SUZAKU VIEW OF THE SWIFT/BAT ACTIVE GALACTIC NUCLEI. III. APPLICATION OF NUMERICAL TORUS MODELS TO TWO NEARLY COMPTON THICK ACTIVE GALACTIC NUCLEI (NGC 612 AND NGC 3081)

SATOSHI EGUCHI1, YOSHIHIRO UEDA1, HISAMITSU AWAKI2, JAMES AIRD3, YUICHI TERASHIMA2, AND RICHARD MUSHOTZKY4

1 Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan
2 Department of Physics, Faculty of Science, Ehime University, Matsuyama 790-8577, Japan
3 Center for Astrophysics and Space Sciences (CASS), Department of Physics, University of California, San Diego, CA 92093, USA
4 Department of Astronomy, University of Maryland, College Park, MD, USA

Received 2010 October 28; accepted 2010 December 30; published 2011 February 7

ABSTRACT

The broadband spectra of two Swift/BAT active galactic nuclei (AGNs) obtained from Suzaku follow-up observations are studied: NGC 612 and NGC 3081. Fitting with standard models, we find that both sources show similar spectra characterized by heavy absorption with $N_H \simeq 10^{24}$ cm$^{-2}$, and the fraction of scattered light is $f_{\text{scat}} = 0.5\%–0.8\%$, and the solid angle of the reflection component is $\Omega/2\pi = 0.4–1.1$. To investigate the geometry of the torus, we apply numerical spectral models utilizing Monte Carlo simulations by Ikeda et al. to the Suzaku spectra. We find that our data are well explained by this torus model, which has four geometrical parameters. The fit results suggest that NGC 612 has a torus half-opening angle of $\approx 60^\circ–70^\circ$ and is observed from a nearly edge-on angle with a small amount of scattering gas, while NGC 3081 has a very small opening angle of $\approx 15^\circ$ and is observed on a face-on geometry, more like the deeply buried “new type” AGNs found by Ueda et al. We demonstrate the potential power of direct application of such numerical simulations to high-quality broadband spectra to unveil the inner structure of AGNs.

Key words: galaxies: active – gamma rays: galaxies – X-rays: galaxies – X-rays: general

Online-only material: color figures

1. INTRODUCTION

The strong correlation between the mass of a supermassive black hole (SMBH) and that of the galactic bulge (e.g., Magorrian et al. 1998; Marconi & Hunt 2003) suggests a fundamental link between the growth of SMBHs and galaxy evolution. Theoretical models predict that most SMBHs in galaxies experience a heavily obscured phase in their growth stage (e.g., Hopkins et al. 2005). Indeed, studies based on population synthesis models of the cosmic X-ray background (CBX) suggest that heavily obscured active galactic nuclei (AGNs), whose line-of-sight hydrogen column density ($N_H$) is greater than $10^{23.5}$ cm$^{-2}$, are a significant fraction of the AGN population (Ueda et al. 2003; Gilli et al. 2007). Due to the difficulty of detecting them in most energy bands, however, our understanding of heavily obscured AGNs (including “Compton-thick” ones with $N_H > 10^{24}$ cm$^{-2}$) is very scarce even in the local universe.

Sensitive hard X-ray observations above 10 keV, where the penetrating power overwhelms photoelectric absorption, provide fruitful information about this population, except for heavily Compton-thick ($N_H \gtrsim 10^{24.5}$ cm$^{-2}$) objects. Recent all sky hard X-ray surveys performed with the Swift/BAT (15–200 keV; Tueller et al. 2008) and International Gamma-Ray Astrophysics Laboratory (INTEGRAL, 10–100 keV; Bassani et al. 2006; Krivonos et al. 2007) are ideal for this purpose as they have much less selection biases than surveys at lower energies.

Our team has been working on a systematic follow-up observation program with Suzaku of Swift/BAT-detected AGNs, whose broadband X-ray spectra were poorly (or never) studied previously, targeting obscured objects in most cases. Ueda et al. (2007) discovered deeply buried AGNs that exhibit very small fractions of scattered soft X-rays ($<0.5\%$) with respect to the transmitted component, with strong reflection signals most probably coming from the inner wall of the Compton-thick tori. Further studies of six Swift AGNs by Eguchi et al. (2009, Paper I hereafter) show that they could be classified into two types, “new type” AGNs with a small scattering fraction and strong reflection strength, and “classical type” ones with a larger scattering fraction and weaker reflection. These types are consistent with SMBHs surrounded by geometrically thick and thin tori, respectively. Using an INTEGRAL-selected sample, Comastri et al. (2009) also suggest that there are distinct AGN populations of new and classical types, although the result depends on whether the absorption for the reflection component is considered or not in the spectral model (see Comastri et al. 2010). Due to the limited number of objects in the sample studied, we are far from reaching a consensus on the torus structure and its dependence on various parameters such as the AGN luminosity, Eddington ratio, and properties of the host galaxy, for entire AGN populations.

High-quality broadband X-ray spectra give unique insight into the structure and geometry of the central regions of AGNs. Most previous studies, however, relied on phenomenological spectral models where the detailed geometry of the torus is not taken into account; usually, an analytical formula for the Compton reflection from matter with infinite optical depths is simply assumed for the reprocessed emission, and absorption column density of the transmitted component is treated independently. Monte Carlo simulation is a powerful tool to reproduce realistic spectra from AGNs with a complex torus structure, which may not always have a sufficiently large optical depth for Compton scattering. Recently, Ikeda et al. (2009) have developed such a Monte Carlo code that can be applicable to the broadband X-ray spectra with several free parameters describing the torus geometry. Similarly, Murphy & Yaqoob (2009) also studied the numerical spectra from a toroidal torus, known as the MYTORUS model, although we do not adopt this model here because the opening angle of the torus is fixed at 60°.

5 http://www.mytorus.com/
Applying such models directly to the observed spectra, we can obtain more accurate constraints on the inner structure of AGNs than from the standard previous analysis.

In this paper, we present the results of detailed X-ray spectral analysis of Suzaku data of two Swift/BAT AGNs, Swift J0134.1−3625 (NGC 612; z = 0.0298), and Swift J0959.5−2258 (NGC 3081; z = 0.0080), whose simultaneous broadband spectra were not available before. NGC 612 is a powerful radio galaxy, which was originally classified as Fanaroff–Riley (FR; Fanaroff & Riley 1974) type II by Morganti et al. (1993). This object hosts prominent double radio sources; the eastern lobe has a bright hot spot near its outer edge, while the western one has a jet-like structure. Since the former and latter morphologies correspond to those of the FR I and II types, respectively, Gopal-Krishna & Wiita (2000) classify it as a hybrid morphology radio source. NGC 612 shows an optical spectrum of Seyfert 2 galaxies, but the intensity of the [O III] emission is much weaker (Parisi et al. 2009). Winter et al. (2008) present the X-ray spectrum observed with XMM-Newton, obtaining a large hydrogen column density of \( N_H \approx 10^{23.9} \text{ cm}^{-2} \) with an apparently very flat power-law index of \( \simeq 0.3 \), suggestive of a reflection-dominant spectrum below 10 keV. NGC 3081 is a Seyfert 2 hosted by a barred galaxy. This object has three rings associated with a tidal interaction (Freeman et al. 2000), and II types, respectively, Gopal-Krishna & Wiita (2000) classify it as a class-II AGN. Since the X-ray flux is too faint to be detected with Suzaku, we applied spaced-row charge injection (SCI) to improve the energy resolution (Nakajima et al. 2008); for instance, it reduces the full width at half-maximum of the 55Fe calibration source from \( \simeq 230 \text{ eV} \) to \( \simeq 160 \text{ eV} \) for Swift-0 (Ozawa et al. 2009). To constrain the broadband spectra above 60 keV, we also utilize the Swift/BAT spectra covering the 15–200 keV band, integrated over the first 22 months of Swift operations.

