.19 | 0.91±0.14 | 2.36±0.19 | 2.03±0.15 | 0.29±0.12 | 0.09±0.05 | 0.54±0.37 | 0.94±0.04 | 180 |
| ESO 337-G034 | 0.80±0.05 | 0.75±0.08 | 0.99±0.10 | 0.37±0.10 | 3.26±0.01 | 0.10±0.03 | 3.17±0.01 | 0.00±0.01 | 0.00±0.01 | 155.7/154.0 |
| ESO 323-G032 | 1.05±0.02 | 0.37±0.29 | 1.43±0.37 | 2.15±0.78 | 0.10±0.02 | 0.08±0.12 | 7.06 (fixed) | 0.07<0.19 | 53.5/64.0 |
| ESO 565-G019 | 0.80±0.09 | 0.50±0.05 | 19.8±0.72 | 2.08±1.54 | 0.43±0.09 | 0.44±0.39 | 7.06 (fixed) | 0.00<0.01 | 12.1/37.0 |
| *Mrk 3 | 1.01±0.02 | 0.50±0.06 | 0.87±0.05 | 1.74±0.04 | 0.57±0.01 | 3.12±0.09 | 7.06 (fixed) | 0.10<0.20 | 55.7/63.0 |
| NGC 1194 | 0.21±0.08 | 1.35±0.43 | 1.15±0.23 | 1.71±0.18 | 0.90±0.17 | 2.28±0.15 | 7.06 (fixed) | 0.050.04 | 2.00<1.12 |
| NGC 3393 | 0.28±0.09 | 0.80±0.19 | 6.52±0.28 | 2.49±1.71 | 5.08±0.09 | 1.32±0.19 | 7.06 (fixed) | 0.07<0.20 | 62.0/53.0 |
| NGC 5728 | 0.16±0.04 | 1.54±0.62 | 0.79±0.09 | 0.12±0.16 | 0.42±0.02 | 0.75±0.14 | 7.06 (fixed) | 0.04<0.06 | 32.1/35.0 |
| NGC 4945 | 0.10±0.03 | 1.50±0.07 | 4.51±0.35 | 1.66±0.08 | 1.89±0.72 | 1.92±0.58 | 7.06 (fixed) | 0.22<0.25 | 496.0/420.0 |
| NGC 6552 | 0.94±0.08 | 0.85±0.16 | 1.30±0.18 | 1.63±0.14 | 0.57±0.41 | 0.72±0.83 | 7.06 (fixed) | 0.13<0.17 | 72.0/61.0 |
| NGC 7130 | 0.39±0.09 | 0.80±0.15 | 0.75±0.23 | 0.17±0.17 | 1.50±1.07 | 0.72±0.17 | 7.06 (fixed) | 0.20<0.26 | 80.5/69.0 |
| NGC 7582 | 0.32±0.07 | 0.60±0.20 | 0.91±0.25 | 0.76±0.09 | 0.45±0.20 | 2.91±2.33 | 7.06 (fixed) | 0.06<0.07 | 23.6/23.0 |
| 0.78±0.21 | 0.52±0.19 | 0.52±0.19 | 0.52±0.19 | 0.52±0.19 | 0.52±0.19 | 0.52±0.19 | 0.52±0.19 | 0.52±0.19 | 0.52±0.19 |

Note. Column (1): galaxy name. Column (2): cross-calibration constant (const1) of the BIXIS relative to the FIXISs. Column (3): time variability constant (const2) of the direct component between Suzaku and Swift. Column (4): hydrogen column density of the direct component in units of $10^{24}$ cm$^{-2}$. Column (5): photon index. Column (6): power-law normalization of the direct component in units of $10^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$. Column (7): scattering fraction in units of percent. Column (8): hydrogen column density of the reflection component in units of $10^{24}$ cm$^{-2}$. Column (9): relative reflection strength in units of $1/2\sigma$, where $\sigma$ is the solid angle of the reflector. Column (10): temperature of the apec1 model in units of keV. Column (11): normalization of the apec1 model in units of $10^{-18}/4\pi[D_{0}(1+z)^{2}]\int_{0}^{\infty}n_{e}n_{H}dV$, where $D_{0}$ is the angular diameter distance to the source (cm) and $n_{e}$ and $n_{H}$ are the electron and hydrogen densities, respectively (cm$^{-3}$). Column (12): temperature of the apec2 model in units of keV. Column (13): normalization of the apec2 model in units of $10^{-18}/4\pi[D_{0}(1+z)^{2}]\int_{0}^{\infty}n_{e}n_{H}dV$, where $D_{0}$ is the angular diameter distance to the source (cm) and $n_{e}$ and $n_{H}$ are the electron and hydrogen densities, respectively (cm$^{-3}$). Column (14): central energy of the Fe K$\alpha$ emission line in units of keV. Column (15): normalization of the Fe K$\alpha$ emission line in units of $10^{-5}$ photons cm$^{-2}$ s$^{-1}$. Column (16): central energy of the Fe K$\beta$ emission line in units of keV. Column (17): normalization of the Fe K$\beta$ emission line in units of $10^{-5}$ photons cm$^{-2}$ s$^{-1}$. 

4 For these targets, we also consider emission lines other than Fe. See Sections 4.5 and 4.8 for details.

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The reflection component from the torus. (4) The Fe K$\alpha$ emission line from the torus, whose relative normalization $N_{\text{FeK}\alpha}/N_{\text{FeK}\beta}$ (const4) to the reflection continuum is set free. The reason why we introduce this factor is to take into account the uncertainties caused by the assumption of geometry and a possible non-solar abundance of Fe. Other emission lines than Fe K$\alpha$ are separately modeled by Gaussians. (5) The optically thin thermal component(s) of the host galaxy if required. The temperature and normalization are fixed at the values obtained with the Baseline2 model, which are difficult to constrain without using the low energy below 1 keV. The photon index and power-law normalization are linked together among the direct, scattered, reflection, and Fe K$\alpha$ line components.