### 2.2. Data Reduction

The Suzaku data are analyzed by using HEASoft version 6.7 and the latest version of CALDB on 2009 December 3. For the XIS data, we analyze the version 2.2 cleaned events distributed by the Suzaku pipeline processing team. To extract the light curves and spectra, we set the source region as a circle around the detected position with a radius of 1.5′, where about 75% of the total source photons are accumulated, to maximize the signal-to-noise ratio. The background for the XIS data is taken from a source-free region in the field of view with an approximately same offset angle from the optical axis as the source. For the non-X-ray background of the HXD, the targets were observed at the HXD nominal position, which is about 5′ off axis from the averaged optical axis of the XISs.\(^6\)

We analyze only the data of the XISs and the HXD/PIN, which covers the energy band of 0.2–12 keV and 10–60 keV, respectively. The fluxes above 50 keV are too faint to be detected with HXD/GSO. Table 2 shows the X-ray spectra observed from this object.

### 2.3. X-ray Observations

#### 2.3.1. Observation

We observed NGC 612 and NGC 3081 with Suzaku in 2008 May and June, respectively. The basic information for our targets is summarized in Table 1. Suzaku (Mitsuda et al. 2007) carries four X-ray CCD cameras called the X-ray Imaging Spectrometer (XIS-0, XIS-1, XIS-2, and XIS-3) as the focal plane imager of four X-ray telescopes, and a non-imaging instrument called the Hard X-ray Detector (HXD) consisting of Si PIN photodiodes and GSO scintillation counters. XIS-0, XIS-2, and XIS-3 are front-side-illuminated CCDs (FI-XISs), while XIS-1 is the back-side-illuminated one (BI-XIS). To maximize the effective area of the HXD, the targets were observed at the HXD nominal position, which is about 5′ off axis from the averaged optical axis of the XISs.\(^6\)

We analyze only the data of the XISs and the HXD/PIN, which covers the energy band of 0.2–12 keV and 10–60 keV, respectively. The fluxes above 50 keV are too faint to be detected with HXD/GSO. Table 2 shows the log of the observations. The net exposure of each target is about 45 ks. Because XIS-2 became inoperable on 2007 November 7 (Dotani et al. 2007), no XIS-2 data are available for both objects. For the XIS observations, we applied spaced-row charge injection (SCI) to the non-X-ray background of the HXD

### Table 1

| Target     | Start Time (UT) | End Time   | Exposure\(^a\) (XIS) | Exposure (HXD/PIN) | SCI\(^b\) |
|------------|-----------------|------------|----------------------|--------------------|----------|
| NGC 612    | 2008 May 20 16:19 | 2008 May 21 20:08 | 48.5 ks | 41.3 ks | On       |
| NGC 3081   | 2008 Jun 18 21:49 | 2008 Jun 19 19:33 | 43.7 ks | 42.4 ks | On       |

#### Notes.

\(^a\) Based on the good time interval for XIS-0.

\(^b\) With/without the SCI for the XIS (Nakajima et al. 2008).

\(^6\) http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/
2.3. Light Curves

Figure 1 shows the background-subtracted light curves of our targets obtained with the XIS and HXD/PIN in the 2–10 keV and 15–40 keV bands, respectively. To minimize any systematic uncertainties caused by the orbital change of the satellite, we merge the data taken during one orbit (≈96 minutes) into one bin. Then, to check if there is any significant time variability during the observations, we perform a simple $\chi^2$ test to each light curve, assuming a null hypothesis of constant flux. The resultant reduced $\chi^2$ value and the degrees of freedom are shown in each panel. As noticed from Figure 1, the 2–10 keV flux of NGC 3081 increased by a factor of 1.5 after ≈20 ks from the start of the observation. Then, a flux decline is suggested between ≈50 ks and ≈60 ks particularly in the 15–40 keV band. Thus, we divide the observation of NGC 3081 into three different time regions, 0–20 ks (epoch 1), 20–60 ks (epoch 2), and 60–80 ks (epoch 3), measured from the observation start. In contrast, no significant time variability on a timescale of hours is detected from NGC 612. Hence, we analyze the time-averaged spectra over the entire observation for NGC 612.

2.4. BAT Spectra

It is known that the incident photon spectra of Seyfert galaxies are roughly approximated by a power law with an exponential cutoff (cutoff power-law model), represented as $A E^{-\Gamma} \exp\left(-E/E_{\text{cut}}\right)$, where $A$, $\Gamma$, and $E_{\text{cut}}$ are the normalization at 1 keV, photon index, and cutoff energy, respectively. We analyze the Swift/BAT spectra in the 15–200 keV band to constrain $E_{\text{cut}}$. Here, we take into account possible contributions from a Compton reflection component from optically thick, cold matter, utilizing the pexrav code (Magdziarz & Zdziarski 1995). The relative intensity of the reflection component to that of the intrinsic cutoff power-law component is defined as $R \equiv \Omega/2\pi$, where $\Omega$ is the solid angle of the reflector ($R = 1$ corresponds to the reflection from a semi-infinite plane).

In the analysis of the Swift/BAT spectra, we assume $R = 0$ or 2 as the two extreme cases just to evaluate the effects of including the reflection components, as done in Paper I. The inclination angle is fixed at 60°. To avoid strong coupling between the power-law slope and cutoff energy, we fix the photon index at 1.9, the canonical slope for AGNs (e.g., Nandra & Pounds 1994). Table 3 gives the fitting results for $E_{\text{cut}}$; we find that $E_{\text{cut}}$ is greater than ≈300 keV for both targets. Accordingly, we fix it at 300 keV (or 360 keV for consistency with the Ikeda model) in the following spectral analysis.