On the basis of this model, we consider two cases (Ikeda1 and Ikeda2) with different settings for spectral parameters. In the Ikeda1 model, we assume an ideal case where the line-of-sight column density ($N_{\text{H}}^{\text{LOS}}$) is purely determined by the torus geometrical parameters, the hydrogen column density along the equatorial plane, the inclination angle, and the half-opening angle, which are set to be free. In the case of $\theta_{\text{incl}} > \theta_{\text{open}}$, it is determined as

$$N_{\text{H}}^{\text{LOS}} = \frac{r(\cos\theta_{\text{incl}} - \cos\theta_{\text{open}}) + \sin(\theta_{\text{incl}} - \theta_{\text{open}})}{(1 - r)(\cos\theta_{\text{incl}} + \sin(\theta_{\text{incl}} - \theta_{\text{open}}))}N_{\text{H}}^{\text{FeK}\alpha}.$$  

(5)

In the Ikeda2 model, the line-of-sight hydrogen column density is an independent free parameter decoupled from the torus parameters. This is based on an idea of clumpy tori, where the hydrogen column density along a single direction can vary from the averaged hydrogen column density of the torus. Accordingly, we replace $\text{torusabs}$ with $\text{cabs}^{\text{phabs}}$. Instead, we fix the inclination angle at 70° (the upper boundary of the half-opening angle) except for Mrk 3 (Section 4.5) and set the lower limit of $\log N_{\text{H}}^{\text{FeK}\alpha}$/cm$^{-2}$ = 23.5, since we find it difficult to constrain the three geometrical parameters in this case.
Table 5

| Galaxy Name   | $N_{\text{FeII}}$ | $N_{\text{FeII}}$ | $N_{\text{FeII}}$ | $\Gamma$ | $N_{\text{FeII}}$ | $E_{\text{FeII}}$ | $N_{\text{FeII}}$ | $E_{\text{FeII}}$ | $E_{\text{FeII}}$ | $E_{\text{FeII}}$ | $\chi^2$/dof |
|---------------|-------------------|-------------------|-------------------|---------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|------------------|
| NGC 420-015   | 1.04              | 0.60              | 0.31              | 3.28    | 2.38              | 4.36              | 0.14              | 2.21              | 0.21              | 0.04             | 0.26            |
| ESO 137-G034  | 0.91              | 0.78              | 0.15              | 0.15    | 0.15              | 0.37              | 0.39              | 0.17              | 0.01              | 0.07             | 7.06            |
| ESO 323-G032  | 1.05              | 0.57              | 0.13              | 0.13    | 0.89              | 0.46              | 0.05              | 0.25              | 0.12              | 0.09             | 7.06            |
| ESO 565-G019  | 0.89              | 0.29              | 0.13              | 0.13    | 0.25              | 0.96              | 0.05              | 0.18              | 0.18              | 0.11             | 7.06            |
| Mrk 3         | 1.01              | 0.52              | 0.17              | 0.17    | 1.74              | 1.02              | 0.28              | 1.64              | 1.34              | 0.66             | 7.06            |
| NGC 1194      | 0.92              | 0.94              | 0.93              | 1.10    | 1.67              | 0.16              | 0.78              | 2.15              | 0.03              | 0.08             | 7.06            |
| NGC 3933      | 1.05              | 0.92              | 0.10              | 0.45    | 2.50              | 1.19              | 0.01              | 1.35              | 0.19              | 0.07             | 7.06            |
| NGC 4945      | 1.04              | 1.54              | 1.15              | 0.79    | 0.42              | 0.64              | 0.02              | 0.74              | 0.04              | 0.05             | 7.06            |
| NGC 5728      | 0.98              | 0.85              | 0.16              | 1.37    | 1.73              | 0.29              | 0.02              | 0.29              | 0.15              | 0.66             | 7.06            |
| NGC 6552      | 0.91              | 0.18              | 0.55              | 0.74    | 1.50              | 0.06              | 0.17              | 1.39              | 1.17              | 1.22             | 7.06            |
| NGC 7130      | 0.99              | 0.15              | 0.58              | 0.74    | 0.17              | 1.50              | 0.02              | 1.38              | 0.13              | 0.07             | 7.06            |
| NGC 7582      | 1.03              | 0.75              | 0.20              | 0.94    | 1.81              | 1.05              | 0.52              | 1.40              | 1.05              | 0.08             | 7.06            |
|              | 0.78              | 0.54              | 0.18              | 0.94    | 1.81              | 1.05              | 0.52              | 1.40              | 1.05              | 0.08             | 7.06            |

Note. Column (1): galaxy name. Column (2): cross-calibration constant ($c_{\text{FeII}}$) of the BIXIS relative to the FIXISs. Column (3): time variability constant ($c_{\text{FeII}}$) of the direct component between Suzaku and Swift. Column (4): hydrogen column density of the direct component in units of 10$^{24}$ cm$^{-2}$. Column (5): photon index. Column (6): power-law normalization of the direct component in units of 10$^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$. Column (7): scattering fraction in units of percent. Column (8): hydrogen column density of the reflection component in units of 10$^{24}$ cm$^{-2}$. Column (9): relative reflection strength in units of $\Omega_{\text{FeII}}$/2$\pi$, where $\Omega$ is the solid angle of the reflector. Column (10): temperature of the apec1 model in units of keV. Column (11): normalization of the apec1 model in units of $10^{-18}$ 4$\pi$ [D$_{0}$ (1 + z)$^{2}$] $\int f_{\text{FeII}}$ dV, where D$_{0}$ is the angular diameter distance to the source (cm) and z$_{e}$ and n$_{H}$ are the electron and hydrogen densities, respectively (cm$^{-3}$). Column (12): temperature of the apec2 model in units of keV. Column (13): normalization of the apec2 model in units of $10^{-18}$ 4$\pi$ [D$_{0}$ (1 + z)$^{2}$] $\int f_{\text{FeII}}$ dV, where D$_{0}$ is the angular diameter distance to the source (cm) and z$_{e}$ and n$_{H}$ are the electron and hydrogen densities, respectively (cm$^{-3}$). Column (14): central energy of the Fe K$\alpha$ emission line in units of keV. Column (15): normalization of the Fe K$\alpha$ emission line in units of 10$^{-8}$ photons cm$^{-2}$ s$^{-1}$. Column (16): central energy of the Fe K$\beta$ emission line in units of keV. Column (17): normalization of the Fe K$\beta$ emission line in units of 10$^{-5}$ photons cm$^{-2}$ s$^{-1}$.

* For these targets, we also consider emission lines other than Fe. See Sections 4.5.3 and 4.8 for details.

Tables 7 and 8 summarize the best-fit parameters of the Ikeda1 and Ikeda2 models, respectively. We note that the fit with the Ikeda1 model for Mrk 3 and NGC 6552 is not good, which is improved with the Ikeda2 model. Figures 2 and 3 (right columns) plot the unfolded spectra and corresponding best-fit models, respectively, based on the Ikeda2 model. Table 9 lists the observed fluxes and intrinsic luminosities in the 0.5–2.0 keV, 2–10 keV, and 10–50 keV ranges; the Fe K$\alpha$ luminosities; and the Eddington ratios (calculated in the same way as described in Section 3.2.1), based on the best-fit Ikeda2 model.