Figure 1. Background-subtracted light curves of Suzaku. One bin corresponds to 96 minutes. The numbers listed in each panel represent the value of reduced $\chi^2$ with the degrees of freedom for the constant flux hypothesis. Left: the light curves of the XIS in the 2–10 keV band. The data from XIS-0 and XIS-3 are summed. Right: the light curves of the HXD/PIN in the 15–40 keV band.
We perform spectral fitting to the Suzaku data in the same manner as in Paper I. We start with the simplest model for each target, and if we find that the fit with a simple model does not give a physically self-consistent picture or that the fit is significantly improved by introducing additional parameters, then we adopt more complicated models. We use only the Suzaku XIS and HXD/PIN data throughout this stage, and finally perform the simultaneous fit of XIS, HXD/PIN, and Swift/BAT spectra with the selected model to obtain the best-fit parameters.

The spectra of FI-XISs are summed, and the relative normalization between the FI-XISs and the PIN is fixed at 1.18 based on the calibration of the Crab Nebula (Maeda et al. 2008). Those of BI-XIS and BAT against FI-XISs are set as free parameters. Galactic absorption ($N_H^\text{Gal}$) is always included in the models, whose hydrogen column densities are fixed at values obtained from the H i map (Kalberla et al. 2005) available with the nh program in the HEAsoft package. We adopt the photoelectric absorption cross section by Balucinska-Church & McCammon (1992, “bcmc”). In contrast to Paper I, we allow the iron abundance to be a free parameter by using zvphabs because non-solar values (as defined by Anders & Grevesse 1989) are required to explain the Suzaku spectra, while solar abundances are adopted for the other metals throughout our analysis.

We use the same three models as defined in Paper I, consisting of an absorbed transmitted component, a scattered component, and/or an absorbed reflection component with an iron-K emission line:

1. Model A: transmission + scattering + iron line.\(^8\)
2. Model B: transmission + scattering + iron line + absorbed reflection.\(^9\)
3. Model C: transmission with dual absorber + scattering + iron line + absorbed reflection.\(^10\)

In our analysis, we adopt an unabsorbed power law with the same photon index as the incident continuum to describe the scattered component, ignoring any emission lines from the photo-ionized gas. Note that here we only introduce a single absorber for the reflection component as the simplest approximation, although we expect both absorbed and unabsorbed ones from the torus as well as that from the accretion disk, as described in following section. The pexrav component in each spectral model (see footnote) represents only the reflection component not including the direct one by setting $R < 0$, and the inclination angle is fixed at 60°. Theoretically, the equivalent width (EW) of the iron-K emission line with respect to the reflection component, $EW_{\text{refl}}$, is expected to be $\sim 1\) keV (Matt et al. 1991). Since this value depends on the geometry of the reflector as well as the iron abundance, we regard the result as physically valid if $EW_{\text{refl}} = 0.5–2\) keV. No other emission lines other than iron $K\alpha$ are significantly detected from the spectra. Considering calibration uncertainties in the energy response of the XISs, we fix the $1\sigma$ line width of the iron-$K\alpha$ emission to the averaged value of the (apparent) line width of the $^{56}$Fe calibration source at 5.9 keV: 45 eV and 47 eV for NGC 612 and NGC 3081, respectively.

### 3.1. NGC 612

Model B is adopted as the most appropriate model of NGC 612. We obtain $(\chi^2, \nu) = (90.8, 85)$ with Model A and $(\chi^2, \nu) = (86.9, 84)$ with Model B from the Suzaku spectra, where $\nu$ is the degree of freedom. Thus, the improvement of the fit by adding a reflection component is found to be significant at the 94% confidence level by an F-test. No significant improvement is found with Model C. For this target, the absorption to the reflection component $N_{H}^{\text{refl}}$ is linked to that for the transmitted component, because making them independent does not give a better fit over the statistics (see below). Since the EW of the iron-K line with respect to the reflection component is $EW_{\text{refl}} = 0.7 \pm 0.1\) keV, the model is physically self-consistent; the iron abundance of NGC 612 is roughly half of the solar value, obtained from the simultaneous fit of the Suzaku and BAT spectra.

To examine the degeneracy in the fitting parameters, in Figure 2 (top) we show the confidence map (in terms of $\Delta\chi^2$) with respect to the strength of the reflection component ($R$) and its absorption ($N_{H}^{\text{refl}}$), based on the Model B fit including the BAT data. Here, we do not link $N_{H}^{\text{refl}}$ to that of the transmitted component ($N_{H}$), and explore a region of $N_{H}^{\text{refl}} < 1.2 \times 10^{24}$ cm$^{-2}$, the upper limit obtained for $N_{H}$. The contours give the confidence levels at 1$\sigma$ and 2$\sigma$ for two interesting parameters. As noticed, while a wide range of $N_{H}^{\text{refl}} (\gtrsim 6 \times 10^{23}$ cm$^{-2}$, 1$\sigma$) is allowed, we can constrain the reflection strength to be $R \approx 0.6$ for $N_{H}^{\text{refl}} < 1.1 \times 10^{24}$ cm$^{-2}$ and $R \approx 0.3$–0.7 otherwise. The case of an unabsorbed reflection component ($N_{H}^{\text{refl}} = 0$) or no reflection component ($R = 0$) is rejected at $>99\%$ confidence level, which corresponds to $\Delta\chi^2 = 9.21$.

### 3.2. NGC 3081

First, we analyze the Suzaku spectra integrated over epoch 1. We obtain $(\chi^2, \nu) = (120.1, 61)$ with Model A and $(\chi^2, \nu) = (80.2, 59)$ with Model B, and thus the improvement of $\chi^2$ is significant at $>99\%$ confidence level by an F-test. No significant improvement is found with Model C. Finally, since positive residuals remain in the energy band below 1 keV, we add the vapec\(^11\) in XSPEC, a spectral model from an optically thin thermal plasma, whose iron abundance is linked to that in the absorber of the transmitted component. This yields a further significantly better fit at $>99\%$ confidence level with $(\chi^2, \nu) = (50.7, 57)$. The EW of the iron-K line with respect to the reflection component is $EW_{\text{refl}} = 1.5 \pm 0.3\) keV, which is self-consistent. Thus, we adopt model B+vapec as the best-fit model for epoch 1.

By fitting the epochs 2 and 3 spectra of Suzaku with the same model, we obtain acceptable fits with $(\chi^2, \nu) = (139.7, 114)$.