4. Results of Individual Spectra

We summarize the main results of the spectral fits for each target. In most cases, we obtain consistent results among the different models applied (i.e., Baseline1, Baseline2, Ikeda1, and Ikeda2) in terms of the line-of-sight hydrogen column density and photon index. Thus, we mainly refer to the values obtained with Ikeda2, which we believe gives the most physically realistic picture (Section 5.2). We also compare our results with previous studies of Chandra, XMM-Newton, Suzaku, and/or NuSTAR data using the MYTorus model (Murphy & Yaqoob 2009). The MYTorus model assumes a uniform-density torus of a donut-like shape with an opening angle fixed at 60$^\circ$ and has two geometrical free parameters: the inclination and equatorial column density. For convenience, we convert the equatorial column density into the line-of-sight column density ($N_{\text{FeII}}$) whenever we refer to results with the MYTorus model.

13 To avoid any confusion, in this paper we do not refer to previous results using the Torus model by Brightman & Nandra (2011a, 2011b), where there was an inconsistency between the assumed geometry and output spectra (Liu & Li 2015). Nevertheless, the Torus model works quite well in reproducing actual CTAGN spectra (J. Buchner et al. 2018, in preparation). The column densities obtained by Ricci et al. (2015) with the Torus model are consistent with our Ikeda2 model results except for NGC 4945.
Figure 2. Unfolded spectra fitted with the Baseline2 model (left) and the Ikeda2 model (right). In the upper panels, the unfolded spectra of Suzaku/BIXIS (black crosses), Suzaku/FIXIS (red crosses), Suzaku/HXD-PIN (green crosses), and Swift/BAT (blue crosses) are represented. The solid curves show the best-fit model. In the lower panels, the residuals are shown.
Figure 2. (Continued.)
Figure 2. (Continued.)
Figure 3. Best-fitting spectral models with the Baseline2 (left) and the Ikeda2 (right). The black, green, orange, blue, magenta, and red lines represent the total, direct component, scattered component, reflection component, emission lines, and emission from an optically thin thermal plasma, respectively.
Figure 3. (Continued.)
Figure 3. (Continued.)
Figure 4. Observed spectra of Suzaku/FIXISs in the 3–9 keV band folded with the energy response. The black crosses and the solid curve represent the data and the best-fit model (Baseline2), respectively. The blue curves show the contribution of the Fe K emission lines; the weak line feature at 4–5 keV is an “Si–K escape” peak of the Fe Kα line caused by the instrumental response of the FIXISs.
4.1. CGCG 420–015

All the models with two apec components well reproduce the broadband spectra. We detect Fe Kα (EW = 0.26^{+0.05}_{-0.10} keV) and Kβ (EW = 0.05^{+0.01}_{-0.01} keV) emission lines. We obtain $N_{\text{H}}^{\text{Dir}} = 1.23^{+0.65}_{-0.27} \times 10^{24}$ cm$^{-2}$, $\Gamma = 2.34(>2.08)$ with the Ikeda2 model. Severgnini et al. (2011) obtained $N_{\text{H}}^{\text{Dir}} = 1.46^{+0.07}_{-0.11} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 2.40^{+0.5}_{-0.5}$ analyzing the Suzaku data combined with Swift/BAT 54-month spectra. Our results are fully consistent with their results.

4.2. ESO 137–G034

All the models with one apec component well reproduce the broadband spectra. We detect Fe Kα (EW = 1.03^{+0.48}_{-0.66} keV) and Kβ (EW = 0.21^{+0.11}_{-0.13} keV) emission lines. We obtain $N_{\text{H}}^{\text{Dir}} = 1.30^{+0.37}_{-0.34} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 2.11^{+0.34}_{-0.32}$ with the Ikeda2 model. Comastri et al. (2010) reported $N_{\text{H}}^{\text{Dir}} = 1.0 \times 10^{25}$ cm$^{-2}$ (fixed) and $\Gamma = 1.58^{+0.16}_{-0.20}$ using the Suzaku data but applying a reflection-dominated model that is different from our models. As described in Section 5.5, the X-ray luminosity we obtain is consistent with that expected from the mid-infrared (MIR) luminosity.

4.3. ESO 323–G032

All the models with one apec component well reproduce the broadband spectra. A Fe Kα line (EW = 1.27^{+0.62}_{-0.48} keV) is detected. We obtain $N_{\text{H}}^{\text{Dir}} = 2.24^{+0.59}_{-0.74} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 2.30(>2.02)$ with the Ikeda2 model. Comastri et al. (2010) obtained $N_{\text{H}}^{\text{Dir}} = 1.0 \times 10^{25}$ cm$^{-2}$ (fixed) and $\Gamma = 1.85^{+0.47}_{-0.40}$ using the Suzaku data with the reflection-dominated model. Again, our X-ray luminosity is consistent with the MIR luminosity (Section 5.5).

4.4. ESO 565–G019

All the models with one apec component well reproduce the broadband spectra. We detect Fe Kα (EW = 1.16^{+0.32}_{-0.39} keV) and Kβ (EW = 0.15^{+0.05}_{-0.03} keV) lines. We obtain $N_{\text{H}}^{\text{Dir}} = 2.17^{+0.50}_{-0.47} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 1.95^{+0.50}_{-0.47}$ with the Ikeda2 model. Gandhi et al. (2013) obtained a line-of-sight column density of $N_{\text{H}}^{\text{Dir}} = 4.4(>2.9) \times 10^{24}$ cm$^{-2}$ and $\Gamma = 1.72^{+0.41}_{-0.27}$ using the Suzaku data with the MYTorus model. Whereas our $\Gamma$ value is consistent with the result of Gandhi et al. (2013), the $N_{\text{H}}^{\text{Dir}}$ values are subtly different. This is most probably due to the difference in the assumed geometry of the two torus models.

4.5. Mrk 3

Since the quality of the X-ray spectrum of this object is very high, we add emission lines\textsuperscript{14} reported by Awaki et al. (2008) to the spectral models. The central energy and width of these

\textsuperscript{14} O{\sc viii} Kα (0.56 keV), O{\sc viii} Lyα (0.65 keV), O{\sc vii} RRC (0.74 keV), O{\sc vii} Lyα (0.87 keV), Ne{\sc xi} Kα (0.92 keV), Ne{\sc x} Lyα (1.02 keV), Fe{\sc xxii} Lyα (1.05 keV), Fe{\sc xxii} Lyα (1.17 keV), Mg Kα (1.25 keV), Mg{\sc xx} Kα (1.33 keV), Mg{\sc xvi} Lyα (1.47 keV), Si{\sc xiv} Lyα (2.01 keV), S Kα (2.31 keV), S{\sc xvi} Lyα (2.45 keV), S{\sc xvi} Lyα (2.62 keV), Fe Kα (6.40 keV), Fe{\sc xxv} Lyα (6.64 keV), Fe Kβ (7.06 keV), and Ni Kα (7.48 keV).
Table 6
Best-fit Parameters with the Ikeda1 Model