---

\(^8\) In XSPEC nomenclature, zvphabs*zhighcut*zpowerlw + const*zhighcut*zpowerlw + zgauss
\(^9\) In XSPEC nomenclature, zvphabs*zhighcut*zpowerlw + const*zhighcut*zpowerlw + zgauss + vapec
\(^10\) In XSPEC nomenclature, zvphabs*zpowerlw + zgauss + vapec
\(^11\) http://cxc.harvard.edu/atomdb/
and NGC 3081 (bottom). The dashed and solid curves correspond to the
epoch 2, and then

Figure 2. Confidence map in $\Delta\chi^2$ (color scale) with respect to the strength of
the reflection component ($R = \Omega/2\pi r$) and its absorption ($N_H^{\text{refl}}$) for NGC 612
(top) and NGC 3081 (bottom). The dashed and solid curves correspond to the
1$\sigma$ and 2$\sigma$ confidence level for two interesting parameters, respectively.
(A color version of this figure is available in the online journal.)

and (19.1, 30), respectively. The best-fit parameters in the three
epochs are plotted in Figure 3 except for the iron abundance
and those of the thin thermal component, which are expected to
show no time variability. We find only a weak indication that
the column density changed during the observation from $N_H =
(113 \pm 10) \times 10^{22}$ cm$^{-2}$ (epoch 1) to $N_H = (98 \pm 6) \times 10^{22}$ cm$^{-2}$
(epoch 2), and then $N_H = (86 \pm 10) \times 10^{22}$ cm$^{-2}$ (epoch 3)
in addition to the unabsorbed power-law luminosity, which
varied from $L_{2-10} = (3.0 \pm 0.2) \times 10^{32}$ erg s$^{-1}$ (epoch 1)
to $L_{2-10} = 3.8_{-0.3}^{+0.2} \times 10^{32}$ erg s$^{-1}$ (epoch 2), and $L_{2-10} =
2.7_{-0.2}^{+0.3} \times 10^{32}$ erg s$^{-1}$ (epoch 3) in the 2–10 keV band.
The other parameters are found to be consistent with being constant
among the three epochs within the errors. The significance of the
variability of the column density is marginal, as the null hypothesis probability of a constant value is found to be 15%
from a $\chi^2$ test. Thus, we sum the epoch 1, 2, and 3 data of
Suzaku and discuss the time-averaged spectra in the following
analysis.

To best constrain the spectral parameters of NGC 3081,
we perform the simultaneous fit to the time-averaged Suzaku
and BAT spectra with the Model B + vadvpec model. This yields
($\chi^2, \nu) = (199.28, 199)$ and $\text{EW}^{\text{refl}} = 1.0 \pm 0.1$ keV, and thus is
physically self-consistent. The iron abundance with respect
to solar is 0.89 ± 0.07, and the temperature of the plasma is
found to be $kT = 0.26 \pm 0.02$ keV with an emission measure of
$n^2V \simeq 1.5 \times 10^{63}$ cm$^{-3}$.

Figure 2 (bottom) shows the confidence contour map with re-
spect to $R$ and $N_H^{\text{refl}}$ based on Model B (including the BAT data)
for NGC 3081. Unlike the case of NGC 612, the solution is well
constrained ($R \simeq 0.8$–1.0, 1$\sigma$) and we do not see strong
degeneracy in the fitting parameters. Again, neither the case of an
unabsorbed reflection component ($N_H^{\text{refl}} = 0$), nor of the no re-
fection component ($R = 0$) is allowed at >99% confidence level.

3.3. Results and Summary of Analytical Models

We summarize the best-fit models and parameters in Table 4.
The observed fluxes in the 2–10 keV and 10–50 keV bands,
and the estimated 2–10 keV intrinsic luminosities corrected for
absorption, are also listed. Figure 4 (left) shows the observed
spectra of the FI-XIS (black), the BI-XIS (red), and the HXD/
PIN (magenta) folded with the detector response in units of
counts s$^{-1}$ keV$^{-1}$, together with the unfolded BAT spectra (blue)
in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$. The best-fit models are
superposed by solid lines. In the lower panels, the corresponding
data-to-model residuals in units of $\chi$ (i.e., normalized by the $1\sigma$
statistical error in each bin) are plotted. Figure 4 (right)
shows the best-fit spectral models in units of $EF_E$ without
Galactic absorption, where the contribution of each component
is plotted separately; the black, red, blue, cyan, and magenta
curves correspond to the total, transmitted component, reflection
component, scattered component, and iron-K emission line,
respectively. For NGC 3081, the additional soft component
is also included in purple.

We find that the fractions of the scattered component with
respect to the transmitted one for both NGC 612 and NGC 3081
are fairly small (0.5%–0.8%). Also, they are heavily obscured
with column densities of $N_H \simeq 10^{24}$ cm$^{-2}$, and hence, can be
regarded as nearly “Compton-thick” AGNs. Figure 5 shows the
correlation between the reflection component $R$ and the scattered
compartment $f_{\text{scat}}$, superposed on the same plot presented in Paper I.
NGC 612 and NGC 3081 are located in a position similar to
each other in this plot. In Paper I, the authors categorize the
observed AGNs into two groups: “new type” with $R \gtrsim 0.8$ and
$f_{\text{scat}} \lesssim 0.5\%$, and “classical type” with $R \lesssim 0.8$ and
$f_{\text{scat}} \gtrsim 0.5\%$. Since our targets are placed just between
the two types, it is not clear to which “type” these AGNs belong
if the intrinsic distribution is indeed distinct. It is also possible
that the distribution is smooth and that they actually represent
an intermediate class bridging the two types.

4. TORUS MODEL

Ikeda et al. (2009) performed a set of Monte Carlo simulations
to calculate a realistic reprocessed emission from the torus
irradiated by a central source, which is assumed to be a
cutoff power-law model. In the simulation, they assume a
three-dimensional axisymmetric uniform torus as illustrated in
Figure 6. It is characterized by the half-opening angle $\theta_{\text{inc}}$
the inclination angle of torus from an observer $\theta_{\text{obs}}$, the
hydrogen column density viewed from the equatorial plane $N_H^{\text{eq}}$,
and the ratio $r_{\text{in}}/r_{\text{out}}$.

4.1. Method

To perform spectral fitting on XSPEC with the Ikeda et al.
(2009) model, we utilize an atable model where the resultant
spectra from Monte Carlo calculations are stored at grids of the
torus parameters in FITS files. Here, we refer to the results of the
continuum reprocessed from the torus (“torus-reflection com-
ponent”) and those of the iron-K fluorescence line, assuming the
geometry with \( r = r_{\text{in}}/r_{\text{out}} = 0.01 \). The cutoff energy is fixed at \( E_{\text{cut}} = 360 \text{ keV} \) throughout our analysis, which is consistent with the constraints from the Swift/BAT spectra for both targets (>300 keV). Since the fit is performed only in the 0.5–100 keV range where the table model is available, the choice of \( E_{\text{cut}} \) hardly affects our results as long as it is higher than \( \sim 300 \text{ keV} \).

We consider two cases for the elemental abundances; “solar” abundances (as defined by Anders & Grevesse 1989) and “sub-solar” ones, where only those of iron and nickel are set to be 0.5 times the solar values. Finally, the table files have five free parameters: \( N_{H}^{\text{Ei}}, \theta_{oa}, \theta_{\text{inc}}, \) the photon index \( \Gamma \) of the incident continuum, and its normalization at 1 keV.

In the assumed geometry of the torus, the line-of-sight hydrogen column density \( N_{H} \) for the transmitted component is related to that along the equatorial plane \( (N_{H}^{\text{Eq}}) \) via Equation (3) in Ikeda et al. (2009):

\[
\frac{N_{H}}{N_{H}^{\text{Eq}}} = \frac{r (\cos \theta_{\text{inc}} - \cos \theta_{oa}) + \sin (\theta_{\text{inc}} - \theta_{oa})}{(1 - r) [r \cos \theta_{\text{inc}} + \sin (\theta_{\text{inc}} - \theta_{oa})]}. \tag{1}
\]

Figure 3. Time variability of the best-fit parameters of NGC 3081 obtained with the analytical model: from left to right and from top to bottom, (a) the line-of-sight hydrogen column density for the transmitted component, (b) the power-law photon index, (c) the fraction of the scattered component relative to the intrinsic power law, (d) the center energy of the iron-K emission line at the rest frame, (e) the EW of the iron-K line with respect to the whole continuum, (f) the line-of-sight hydrogen column density for the reflection component, (g) the solid angle of the reflection component, (h) the 2–10 keV intrinsic luminosity corrected for the absorption.
Table 4

| Targets | Best-fit model | NGC 612 | NGC 3081 |
|---------|---------------|---------|----------|
| (1)     | $N_H^{\text{eq}} \left(10^{22} \text{ cm}^{-2}\right)$ | 0.0195  | 0.0388   |
| (2)     | $N_H \left(10^{22} \text{ cm}^{-2}\right)$ | 111.5 ± 5 | 98 ± 4    |
| (3)     | $Z_{\text{Fe}}$ | 0.54$^{+0.10}_{-0.07}$ | 0.89 ± 0.07 |
| (4)     | $f_{\text{scat}}$ | 1.90 ± 0.04 | 1.88 ± 0.02 |
| (5)     | $f_{\text{scat}} \%$ | 0.55 ± 0.06 | 0.73 ± 0.07 |
| (6)     | $E_{\text{scat}} \left(\text{keV}\right)$ | 6.4$^{+0.03}_{-0.02}$ | 6.41 ± 0.02 |
| (7)     | E. W. (keV) | 0.28 ± 0.06 | 0.35 ± 0.05 |
| (8)     | E.W.$^{\text{refl}}$ (keV) | 0.7 ± 0.1 | 1.0 ± 0.1 |
| (9)     | $N_H^{\text{eq}} \left(10^{22} \text{ cm}^{-2}\right)$ | ($= N_{\text{H}}$) | 16$^{+4}_{-3}$ |
| (10)    | $R$ | 0.6 ± 0.2 | 0.9 ± 0.2 |
| (11)    | $F_{2-10} \left(\text{erg cm}^{-2} \text{s}^{-1}\right)$ | 1.6 × 10$^{-12}$ | 2.7 × 10$^{-12}$ |
| (12)    | $F_{10-50} \left(\text{erg cm}^{-2} \text{s}^{-1}\right)$ | 1.9 × 10$^{-11}$ | 3.1 × 10$^{-11}$ |
| (13)    | $L_{2-10} \left(\text{erg s}^{-1}\right)$ | 3.0 × 10$^{39}$ | 3.0 × 10$^{42}$ |
| $\chi^2$/d.o.f. | 100.4/91 | 199.3/199 |

Notes. (1) The hydrogen column density of Galactic absorption by Kalberla et al. (2005). (2) The line-of-sight hydrogen column density for the transmitted component. (3) The iron abundance relative to the solar value. (4) The power-law photon index. (5) The fraction of the scattered component relative to the intrinsic power law. (6) The center energy of the iron-K emission line at the rest frame of the source redshift. (7) The observed EW of the iron-K line with respect to the whole continuum. (8) The observed EW of the iron-K line with respect to the reflection component. (9) The line-of-sight hydrogen column density for the reflection component. (10) The relative strength of the reflection component to the transmitted one, defined as $R = \Omega / 2\pi$, where $\Omega$ is the solid angle of the reflector viewed from the nucleus. (11) The observed flux in the 2–10 keV band. (12) The observed flux in the 10–50 keV band. (13) The 2–10 keV intrinsic luminosity corrected for the absorption. The errors are 90% confidence limits for a single parameter.

* An additional emission from an optically thin thermal plasma is required, modeled by the vpec code with a temperature of $kT = 0.26 \pm 0.02$ keV and an emission measure of $1.5 \times 10^{68}$ cm$^{-3}$. The iron abundance is linked to that in the absorber of the transmitted component (see the text).

We introduce torusabs (for the fixed solar abundances) and vtorusabs models (for variable abundances) as local models of XSPEC to represent photoelectric absorption of the transmitted component, whose line-of-sight column density is related to the torus parameters according to the above equation. In these models we take into account Compton scattering processes in addition to photoelectric absorption, and hence they can be reliably used even for the Compton-thick case. We adopt the photoelectric absorption cross section by Verner et al. (1996) for consistency with Ikeeda et al. (2009). As noted by Ikeeda et al. (2009), the cross section by Verner et al. (1996) is more accurate for energies above 10 keV than that by Balucinska-Church & McCammon (1992), and is nearly equal to the NIST XCOM database. Since the results become physically meaningless for obscured AGNs if we obtain $\theta_{\text{inc}} < \theta_{\text{oa}}$, we impose the condition that $\theta_{\text{inc}} > \theta_{\text{oa}} + 10^\circ$ in the fitting process.

The fraction of the scattered component to the transmitted component, $f_{\text{scat}}$, should be proportional to the opening solid angle of the torus if the column density of the scattering gas is constant. Thus, we have the constraint that

$$\cos \theta_{\text{oa}} = 1 - \frac{f_{\text{scat}}}{f_{\text{scat,0}}} (1 - \cos \theta_{\text{oa},0}),$$

where we normalize $f_{\text{scat}} = f_{\text{scat,0}}$ at $\theta_{\text{oa}} = \theta_{\text{oa},0} = 45^\circ$. Similarly, we also developed the fscat model for XSPEC to calculate the normalization of the scattered emission as a function of two parameters, $\theta_{\text{oa}}$ and $f_{\text{scat,0}}$. Here, the normalization parameter $f_{\text{scat,0}}$ reflects the averaged column density of the scattering gas and is treated as a free parameter. We allow it to vary within 0.1%–5%; note that the typical value in Seyfert 2 galaxies is $f_{\text{scat}} = 3\%$ (Guainazzi et al. 2005).

In addition to the reprocessed emission from the torus, we should also expect a reflection component from the accretion disk in AGN spectra. Thus, in the transmitted component, we include this effect by utilizing the pexrav model (Magdziarz & Zdziarski 1995), which is appropriate to represent the reflection component from the semi-infinite plane, such as that from accretion disks. Here, we fix the strength of the disk reflection to be $R = \Omega / 2\pi = 1$, where $\Omega$ is the solid angle of the accretion disk. The inclination angle of the accretion disk is linked to that of the torus. Although the contribution of this component is not included in the incident photon spectrum in the Ikeeda et al. (2009) model, the effects of the “torus-reflection” spectra are only of second order and are negligible. For simplicity, hereafter we refer to the total spectrum including the reflection component from the accretion disk as the “torus model.”