| Galaxy Name | $N_{\text{bxis}}$ | $N_{\text{neaka}}$ | $N_{\text{e0}}$ | $N_{\text{e0}}^{\text{OS}}$ | $\theta_{\text{open}}$ | $\theta_{\text{incl}}$ | $\Gamma$ | $\chi^2$/dof |
|-------------|------------------|-------------------|---------------|----------------|----------------|----------------|-------|-------------|
| CGCG 420–015 | 0.05+0.0005 | 0.39+0.16 | 0.98+0.13 | 0.79+0.16 | 19.9+1.1 | 23.7+1.6 | 23.0+0.5 | 148.0/145.0 |
| ESO 137–G034 | 0.93+0.03 | 0.11+0.55 | 1.40+0.02 | 1.65+0.02 | 70.0+0.82 | 74.8+0.66 | 1.93+0.29 |
| ESO 323–G033 | 1.03+0.05 | 0.15+0.20 | 2.49+0.05 | 2.36+0.05 | 67.9+0.10 | 71.3+0.08 | 2.05+0.38 |
| ESO 565–G019 | 0.88+0.08 | 4.83+2.95 | 7.78+3.42 | 2.05+1.15 | 10.0+1.87 | 10.2+0.93 | 2.10+0.19 |
| aMkr 3 | 1.00+0.02 | 1.11+0.06 | 10.0+0.86 | 1.54+1.52 | 14.3+0.01 | 14.6+0.01 | 2.10+0.02 |
| NGC 1194 | 0.93+0.08 | 1.25+0.38 | 6.03+0.50 | 0.94+0.19 | 18.3+1.09 | 19.0+0.30 | 1.95+0.08 |
| NGC 3393 | 0.10+0.04 | 0.25+0.20 | 5.05+3.55 | 4.98+2.51 | 69.8+7.09 | 72.9+5.06 | 2.29+1.71 |
| NGC 4945 | 1.05+0.03 | 4.43+3.97 | 3.50+5.26 | 2.93+2.22 | 11.7+0.36 | 15.0+0.78 | 1.50+0.15 |
| NGC 5728 | 0.99+0.09 | 0.71+0.20 | 1.34+0.19 | 1.24+0.18 | 13.2+2.85 | 19.1+5.45 | 1.68+0.13 |
| NGC 6552 | 0.89+0.08 | 0.76+0.61 | 7.25+2.13 | 1.14+0.34 | 19.0+1.38 | 19.1+1.38 | 1.76+0.19 |
| NGC 7130 | 0.99+0.03 | 0.63+1.71 | 2.25+5.56 | 2.25+5.56 | 0.00+0.00 | 70.0+10.0 | 89.0+62.6 | 2.35+2.01 |
| NGC 7582 | 1.03+0.07 | 0.57+0.18 | 2.36+2.23 | 0.71+0.67 | 34.5+2.97 | 34.7+2.99 | 1.80+0.09 |
| a For these targets, we also consider emission lines other than Fe. See Sections 4.5 and 4.8 for details.

Note. Column (1): galaxy name. Column (2): cross-calibration constant (const1) of the BIXIS relative to the FIXISs. Column (3): time variability constant (const2) of the direct component between Suzaku and Swift. Column (4): hydrogen column density along the equatorial plane in units of $10^{22}$ cm$^{-2}$. Column (5): hydrogen column density along the line of sight in units of $10^{24}$ cm$^{-2}$. Column (6): half-opening angle of the torus in units of degree. Column (7): inclination angle of the torus in units of degree. Column (8): photon index. Column (9): power-law normalization of the direct component in units of $10^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$. Column (10): scattering fraction in units of percent. Column (11): relative normalization of the Fe Kα emission line to the reflection component. Column (12): energy of the Fe Kβ emission line in units of keV. Column (13): normalization of the Fe Kβ emission line in units of $10^{38}$ total photons cm$^{-2}$ s$^{-1}$. Column (14): equivalent width of the Fe Kα emission line with respect to the whole continuum in units of keV. Column (15): equivalent width of the Fe Kβ emission line with respect to the whole continuum in units of keV.

For these targets, we also consider emission lines other than Fe. See Sections 4.5 and 4.8 for details.

lines are fixed at the literature value and 10 eV, respectively, whereas the normalizations are set free. No apec model is considered.

We are unable to reproduce the spectra with the Ikeda1 model ($\chi^2$/dof $= 1002.4/658.0$). In the Ikeda2 model, we fix the torus opening angle and inclination angles at 50° and 51° (Ikeda et al. 2009), respectively. This yields a much better fit than the Ikeda1 model ($\chi^2$/dof $= 766.7/659.0$). We obtain $N_{H}^{\text{Dir}} = 1.11_{-0.04}^{+0.09} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 1.60_{-0.02}^{+0.05}$ with the model. Our results are consistent with the previous Suzaku study by Ikeda et al. (2009), who obtained $N_{H}^{\text{Dir}} = 1.1 \times 10^{24}$ cm$^{-2}$ and $\Gamma = 1.82$ with the Ikeda torus model. Using the same Suzaku data, Yaqoob et al. (2015) obtained $N_{H}^{\text{Dir}} = 0.90_{-0.01}^{+0.03} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 1.47_{-0.01}^{+0.03}$ with the MYTorus model, and Guainazzi et al. (2016) obtained $N_{H} = 0.86_{-0.01}^{+0.01} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 1.76_{-0.02}^{+0.05}$ using NuSTAR data taken on 2014 September 07 (the closest epoch to the Suzaku observation among their nine observation epochs) with the Ikeda torus model. These values are slightly different from our results. The discrepancy is most probably due to the different torus geometry ($\theta_{\text{open}} = 66^\circ$ and $\theta_{\text{incl}} = 70^\circ$) are assumed in Guainazzi et al. (2016) and/or possible time variability (Guainazzi et al. 2016).

4.6. NGC 1194

The Suzaku spectra are reported for the first time here. We detect Fe Kα (EW = 0.57_{-0.08}^{+0.08}$ keV) and Fe Kβ (EW = 0.16_{-0.08}^{+0.08}$ keV) emission lines. No apec component is required. The baseline models are able to reproduce the spectra, while the Ikeda torus models give worse fits. Nevertheless, we obtained $N_{H}^{\text{Dir}} = 1.55_{-0.41}^{+0.41} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 1.63_{-0.12}^{+0.25}$ with the Ikeda2 model. They are consistent with those with the baseline models.

4.7. NGC 3393

All the models with two apec components provide acceptable fits. We detect an Fe Kα (EW = 2.13_{-0.20}^{+0.30}$ keV) emission line. We obtain $N_{H}^{\text{Dir}} = 2.78_{-1.72}^{+1.48} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 2.11_{-1.72}^{+1.48}$ with the Ikeda2 model. Our results are consistent with the results using the NuSTAR data with the
Table 7

Best-fit Parameters with the Ikeda2 Model

| Galaxy Name | N_{H, ISIS} | N_{H, code} | N_{H, ISIS}^D | N_{H} | N_{H}^D | \theta_{open} | \theta_{incl} | \Gamma | \chi^2/dof |
|-------------|-------------|-------------|-------------|------|--------|-------------|-------------|------|-----------|
| CGCG 420−015 | 1.05^{+0.06}_{-0.07} | 0.53^{+0.77}_{-0.77} | 1.23^{+0.66}_{-0.24} | 6.66^{+0.29}_{-0.24} | 64.7^{+1.0}_{-1.0} | 70.0 (fixed) | 2.34^{+2.08}_{-2.08} |
| ESO 137−G034 | 4.63^{+0.28}_{-0.24} | 0.12^{+0.08}_{-0.08} | 0.29^{+0.15}_{-0.15} | 7.06 (fixed) | 0.18^{+0.22}_{-0.13} | 0.26^{+0.05}_{-0.03} | 0.05^{+0.28}_{-0.12} |
| ESO 323−G034 | 3.50^{+0.25}_{-0.13} | 0.33^{+0.15}_{-0.56} | 1.30^{+0.34}_{-0.34} | 10.0 (fixed) | 65.9^{+0.40}_{-0.40} | 70.0 (fixed) | 2.11^{+0.32}_{-0.32} |
| ESO 565−G019 | 2.90^{+0.28}_{-0.28} | 0.09^{+0.07}_{-0.07} | 0.90^{+0.44}_{-0.44} | 7.06 (fixed) | 0.03^{+0.11}_{-0.11} | 1.27^{+0.62}_{-0.62} | 0.05^{+0.19}_{-0.19} |
| NGC 1194 | 0.40^{+0.07}_{-0.10} | 0.39^{+0.16}_{-0.16} | 1.20^{+0.40}_{-0.40} | 7.06 (fixed) | 0.14^{+0.05}_{-0.10} | 1.16^{+0.19}_{-0.19} | 0.15^{+0.23}_{-0.23} |
| NGC 3393 | 0.00^{+0.02}_{-0.02} | 0.36^{+0.05}_{-0.05} | 3.11^{+0.12}_{-0.12} | 0.31^{+0.39}_{-0.39} | 50.0 (fixed) | 51.0 (fixed) | 1.60^{+0.02}_{-0.02} |
| NGC 4945 | 1.40^{+0.10}_{-0.09} | 0.34^{+0.23}_{-0.23} | 0.65^{+0.12}_{-0.12} | 7.06 (fixed) | 0.71^{+0.16}_{-0.16} | 0.42^{+0.08}_{-0.07} | 0.07^{+0.02}_{-0.02} |
| NGC 5728 | 0.93^{+0.02}_{-0.08} | 1.38^{+0.14}_{-0.14} | 1.55^{+0.41}_{-0.41} | 0.50^{+0.32}_{-0.32} | 69.3^{+6.51}_{-6.51} | 70.0 (fixed) | 1.63^{+0.12}_{-0.12} |
| NGC 6552 | 0.58^{+0.14}_{-0.21} | 0.37^{+0.41}_{-0.41} | 0.62^{+0.27}_{-0.27} | 7.06 (fixed) | 0.30^{+0.16}_{-0.16} | 0.57^{+0.55}_{-0.55} | 0.16^{+0.08}_{-0.08} |
| NGC 7130 | 0.00^{+0.01}_{-0.01} | 0.18^{+0.05}_{-0.05} | 0.15^{+0.01}_{-0.01} | 1.66^{+0.26}_{-0.26} | 2.82^{+4.21}_{-4.21} | 70.0 (fixed) | 2.11^{+1.72}_{-1.72} |
| NGC 7582 | 1.02^{+0.04}_{-0.07} | 0.20^{+0.07}_{-0.06} | 3.23^{+1.33}_{-1.33} | 7.14^{+1.56}_{-1.56} | 0.50^{+0.88}_{-0.88} | 67.1^{+5.39}_{-5.39} | 1.62^{+1.76}_{-1.76} |

Note. Column (1): galaxy name. Column (2): cross-calibration constant (const1) of the BIXIS relative to the FIXISs. Column (3): time variability constant (const2) of the direct component between Suzaku and Swift. Column (4): hydrogen column density of the direct component in units of 10^{22} cm^{-2}. Column (5): hydrogen column density along the line of sight in units of 10^{24} cm^{-2}. Column (6): half-opening angle of the torus in units of degree. Column (7): inclination angle of the torus in units of degree. Column (8): photon index. Column (9): power-law normalization of the direct component in units of 10^{-7} photons keV^{-1} cm^{-2} s^{-1}. Column (10): scattering fraction in units of percent. Column (11): relative normalization of the Fe K\alpha emission line to the reflection component. Column (12): energy of the Fe K\beta emission line in units of keV. Column (13): normalization of the Fe K\beta emission line in units of 10^{-7} total photons cm^{-2} s^{-1}. Column (14): equivalent width of the Fe K\alpha emission line with respect to the whole continuum in units of keV. Column (15): equivalent width of the Fe K\beta emission line with respect to the whole continuum in units of keV.

* For these targets, we also consider emission lines other than Fe. See Sections 4.5 and 4.8 for details.

4.8. NGC 4945

NGC 4945 is a nearby Seyfert 2 galaxy and one of the brightest AGNs above 10 keV. This object has been observed by many X-ray satellites since Ginga, such as RXTE (Madsjek et al. 2000), BeppoSAX (Guanazzi et al. 2000), XMM-Newton (Schurch et al. 2002), Chandra (Done et al. 2003), Swift (Tueler et al. 2008, 2010; Winter et al. 2008, 2009a), Suzaku (Itoh et al. 2008; Yaqoob 2012), and NuSTAR (Puccetti et al. 2014; Brightman et al. 2016). The soft X-ray spectrum of NGC 4945 is known to be very complex, originating from the starburst activities in the host galaxy (Itoh et al. 2008; Yaqoob 2012). Thus, we exclude the 0.5–2.0 keV range from our spectral analysis to focus on the AGN component. Following Itoh et al. (2008), we add emission lines of Fe K\alpha (6.40 keV), Fe XXV L\alpha (6.64 keV), Fe K\beta (7.06 keV), and Ni K\alpha (7.48 keV) in the spectral models. All models with these emission lines (with no apec component) reproduce the spectra reasonably well. The best-fit Ikeda1 model predicts that most of the hard X-ray emission comes from the torus reflection component. This picture seems incompatible with the observed fast time variability in the hard X-ray band (Itoh et al. 2008; Yaqoob 2012). In fact, to explain the time variability, Yaqoob (2012) concluded that the hard X-ray emission was dominated by the direct component, indicating a clumpy torus where a high column density cloud is present in the line of sight. Hence, we consider that the fitting results of the Ikeda1 model for this target are unphysical, and we discuss the results obtained by the Ikeda2 model.