To summarize, we can write the torus model of the photon spectrum $F(E)$ without the Galactic absorption as follows:

$$F(E) = \exp \left\{ -N_{\text{H}}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}}) \sigma(E) \right\} I(E) + f_{\text{scat}}(\theta_{\text{oa}}, f_{\text{scat,0}}) I(E) + \exp \left\{ -N_{\text{H}}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}}) \right\} R_{\text{disk}}(\theta_{\text{inc}}, E) + R_{\text{refl},1}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}}) + R_{\text{refl},2}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}}) + \epsilon_{\text{Fe}} L_{\text{Fe}}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}}) + S(E),$$

where $I(E) \equiv AE^{-1} \exp (-E/E_{\text{cut}})$ is the intrinsic cutoff power-law component, $A$ is the normalization parameter of the intrinsic cutoff power law at 1 keV, $N_{\text{H}}^{\text{eq}}$ is the hydrogen column density of the torus viewed from the equatorial plane, $\theta_{\text{oa}}$ is the half-opening angle of the torus, $\theta_{\text{inc}}$ is the inclination angle of the torus, $f_{\text{scat,0}}$ is the normalization parameter at $\theta_{\text{oa}} = 45^\circ$, $N_{\text{H}}^{\text{eq}}(\theta_{\text{oa}}, \theta_{\text{inc}})$ is the absorption column density for the transmitted component, $\sigma(E)$ is the cross section of photoelectric absorption, $f_{\text{scat}}(\theta_{\text{oa}}, f_{\text{scat,0}})$ is the scattered fraction, $R_{\text{disk}}(\theta_{\text{inc}}, E)$ is the Compton reflection component from the accretion disk, $R_{\text{refl},1}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}})$ is the torus-reflection component 1 (see Figure 6), $R_{\text{refl},2}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}})$ is the torus-reflection component 2 (see Figure 6), $\epsilon_{\text{Fe}}$ is the normalization parameter for the iron-K emission line, $L_{\text{Fe}}(N_{\text{eq}}^{\text{E}}, \theta_{\text{oa}}, \theta_{\text{inc}})$ is the iron-K emission line, and $S(E)$ represents additional soft components (for the case of NGC 3081 where the apec model is used). We allow the relative normalization of the iron-K line $L_{\text{Fe}}$ with respect to the torus-reflection components to float between 0.5 and 2, in order to cover the iron abundance range over the fixed values (0.5 or 1.0) and to model the effects of time variability between the transmitted component and the averaged reprocessed emission.

In short, Equation (3) is expressed as absorbed transmission$^{13}$ + scattering$^{14}$ + absorbed accretion disk reflection$^{15}$ + absorbed

---

12 http://www.nist.gov/pml/data/xcom/index.cfm
13 In XSPEC nomenclature. torusabs*highg*ht*photo*wl
14 In XSPEC nomenclature. fscat*highg*ht*photo*wl
15 In XSPEC nomenclature. torusabs*torus*photo*wl
torus reflection\textsuperscript{16} + unabsorbed torus reflection\textsuperscript{17} + iron line\textsuperscript{18}. There are eight free parameters: $\theta_{\text{inc}}$, $\theta_{\text{oa}}$, $N_{\text{H}}$, $f_{\text{scat}}$, $E_{\text{cen}}$, $E_{\text{Fe}}$, $A$, and $\Gamma$. In the spectral fit, we employ the MINUIT MIGRAD method (“migrad”) as the fitting algorithm, which is found to be more stable than the standard Levennerg–Marquardt method (“leven”) in our case utilizing the numerical models. Both of the Suzaku and BAT spectra (but below 100 keV) are used throughout this section.

4.2. Application

4.2.1. NGC 612

Figure 7 plots the best-fit torus model, whose parameters are summarized in Table 5. The torus model with “subsolar” abundances is adopted for this target, based on the fitting result with the analytical models (Section 3). We find that $\theta_{\text{oa}} \simeq 60^\circ$–$70^\circ$ and $\theta_{\text{inc}} \gtrsim 76^\circ$. As shown in Figure 7, the contribution from the reflection component 2 (unabsorbed one) is very small, suggesting that we are seeing the target from

\textsuperscript{16} In XSPEC nomenclature, \texttt{atable[refl1_torus.fits]}
\textsuperscript{17} In XSPEC nomenclature, \texttt{atable[refl2_torus.fits]}
\textsuperscript{18} In XSPEC nomenclature, \texttt{constant*atable[refl_fe_torus.fits]}

Figure 5. Correlation between the strength of the Compton reflection component ($R = \Omega/2\pi$) and the fraction of the scattered component ($f_{\text{scat}}$) for our targets (filled circles), superposed on the same figure taken from Paper I, where open circle and open diamond represent “new type” ($R \gtrsim 0.8$ and $f_{\text{scat}} \lesssim 0.5\%$) and “classical type” ($R \lesssim 0.8$ and $f_{\text{scat}} \gtrsim 0.5\%$) AGNs, respectively.

(A color version of this figure is available in the online journal.)
The torus structure is characterized by the half-opening angle $\theta_{oa}$, the inclination angle of the torus from an observer $\theta_{inc}$, the hydrogen column density viewed from the equatorial plane $N_{H}^{\text{eq}}$, and the ratio of $r_{\text{in}}$ to $r_{\text{out}}$. The observed lights consist of a transmitted component absorbed by the torus (dashed red), a reflection component from the accretion disk absorbed by the torus (dashed red), and two reflection components by the torus: “reflection component 1” absorbed by the torus (dash-dotted blue) and “reflection component 2” not absorbed by it (dashed orange). We also consider a scattered component by the surrounding gas, which is not absorbed by the torus (dash-dotted cyan).

(A color version of this figure is available in the online journal.)

Figure 7. Observed spectra (left) and the best-fit spectral model (right) with the torus model. Left: same as Figure 4 (left). Right: the best-fit spectral model in units of $E_{PE}$ (where $E$ is the energy and $F_{E}$ is the photon spectrum); total (thick black) transmitted component (thick dashed red), reflection component from the accretion disk (thin dotted-dashed green), torus-reflection component 1 (thin blue), torus-reflection component 2 (thin dotted orange), scattered component (thin dotted-dashed cyan), and iron-K emission line (thin dotted-dashed magenta). The purple dashed curve below 2 keV in NGC 3081 represents the emission from an optically thin thermal plasma.

(A color version of this figure is available in the online journal.)
First, we found a broadband spectra covering the 0.5–60 keV band of two torus and is observed from a rather face-on angle.