We obtain N_{H} = 3.45^{+0.35}_{-0.32} \times 10^{24} cm^{-2} and \Gamma = 1.62^{+0.04}_{-0.04} with the Ikeda2 model. Using the same Suzaku data, Itoh et al. (2008) obtained N_{H} = 3.5^{+0.05}_{-0.05} \times 10^{24} cm^{-2} and \Gamma = 1.62^{+0.02}_{-0.02} and Yaqoob (2012) obtained N_{H} = 4.00^{+10}_{-10} \times 10^{24} cm^{-2} with the MYTorus model where the line-of-sight absorption is decoupled from the torus parameters. Note that they utilized the Suzaku/HXD-GSO data instead of the Swift/BAT spectrum, which may cause the small difference in N_{H}. Using the NuSTAR data, Puccetti et al. (2014) obtained N_{H} = 3.5^{+0.2}_{-0.2} \times 10^{24} cm^{-2} and \Gamma = 1.7^{+0.09}_{-0.09} in the low
Table 8
Fluxes and Luminosities with the Baseline2 Model

| Galaxy Name | \( F_{0.5-2}\) (2) | \( F_{2-10}\) (3) | \( F_{2-10}^{\text{Swift}}\) (4) | \( F_{0.5-2}^{\text{Swift}}\) (5) | \( L_{2-10}^{\text{Swift}}\) (6) | \( L_{0.5-2}^{\text{Swift}}\) (7) | \( L_{2-10}^{\text{Swift}}\) (8) | \( L_{0.5-2}^{\text{Swift}}\) (9) | \( L_{2-10}^{\text{Swift}}\) (10) | \( \log N_{\text{FeK}}\) (11) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| CGCG 420-015 | -12.68          | -11.75          | -10.88          | -10.79          | 44.04           | 43.85           | 43.57           | 43.78           | 43.12           | -1.04           |
| ESO 137-034  | -12.85          | -12.26          | -11.20          | -10.90          | 42.80           | 42.70           | 42.51           | 42.93           | 40.20           | -1.69           |
| ESO 323-032  | -13.33          | -12.40          | -11.06          | -11.17          | 43.53           | 43.48           | 43.34           | 43.30           | 40.67           | -0.92           |
| ESO 565-019  | -13.05          | -12.20          | -10.71          | -11.13          | 43.70           | 43.76           | 43.74           | 43.26           | 40.85           | ...             |
| Mkn 3        | -12.23          | -11.21          | -10.06          | -10.22          | 43.15           | 43.37           | 43.53           | 43.33           | 41.32           | -1.58           |
| NGC 1194     | -13.28          | -11.94          | -10.64          | -10.80          | 42.45           | 42.72           | 42.92           | 42.63           | 40.75           | -2.49           |
| NGC 3393     | -12.59          | -12.58          | -10.95          | -10.98          | 44.92           | 44.67           | 44.29           | 44.32           | 40.41           | 0.70            |
| NGC 4945     | -12.18          | -11.54          | -09.81          | -10.03          | 43.57           | 43.63           | 43.62           | 43.45           | 39.41           | 0.53            |
| NGC 5728     | -12.86          | -11.84          | -10.40          | -10.42          | 42.82           | 43.06           | 43.22           | 43.29           | 40.64           | -1.74           |
| NGC 6552     | -13.45          | -12.19          | -10.98          | -11.09          | 42.36           | 42.73           | 43.07           | 42.95           | 41.30           | ...             |
| NGC 7130     | -12.62          | -12.65          | -11.20          | -11.15          | 44.13           | 43.87           | 43.50           | 43.61           | 40.41           | -0.42           |
| NGC 7582     | -12.37          | -11.59          | -10.42          | -10.40          | 41.92           | 42.11           | 42.21           | 42.44           | 40.13           | -2.03           |

Note. Column (1): galaxy name. Columns (2)–(5): logarithmic observed flux in 0.5–2.0 keV (Suzaku/BIXIS), 2–10 keV (Suzaku/FIXIS), 10–50 keV (Suzaku/HXD), and 10–50 keV (Swift/BAT) in units of erg cm\(^{-2}\) s\(^{-1}\). Columns (6)–(9): logarithmic absorption-corrected luminosity in the same energy as columns (2)–(5) in units of erg s\(^{-1}\). Column (10): logarithmic Fe K\(\alpha\) luminosity. Column (11): logarithmic Eddington ratio. We define the Eddington luminosity as \(L_{\text{Edd}} = 1.26 \times 10^{38} M_{\odot} \text{yr}^{-1}\) and adopt the 2–10 keV to bolometric correction factor of 20.

We obtain \(N_{\text{FeK}} = 3.23^{+3.33}_{-1.78} \times 10^{24} \text{cm}^{-2}\) and \(\Gamma = 1.88^{+0.11}_{-0.12}\). Piconcelli et al. (2007) obtained \(N_{\text{FeK}} = 1.29^{+0.06}_{-0.07} \times 10^{24} \text{cm}^{-2}\) and \(\Gamma = 1.93^{+0.03}_{-0.01}\) using the XMM-Newton data with an analytical model, Bianchi et al. (2009) obtained \(N_{\text{FeK}} = 1.20^{+0.20}_{-0.20} \times 10^{24} \text{cm}^{-2}\) and \(\Gamma = 1.92^{+0.24}_{-0.16}\) using the Suzaku data with an analytical model, and Rivers et al. (2015) obtained \(N_{\text{FeK}} = 1.04^{+0.13}_{-0.13} \times 10^{24} \text{cm}^{-2}\) and \(\Gamma = 1.85^{+0.07}_{-0.07}\) using the NuSTAR data with the MYTorus model. Our \(N_{\text{FeK}}\) value is larger than that found by previous studies, because our best-fit Ikeda2 model shows a reflection-dominant spectrum (Figure 3).

5. Discussion

We have presented the broadband X-ray spectra of 12 CTAGNs observed with Suzaku and Swift. They are one of the best-quality data sets covering the 0.5–100.0 keV range ever observed from local CTAGNs. We have shown that the spectra can be successfully described with analytic models with the pexrav code (Baseline1 and Baseline2) and numerical models with the Ikeda et al. (2009) torus model (Ikeda1 and Ikeda2) except for a few cases. The four models give consistent results on the line-of-sight hydrogen column density and photon index, confirming the heavy obscuration of all the targets. We find, however, that the estimates of the intrinsic luminosity and the decomposition of the transmitted and reflection components are not always unique, depending on the assumed spectral model (i.e., the torus geometry). We discuss the details in the following.