The best-fit parameters with the torus model for NGC 3081

| Targets        | NGC 612 | NGC 3081 |
|---------------|---------|----------|
| (1) Table model | Solar + apec\(\text{a}\) | Solar + apec\(\text{a}\) |
| (2) \(N_H^\text{subsol} (10^{24} \text{ cm}^{-2})\) | 0.0195 | 0.0388 |
| (3) \(N_H^\text{NGC 612} (10^{24} \text{ cm}^{-2})\) | 113^{+10}_{-8} | 91^{+10}_{-9} |
| (4) \(\theta_\text{inc}\) (degrees) | 70 (>58) | 15 ± 2 |
| (5) \(\theta_\text{inc}\) (degrees) | 87 (>76) | 19\(\text{a}\) |
| (6) \(\Gamma\) | 1.9 ± 0.1 | 2.0 ± 0.1 |
| (7) \(f_\text{scat} (\%)\) | 0.14 (<0.19) | 4.6 (>3.1) |
| (8) \(E_\text{esc} (\text{keV})\) | 6.43^{+0.11}_{-0.02} | 6.42^{+0.03}_{-0.06} |
| (9) \(\epsilon_{\text{Fe}}\) | 1.6^{+0.4}_{-0.4} | 0.57 (<0.69) |

Notes. (1) The Table model used in the fit. “Solar” means the table with solar abundances, while “subsol” means the table with 0.5 times iron and nickel abundances with respect to solar ones. (2) The hydrogen column density of Galactic absorption by Kalberla et al. (2005). (3) The hydrogen column density of the torus viewed from the equatorial direction. (4) The half-opening angle of the torus. (5) The inclination angle of the torus. (6) The power-law photon index. (7) The fraction of the scattered component relative to the intrinsic power law when the half-opening angle of the torus is 45\(\text{a}\). (8) The center energy of the iron-K emission line at the rest frame of the source redshift. (9) The relative strength of the iron-K emission line to that predicted by the torus model.

The errors are 90% confidence limits for a single parameter.

\(\text{a}\) An additional emission from an optically thin thermal plasma with solar abundances is required, modeled by the apec code with a temperature of \(kT = 0.25 \pm 0.02\) keV and an emission measure of \(1.5 \times 10^{62} \text{ cm}^{-3}\) (see the text).

\(\text{b}\) The range of the \(\theta_\text{inc}\) is limited to <70\(\text{a}\) in the torus model.

an edge-on angle. In such case, the inclination angle \(\theta_\text{inc}\) can be poorly determined above a certain threshold, because the observed line-of-sight hydrogen column density is rather insensitive to \(\theta_\text{inc}\) for a given \(N_H^\text{eq}\) value. Actually, we find that the column density in the equatorial plane, \(N_H^\text{eq}\) \(\approx 10^{24.1} \text{ cm}^{-2}\), is close to that along the line of sight (\(N_H\)) as estimated from the analytical model fit. We also find that \(f_\text{scat} < 0.14\%\), which indicates that the amount of scattering gas around the nucleus is remarkably small.

4.2.2. NGC 3081

The best-fit parameters with the torus model for NGC 3081 are summarized in Table 5, and the model is plotted in Figure 7. For this target, we adopt the “solar” abundance tables based on the analytical model fit. We obtain \(\theta_\text{inc} \approx 15\text{a}, \theta_\text{inc} \approx 19\text{a}, \text{N}_H^\text{eq} \approx 10^{24.1} \text{ cm}^{-2}\), and \(f_\text{scat} < 4.6\%\). In contrast to NGC 612, \(f_\text{scat} < 4.6\%\) is rather large, and there is a significant contribution from the unabsorbed reflection component, indicating that the inclination angle must be close to the torus opening angle. The results are consistent with the picture proposed for the “new type” AGN, SWIFT J0601.9–8636 (ESO 005–G004) by Ueda et al. (2007), wherein the nucleus is deeply buried in the geometrically thick torus and is observed from a rather face-on angle.

5. DISCUSSION AND CONCLUSION

With Suzaku followup, we have obtained the best-quality broadband spectra covering the 0.5–60 keV band of two Swift/BAT AGNs, NGC 612 and NGC 3081. First, we found a range in the iron abundance; NGC 612 has about 0.5 times solar abundance of iron (where “solar” corresponds to Fe/H = 4.68 \times 10^{-5}), which is significantly smaller than that of NGC 3081. Applying the analytical models, we find that these objects are nearly Compton-thick AGNs with \(N_H < 10^{24} \text{ cm}^{-2}\) and the fraction of the scattered component with respect to the transmitted component is small, \(f_\text{scat} < 0.8\%\), suggesting that these belong to a “hidden” population according to Winter et al. (2009). Plotting the results in the \(f_\text{scat} - r_{\text{in}}/r_{\text{out}}\) plane, we find that these two targets are located just between those occupied by “new type” (geometrically thick tori) and “classical type” AGNs defined in Paper I, implying that they would be an intermediate class bridging the two types. We need a larger sample to reveal the true distribution of the entire AGN population in this plane. In this context, simultaneous broadband observations of more “new type” candidates are important to examine their reflection strengths, like those with small scattering fractions identified from the XMM-Newton catalog (Noguchi et al. 2009).

To further investigate the details of the torus geometry of the two AGNs, we apply numerical spectral models based on Monte Carlo simulations where a simple three-dimensional geometry of the torus is assumed, following the works by Ikeda et al. (2009) and Awaki et al. (2009). We also consider the Compton reflection component from the accretion disk. To our knowledge, this is the first time all effects from both the torus and disk are self-consistently considered in spectral analyses of obscured AGNs. It is remarkable that we are able to reproduce the observed spectra quite well with this torus model, which has only three free geometrical parameters: the opening angle, inclination, and equatorial column density.

The column density along the equatorial plane is found to be \(N_H < 10^{24} \text{ cm}^{-2}\) for both sources, which is also similar to that found from the Seyfert 2 galaxy Mrk 3 by Ikeda et al. (2009). The relative absence of higher column densities, though very limited in number, may be consistent with the fact that even hard X-rays above 10 keV have a bias against detecting heavily Compton-thick AGNs with \(N_H > 10^{25} \text{ cm}^{-2}\), unless the sample is limited to the very local universe (Malizia et al. 2009). Thus, a majority of Swift/BAT AGNs do not have extremely Compton-thick tori defined at the equatorial plane unless observed from a face-on angle. Future sensitive hard X-ray surveys may start to pick up such populations, whose number density and cosmological evolution are still open questions.

The analysis with the torus model suggest that the torus geometry of the two targets may be different in spite of the very similar results obtained from the analytical models. Our results confirm that the fundamental assumption of the unified model where the opening angles are all the same is too simple. For NGC 612, we find that the opening angle is relatively large (>70\text{a}) and the object is observed from an edge-on angle, consistent with a picture of “classical type” Seyfert 2 galaxies. Similar torus parameters are obtained for Mrk 3 by Ikeda et al. (2009). In contrast, the torus opening angle of NGC 3081 is much smaller (<15\text{a}), and we observe it from a face-on angle. This implies that NGC 3081 is closer to a “new type” AGN discovered by Ueda et al. (2007) surrounded by a geometrically thick torus. This picture for NGC 3081 is consistent with the time variability of the column density, because we are seeing the thinnest part of the torus that is expected to be highly patchy (Risaliti et al. 2002). We note, however, that the best-fit torus parameters we obtain from the present analysis should not be taken at their face values, which could depend on the initial assumption of the torus geometry. For instance, as discussed in Ikeda et al. (2009), if we assume a lower value for \(r_{\text{in}}/r_{\text{out}}\) than 0.01, we would obtain a slightly larger half-opening angle.
\( \theta_\text{ac} \) for the same \( N_\text{H}^{\text{Ed}} \) and \( \theta_\text{sc} \) to account for the increased contribution of the unabsorbed reflection component.