5.1. Comparison of Intrinsic Luminosities among Models

Estimating true intrinsic X-ray luminosities of obscured AGNs is an important yet nontrivial issue. It depends on the decomposition of multiple components, particularly the torus reflection, as previously discussed (see, e.g., Ikeda et al. 2009; Murphy & Yaqoob 2009). Murphy & Yaqoob (2009) pointed out that the effect of Compton scattering along the line of sight is important to derive correct intrinsic luminosities in CTAGNs. They also showed that the spectral shape of the reflection continuum in the MYTorus model is quite different from that calculated with the pexrav model at energies both below and above 10 keV (see their Figure 7), which could
affect the spectral fitting results. In this subsection, on the basis of our uniform spectral analysis of a large sample of local CTAGNs, we discuss how estimates of the intrinsic luminosities would be changed by spectral models.

We compare the intrinsic 10–50 keV luminosities obtained with different models. Here we adopt the 10–50 keV range instead of the canonical 2–10 keV range because the transmitted component is directly measured only at energies above 10 keV in CTAGNs. Figures 5(a), (b), (c), and (d) compare the luminosities obtained from the (a) Baseline1 and Baseline2 models, (b) Ikeda1 and Ikeda2 models (except for Mrk 3 and NGC 4945, whose Ikeda1 fit is poor or unphysical), (c) Baseline1 and Ikeda2 models, and (d) Baseline2 and Ikeda2 models, respectively. Figures 5(e) and (f) plot the logarithmic luminosity differences between the Baseline1 and Ikeda2 models and between the Baseline2 and Ikeda2 models, respectively, as a function of line-of-sight hydrogen column density.

The Baseline2 model always gives higher luminosities than the Baseline1 model by ~0.5 dex (Figure 5(a)). This is due to the Compton scattering term. The Baseline2 model assumes an extreme case where the absorber is located only along the line of sight, whereas the Baseline1 model corresponds to the other extreme case where photons scattering into the line of sight from other directions completely cancel out the scattered-out photons. In Figure 5(b), the luminosity differences between the Ikeda1 and Ikeda2 models are less noticeable, although the Ikeda2 model tends to give higher luminosities than the Ikeda1 model by ~0.2 dex. This is because the Ikeda1 model often favors a solution of a small opening angle (Section 5.2), which predicts strong reflection components and hence a weaker transmitted component. We consider that the torus geometry derived from the Ikeda1 model may be artificial in several cases (Section 5.2).

We find that the Baseline1 model always underestimates the true 10–50 keV luminosities (Figures 5(c) and (e)). This result is consistent with the argument by Murphy & Yaqoob (2009). In fact, Masini et al. (2017) found the same trend by applying the MYTorus model to the Phoenix galaxy. Similarly, Ikeda et al. (2009) found that the intrinsic luminosity of Mrk 3 obtained with the Ikeda torus model is about 1.3 times larger than that obtained with an analytical model without the line-of-sight Compton scattering. On the other hand, the Baseline2 model overestimates them at high column densities (Figures 5(d) and (f)). The real physical situation would be between the two cases. Hereafter, we refer to the results of the Ikeda2 model as the most realistic case.

### 5.2. Torus Parameters

Figure 6 plots the correlation between the half-opening angle and inclination obtained from the Ikeda1 model fit. Remarkably, in most cases the differences between the two angles are very small, even <1°. This happens because the spectra require a large amount of the unabsorbed reflection component that is noticeable below the Fe K edge (7.1 keV). If we took these results naively, it would mean that the line of sight is intercepted by the boundary edge of the torus. However, considering the fact that similar results have been obtained from a large fraction of heavily obscured AGNs (e.g., NGC 2273, Awaki et al. 2009; NGC 3081, Eguchi et al. 2011; 3C 403, Takazi et al. 2011), such a picture would be unrealistic.

Our results reinforce the interpretation by Tanimoto et al. (2016) that these spectral features are caused by clumpy tori (Krolik & Begelman 1988; Nenkova et al. 2008a, 2008b; Kawaguchi & Mori 2011), from which unabsorbed reflection components are easily observable (Liu & Li 2014; Furui et al. 2016).

We thus consider that the fitting results with the Ikeda1 model are artificial in several cases and should not be taken at their face values. For instance, we obtain small inclination angles from three water megamaser AGNs in our sample, NGC 1194, NGC 3393, and NGC 4945, which must be observed close to edge-on in reality. In the Ikeda2 model, we have assumed an inclination of 70° (a practical upper limit in the Ikeda model) except for Mrk 3, which would be more proper for CTAGNs. We then obtain best-fit half-opening angles of ≈65°–70° in order to reproduce the unabsorbed reflection component. The column density at the equatorial plane derived from the Ikeda2 model is determined to account for the intensities of the reflection continuum. Even with an apparently large opening angle (e.g., >65°), we do not rule out the possibility that Compton-thin
material ($N_H \lesssim 10^{24} \text{ cm}^{-2}$) is present in the torus-hole region (i.e., at inclinations lower than this half-opening angle) and “buried” the nucleus, because it would not affect significantly the broadband spectra except for the scattered component. In fact, such a geometry is proposed for the CTAGN in UGC 5101 (Oda et al. 2017) and possibly for NGC 4945.

5.3. Correlations among Basic Parameters

Figure 7 shows the distribution of the (a) line-of-sight hydrogen column density, (b) photon index, (c) scattered fraction, (d) 10–50 keV luminosity, and (e) Eddington ratio, all based on the Ikeda2 model fit. Figure 7(a) confirms that all the objects are CTAGNs. We find that 10 AGNs show a scattered fraction smaller than 0.5% (Figure 7(c)), which are referred to as new type AGNs by Ueda et al. (2007).
Figure 8 shows the relation between the (a) hydrogen column density and scattered fraction, (b) hydrogen column density and 10–50 keV luminosity, (c) hydrogen column density and Eddington ratio, (d) photon index and 10–50 keV luminosity, and (e) photon index and Eddington ratio. For comparison, hereafter we also plot the data of Compton-thin AGNs obtained by Kawamuro et al. (2016a) with blue squares; we refer to their results of the intrinsic (de-absorbed) 10–50 keV luminosity that does not include the reflection component, instead of the observed 10–50 keV luminosity, for consistency with our plot.

Figure 8 suggests that the fraction of small scattered-fraction AGNs is larger in more heavily obscured AGNs, particularly in CTAGNs, even though the samples are not statistically complete. This implies that a majority of CTAGNs are deeply buried in geometrically thick tori, that is, there is a link between the column density and geometry (covering fraction) in AGN tori (Kawamuro et al. 2016a). A similar implication is also obtained from a sample of distant AGNs (Brightman & Ueda 2012). As noted above, this interpretation does not conflict with the relatively large opening angles derived from the Ikeda2 model fit if the torus-hole region is covered by Compton-thin material that only affects the scattered component below several keV.

For this sample of obscured AGNs we do not find any statistically significant correlation between the column density and the X-ray luminosity (Figure 8(b)) or between the column density and the Eddington ratio (Figure 8(c)). Our CTAGN sample is located within the scatter of the $\Gamma$ versus X-ray luminosity relation (Figure 8(d)) and the $\Gamma$ versus Eddington ratio plot (Figure 8(e)) obtained from the Compton-thin AGNs. We note that NGC 4945 may be an outlier showing a
somewhat flat photon index ($\Gamma \approx 1.6$) at a high Eddington ratio ($\log \lambda_{\text{Edd}} = -0.10$).

5.4. Fe Kα Line

We detected a strong Fe Kα emission line (EW = 0.26–2.13 keV) from all targets. Figure 9 plots the (a) equivalent width of Fe Kα line against the column density, (b) luminosity ratio between the Fe Kα line and intrinsic 10–50 keV continuum against the column density, and (c) that against the 10–50 keV luminosity.

Figure 9(a) confirms the general correlation between the line-of-sight hydrogen column density and the equivalent width of the Fe Kα line as previously reported (e.g., Turner et al. 1998; Turner & Miller 2009; Fukazawa et al. 2011). The correlation at $\log N_H > 23.0$ cm$^{-2}$ is mainly caused by the attenuation of the transmitted component by photoelectric absorption at the same energy, which makes the equivalent width of the Fe Kα line larger. This indicates that the Fe Kα equivalent width is a good indicator to identify CTAGNs.

The ratio between the Fe Kα and hard X-ray (>10 keV) luminosities is proposed to be a better indicator than the equivalent width to constrain the solid angle of the torus (Ricci et al. 2014). As noticed from Figure 9(b), this luminosity ratio tends to decrease toward larger hydrogen column densities. This effect is attributable to self-absorption of the emitted Fe Kα line by the near-side torus (Ricci et al. 2014). It would explain the reason why our CTAGN sample, though limited in number, apparently does not follow the anticorrelation between the $L_{\text{FeKα}}/L_{10-50}$ ratio and the 10–50 keV luminosity found for Compton-thin AGNs by Ricci et al. (2014) and Kawamuro et al. (2016a) (Figure 9(c)).
Koss et al. (2016) propose a new method that uses the “spectral curvature” above 10 keV to identify CTAGNs with Swift/BAT data. They focus on data below 50 keV because this energy band shows the strongest difference in the curvature compared with unobscured AGNs. The definition of the spectral curvature is

$$SC_{\text{BAT}} = \frac{-3.42A - 0.82B + 1.65C + 3.58D}{\text{Total Rate}},$$

where $A$, $B$, $C$, and $D$ refer to the 14–20 keV, 20–24 keV, 24–35 keV, and 35–50 keV Swift/BAT count rates, respectively, and the total rate refers to the 14–50 keV count rate. The spectral curvature is calibrated so that a heavily CTAGN in an edge-on torus has a value of $1 \times 10^{24}$ cm$^{-2}$ and an unobscured AGN has a value of 0. Table 10 lists the spectral curvatures calculated from the Swift/BAT 70-month spectra for our CTAGN sample.

5.5. Correlation of X-Ray and MIR Luminosities

We discuss the correlation between X-ray and MIR luminosities. The MIR emission of an AGN mainly comes from the dust in the torus heated by the primary radiation from the central engine. It is known that there is a good correlation between the X-ray and MIR luminosities in AGNs (Gandhi et al. 2018).
Figure 10. Correlation between the line-of-sight hydrogen column density and hard X-ray spectral curvature. The blue squares and red circles correspond to the Compton-thin AGNs of Kawamuro et al. (2009; Ichikawa et al. 2012; Asmus et al. 2015; Kawamuro et al. 2016a; Ichikawa et al. 2017) and our sample, respectively. The black line shows the result of Ichikawa et al. (2017) obtained from the whole unbeamed AGN sample in the Swift/BAT 70-month catalog.

Figure 11. Correlation between the 10–50 keV and 12 μm luminosities. The blue squares and red circles represent the Compton-thin AGNs of Kawamuro et al. (2016a) and our sample, respectively. The black line shows the result of Ichikawa et al. (2017) obtained from the whole unbeamed AGN sample in the Swift/BAT AGNs matched to the WISE observatory or ground-based facilities (Wright et al. 2010; Asmus et al. 2015). Figure 11 shows the correlation between the 10–50 keV luminosity and the 12 μm luminosity for our CTAGNs and the Compton-thin AGNs in Kawamuro et al. (2016a). In this figure we also show the regression line derived by Ichikawa et al. (2017) by using a large (~700) sample of Swift/BAT AGNs matched to the WISE catalog; here we convert the 14–195 keV luminosities into the 10–50 keV ones by assuming a photon index of 1.8.

We confirm that our sample generally follows the same correlation as for less obscured AGNs (Gandhi et al. 2009; Ichikawa et al. 2012, 2017; Asmus et al. 2015; Kawamuro et al. 2016a). It is naively expected that deeply buried AGNs with geometrically thick tori may emit stronger MIR emission at the same hard X-ray luminosity. However, according to detailed theoretical calculations of the infrared radiation from clumpy tori (Stalevski et al. 2016), the MIR emission decreases with the inclination (see their Figures 8 and 11 for the face-on and edge-on cases, respectively). Thus, if many of our CTAGNs are observed close to edge-on, the two effects would cancel each other out. More detailed comparison between the infrared and X-ray properties of CTAGNs will be useful to reveal the geometry of their tori.

6. Conclusion

1. The estimate of the intrinsic luminosity of a CTAGN strongly depends on the spectral model. Applying Compton scattering to the transmitted component in an analytic model may largely overestimate the true luminosity at large column densities. The usage of a Monte-Carlo-based model assuming a realistic geometry is required to estimate the intrinsic luminosity most reliably.

2. Uniform-density torus models tend to give a geometrical solution where the line of sight is intercepted near the edge of the torus, in order to explain a large amount of unabsorbed reflection components from the far-side torus. We interpret this as evidence of clumpiness in the torus.

3. A large fraction of the objects of our sample (10 out of 12) shows small scattering fractions (<0.5%). This implies that a majority of CTAGNs are deeply buried in geometrically thick tori, which might imply that there is a link between the column density and covering fraction in AGN tori.

4. We confirm that the Fe Kα equivalent width is a good indicator to identify CTAGNs without detailed spectral modeling.

5. The overall results confirm that the properties of hard-X-ray-selected CTAGNs can be understood as a smooth extension from Compton-thin AGNs with heavier obscuration; we find no evidence that they are distinct populations from less obscured AGNs.

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ORCID iDs

Atsushi Tanimoto @ https://orcid.org/0000-0002-0114-5581
Yoshihiro Ueda @ https://orcid.org/0000-0001-7821-6715
Taiki Kawamuro @ https://orcid.org/0000-0002-6808-2052
Claudio Ricci @ https://orcid.org/0000-0001-5231-2645
Hisamitsu Awaki @ https://orcid.org/0000-0001-7204-4350
Yuichi Terashima @ https://orcid.org/0000-0003-1780-5481

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