Since the observed scattering fraction is similar between the two targets, this difference in the torus opening angle indicates that the amount of scattering gas around the nucleus is much smaller in NGC 621 than in NGC 3081, as represented in the obtained \( f_\text{scat,0} \) value, \( f_\text{scat,0} < 0.2\% \) for NGC 612, and \( f_\text{scat,0} > 3\% \) for NGC 3081. The small amount of gas in NGC 612 may be consistent with its classification as a “weak emission line” radio galaxy, where the jets expel the surrounding gas. In contrast, the detection of the optically thin components in NGC 3081 could represent the abundance of the ambient gas around the nucleus.

An important implication from the present study is that the classification of different types of tori (e.g., geometrically thin or thick) based solely on the scattered fraction may be difficult in some cases. Our work has demonstrated the power of the application of numerical torus models based on Monte Carlo simulation to best extract the physical view of the nucleus beyond the simple phenomenological spectral analysis, although caution must be taken because we have considered only the simplest geometry by assuming uniform density. Combinations of the high-quality broadband X-ray spectra with more realistic numerical simulations will be a key approach for further understanding the nature of AGNs.

This work was partly supported by the Grant-in-aid for JSPS Fellows for young researchers (SE), Scientific Research 20540230 (YU), 21244017 (HA), and 20740109 (YT), and JSPS Fellows for young researchers (SE), Scientific Research (B), 21244017, and (C), 20740109 (YT). The authors are grateful for the financial support from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Awaki, H., Terasima, Y., Higaki, Y., & Fukazawa, Y. 2009, PASJ, 61, 317
Balucinska-Church, M., & McCammon, D. 1992, ApJ, 400, 699
Bassani, L., et al. 2006, ApJ, 636, L65
Comastri, A., Iwasawa, K., Gilli, R., & Ranalli, P. 2009, arXiv:0910.1025
Comastri, A., Iwasawa, K., Gilli, R., Vignali, C., & Ranalli, P. 2009, ApJ, 717, 787

dotani, T., & the XIS team 2007, JX-ISAS-SUZAKU-MEMO-2007-08; http://www.astro.isas.ac.jp/suzaku/doc/suzakumemo/suzakumemo-2007-08.pdf
eguchi, S., Ueda, Y., Terasima, Y., Mushotzky, R., & Tueller, J. 2009, ApJ, 696, 1657
fanaroff, B. L., & riley, J. M. 1974, MNras, 167, 31P
freeman, T., Byrd, G., & Osley, D. 2000, in ASP Conf. Ser. 209, IAU Colloq. 174: Small Galaxy Groups, ed. M. J. Valtonen & C. Flynn (San Francisco, CA: ASP), 325
gilli, R., Comastri, A., & Hasinger, G. 2007, A&A, 463, 79
gopal-krishna, & wiita, P. J. 2000, A&A, 363, 507
Guainazzi, M., Matt, G., & Perola, G. C. 2005, A&A, 444, 119
Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Martini, P., Robertson, B., & Springel, V. 2005, ApJ, 630, 705
Ikeda, S., Awaki, H., & Terasima, Y. 2009, ApJ, 692, 608
Joshi, U. C., Jain, R., & Deshpande, M. R. 1989, in IAU Symp. 134, Active Galactic Nuclei, ed. D. E. Osterbrock & J. S. Miller (Dordrecht: Kluwer Academic Publishers), 321
Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Morras, R., & Poppe1, W. G. L. 2005, A&A, 440, 775
Krivoson, R., Revnivtsev, M., Lutovinov, A., Sazonov, S., Churazov, E., & Sunyaev, R. 2007, A&A, 475, 775
Maeda, Y., Someya, K., Ishida, M., & the XRT team, Hayashida, K., Mori, H., & the XIS team 2008, JX-ISAS-SUZAKU-MEMO-2008-06; http://www.astro.isas.ac.jp/suzaku/doc/suzakumemo/suzakumemo-2008-06.pdf
Magdziarz, P., & Zdziarski, A. A. 1995, MNras, 273, 837
Magorrian, J., et al. 1999, AJ, 115, 2285
Malizia, A., Stephen, J. B., Bassani, L., Bird, A. J., Panessa, F., & ubertiini, P. 2009, MNras, 599, 944
Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21
Matt, G., Perola, G. C., & Piro, L. 1991, A&A, 247, 25
Mitsuda, K., et al. 2007, PASJ, 59, 1
Mizuno, T., et al. 2008, JX-ISAS-SUZAKU-MEMO-2008-03; http://www.astro.isas.ac.jp/suzaku/doc/suzakumemo/suzakumemo-2008-03.pdf
Moran, E. C., Kay, L. E., Davis, M., Filippenko, A. V., & Barth, A. J. 2001, ApJ, 556, L77
Morganti, R., Killeen, N. E. B., & Tadhunter, C. N. 1993, MNras, 263, 1023
Murphy, K. D., & Yaqoob, T. 2009, MNras, 397, 1549
Nakajima, H., et al. 2008, PASJ, 60, 1
Nandra, K., & Pounds, K. A. 1994, MNras, 268, 405
Noguchi, K., Terasima, Y., & Awaki, H. 2009, ApJ, 705, 454
Ozawa, M., et al. 2009, PASJ, 61, 1
Parisi, P., et al. 2009, A&A, 507, 1345
Risaliti, G., Elvis, M., & Nicastro, F. 2002, ApJ, 571, 234
Storchi-Bergmann, T., Kinney, A. L., & Challis, P. 1995, ApJS, 98, 103
Tueller, J., Mushotzky, R. F., Barthelmy, S., Cannizzo, J. K., Gehrels, N., Markwardt, C. B., Skinner, G. K., & Winter, L. M. 2008, ApJ, 681, 113
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 866
Ueda, Y., et al. 2007, ApJ, 664, L79
Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, ApJ, 465, 487
Winter, L. M., Mushotzky, R. F., Reynolds, C. S., & Tueller, J. 2009, ApJ, 690, 1322
Winter, L. M., Mushotzky, R. F., Tueller, J., & Markwardt, C. 2008, ApJ, 674, 686

This work was partly supported by the Grant-in-aid for JSPS Fellows for young researchers (SE), Scientific Research 20540230 (YU), 21244017 (HA), and 20740109 (YT), and by the Grant-in-aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” by the Grant-in-aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence”