1. INTRODUCTION

X-ray surveys of active galactic nuclei (AGNs) have revealed that the cosmological evolution of AGN luminosity function is well described by the luminosity-dependent density evolution characterized by “down-sizing,” where the low-luminosity AGNs (LLAGNs) show the peak of their comoving space density at lower redshift than that of high-luminosity ones (e.g., Ueda et al. 2003; Hasinger et al. 2005). It is being confirmed that the cosmological evolution of AGN luminosity function is characterized by “down-sizing,” where the low-luminosity AGNs show the peak of their comoving space density at lower redshift than that of high-luminosity ones (e.g., Ueda et al. 2003; Hasinger et al. 2005). We do not significantly detect a broad iron-Kα line from the inner accretion disk in both targets, and obtain an upper limit on the corresponding solid angle of Ω/2π < 0.3 in NGC 1566. The reflection strength from the torus is moderate, Ω/2π = 0.45±0.15 in NGC 1566 and Ω/2π = 0.64±0.07 in NGC 4941. Comparison of the equivalent width of the narrow iron-Kα line with a model prediction based on a simple torus geometry constrains its half-opening angle to be θ_{tot} ≃ 60°–70° in NGC 4941. These results agree with the obscured AGN fraction obtained from hard X-ray and mid-infrared selected samples at similar luminosities. Our results support the implication that the averaged covering fraction of AGN tori is peaked at L ∼ 10^{42–43} erg s^{-1} but decreases toward lower luminosities.

Key words: galaxies: active – galaxies: individual (NGC 1566, NGC 4941) – X-rays: galaxies

Online-only material: color figures

BROADBAND X-RAY SPECTRA OF TWO LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI
NGC 1566 AND NGC 4941 OBSERVED WITH SUZAKU

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Received 2013 February 8; accepted 2013 May 1; published 2013 June 6

ABSTRACT

We report the first broadband X-ray spectra of the low-luminosity active galactic nuclei (LLAGNs), NGC 1566 (type 1.5) and NGC 4941 (type 2), observed with Suzaku and Swift/BAT covering the 0.5–195 keV band. Both targets have hard X-ray luminosities of ∼10^{41–42} erg s^{-1} in the 15–55 keV band. The spectra of the nucleus are well reproduced by a sum of partially or fully covered transmitted emission and its reflection from the accretion disk, reprocessed emission from the torus accompanied by a strong narrow iron-Kα line, and a scattered component (for NGC 4941). We do not significantly detect a broad iron-Kα line from the inner accretion disk in both targets, and obtain an upper limit on the corresponding solid angle of Ω/2π < 0.3 in NGC 1566. The reflection strength from the torus is moderate, Ω/2π = 0.45±0.15 in NGC 1566 and Ω/2π = 0.64±0.07 in NGC 4941. Comparison of the equivalent width of the narrow iron-Kα line with a model prediction based on a simple torus geometry constrains its half-opening angle to be θ_{tot} ≃ 60°–70° in NGC 4941. These results agree with the obscured AGN fraction obtained from hard X-ray and mid-infrared selected samples at similar luminosities. Our results support the implication that the averaged covering fraction of AGN tori is peaked at L ∼ 10^{42–43} erg s^{-1} but decreases toward lower luminosities.

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Key words: galaxies: active – galaxies: individual (NGC 1566, NGC 4941) – X-rays: galaxies

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was estimated to be $L_{2-10} \sim 10^{41.5}$ erg s$^{-1}$ for an assumed photon index of $\Gamma = 1.7$ (Levenson et al. 2009). Using archival data of the ROSAT High Resolution Imager, Liu & Bregman (2005) detected four ultraluminous X-ray sources within NGC 1566, whose summed luminosity is $\sim 10^{40}$ erg s$^{-1}$ in the 0.3–8 keV band. Thus, we neglect their contribution except for the flux normalization between the first and second exposure of XIS-3) as focal plane detectors of four X-Ray Telescopes (XIS-0, XIS-1, XIS-2, and XIS-3) as focal plane detectors of four X-Ray Telescopes (BeppoSAX). The X-Ray Imaging Spectrometer (XIS-0, XIS-1, XIS-2, and XIS-3) as focal plane detectors of four X-Ray Telescopes (BeppoSAX), and the Eddington ratio $\log L_{\text{bol}}/L_{\text{Edd}} \approx 2.4$ from the Swift/BAT one for $\Gamma = 2.0$ (our best-fit). Here we assume a bolometric correction factor of $L_{\text{bol}}/L_{\text{bol}} \approx 10$ (Ho 2009; Vasudevan et al. 2009).

NGC 4941 is a Seyfert 2 galaxy (Véron-Cetty & Véron 2006) with a morphology type of Sa (Fisher & Drory 2008). In the X-ray band, this source was observed with ASCA in 1996 July and 1997 January (Terashima et al. 2002; Cardamone et al. 2007), with BeppoSAX in 1997 January (Maiolino et al. 1998), and with Chandra in 2011 March (Bottacini et al. 2012). The ASCA and BeppoSAX observations reveal that the spectra are heavily absorbed with a strong iron-K$\alpha$ emission line. As the BeppoSAX/PDS data above 10 keV are not usable due to the poor statistics (Maiolino et al. 1998), our Suzaku data provide the first simultaneous broadband X-ray spectra in the 0.5–30 keV band from this source. The black hole mass of NGC 4941 is estimated to be $\log M_{\text{BH}}/M_\odot \approx 6.9$ (Asmus et al. 2011), and the Eddington ratio is $\log L_{\text{bol}}/L_{\text{Edd}} \approx 2.4$ from the Swift/BAT luminosity with $\Gamma = 1.9$ and $L_{\text{bol}}/L_{\text{bol}}^{2-10} = 10$.

The organization of this paper is as follows. Section 2 describes the observations and data reduction. The analysis and results are presented in Section 3. A discussion and our conclusions are given in Section 4. Throughout the paper, we adopt distances of 16.5 Mpc for NGC 1566 and 19.7 Mpc for NGC 4941 (Theureau et al. 2007) in calculating the luminosities unless otherwise stated. In all spectral analysis, we apply the Galactic absorption fixed at $N_{\text{H}} = 8.61 \times 10^{19}$ cm$^{-2}$ for NGC 1566 and $2.17 \times 10^{20}$ cm$^{-2}$ for NGC 4941, which are estimated from the H I map (Kalberla et al. 2005). The solar abundances by Anders & Grevesse (1989) are assumed in all cases. The errors attached to spectral parameters are given at 90% confidence limits for a single parameter of interest.

## 2. OBSERVATION AND DATA REDUCTION

### 2.1. Observations

We observed NGC 1566 and NGC 4941 with Suzaku (Mitsuda et al. 2007) in 2012 May and June, respectively, for a net exposure of $\sim$80 ks each. Suzaku is the Japan–U.S. X-ray astronomy satellite. It carries four X-ray CCD cameras called X-Ray Imaging Spectrometer (XIS-0, XIS-1, XIS-2, and XIS-3) as focal plane detectors of four X-Ray Telescopes (XIS-0, XIS-1, XIS-2, and XIS-3) as focal plane detectors of four X-Ray Telescopes (XIS-0, XIS-1, XIS-2, and XIS-3) as focal plane detectors of four X-Ray Telescopes (XIS-0, XIS-1, XIS-2, and XIS-3) as focal plane detectors of four X-Ray Telescopes. The XIS-3 (CALDB) released on 2012 September 12.

The XIS events are extracted from a circular region with a radius of 2.8 arcmin (NGC 1566) or 1.8 arcmin (NGC 4941) around the peak of the point-spread function of the XRT. The background is taken from source-free, circular regions within the field of view. We only use the PIN data from the HXD, as our targets are too faint in the energy band above 50 keV to be detected with the GSO. We utilize the so-called tuned non-X-ray background (NXB) model of HXD/PIN produced with the LCFITDT method (Fukazawa et al. 2009). Then, the modeled cosmic X-ray background spectrum based on the formula of Gruber et al. (1999) is added on that of the NXB. The systematic error of the NXB is estimated to be $\pm 0.34\%$ in the 15–40 keV band for a unit of 40 ks exposure, which does not significantly affect our results.

### 2.2. Data Reduction

We analyze the Suzaku data using the HEAsoft version 6.12 package, starting from the unfiltered event data produced by the pipeline processing version 2.7.16.33. The spectral analysis is performed on XSPEC version 12.7.1. To apply the latest energy calibration of XIS, we reprocess the unfiltered data with the @xisrepro and xisrepro on the basis of the calibration database (CALDB) released on 2012 September 12.

The XIS events are extracted from a circular region with a radius of 2.8 arcmin (NGC 1566) or 1.8 arcmin (NGC 4941) around the peak of the point-spread function of the XRT. The background is taken from source-free, circular regions within the field of view. We only use the PIN data from the HXD, as our targets are too faint in the energy band above 50 keV to be detected with the GSO. We utilize the so-called tuned non-X-ray background (NXB) model of HXD/PIN produced with the LCFITDT method (Fukazawa et al. 2009). Then, the modeled cosmic X-ray background spectrum based on the formula of Gruber et al. (1999) is added on that of the NXB. The systematic error of the NXB is estimated to be $\pm 0.34\%$ in the 15–40 keV band for a unit of 40 ks exposure, which does not significantly affect our results.

### 2.3. Light Curves

Figure 1 shows the background-subtracted light curves of NGC 1566 and NGC 4941 in the 2–10 keV band (XIS0 + XIS3; upper panel), $f_{2-10}$, and in the 16–40 keV band (PIN; middle), $f_{16-40}$. The lower panels plot the hardness ratio between the above two energy bands, $f_{16-40}/f_{2-10}$. The bin size is set to be 5760 s (orbital period of Suzaku) to exclude any modulations that depend on orbital phase. As noted from the figure, the 2–10 keV flux of NGC 1566 slightly increased around $t \sim 50$ ks since the start of the observation, although it is not evident in the 16–40 keV band. We find, however, no differences over statistical errors in the best-fit spectral parameters of NGC 1566 except for the flux normalization between the first and second half of the observation. The XIS and PIN light curves of

| Target Name | NGC 1566 | NGC 4941 |
|-------------|----------|----------|
| Start Time (UT) | 2012 May 19 1:36 | 2012 Jun 22 11:16 |
| End Time (UT) | 2012 May 20 6:34 | 2012 Jun 24 5:52 |
| Exposure (XIS) (ks) | 72.8 | 80.8 |
| Exposure (HXD/PIN) (ks) | 76.9 | 72.0 |

Note. Based on the good time interval of XIS-0.

| Target Name | NGC 1566 | NGC 4941 |
|-------------|----------|----------|
| SWIFT ID | SWIFT J0420.0-5457 | SWIFT J1304.3-0532 |
| R.A. (J2000) | 04 20 00.42 | 13 04 13.14 |
| Decl. (J2000) | -54 56 16.1 | -05 33 05.8 |
| Redshift | 0.0050 | 0.0037 |
| Classification | Seyfert 1.5 | Seyfert 2 |

Note. The position of each source is taken from the NASA/IPAC Extragalactic Database.
NGC 4941 suggest only weak flux variation. Thus, we analyze the time-averaged spectra of Suzaku for both targets.

3. ANALYSIS AND RESULTS

3.1. Broadband Spectral Analysis

For spectral analysis, we use the data of FI-XISs (XIS0 + XIS3), BI-XIS (XIS1), and HXD/PIN in the energy band of 1–12 keV, 0.5–8 keV, and 16–60 keV (16–30 keV for NGC 4941), respectively, where sufficient signal-to-noise ratio is achieved. To obtain better constraint on the hard X-ray spectra, we include the Swift/BAT spectra in the 14–195 keV band averaged over 70 months (Baumgartner et al. 2012). The 1.7–1.9 keV band in the XIS spectra is excluded to avoid systematic uncertainties in the energy response around the Si K-edge region. The Suzaku spectra folded with the responses are plotted in the upper panels of Figure 2. The Swift/BAT spectra in the photon flux unit are also shown there. As noted, the spectrum of NGC 1566 is essentially unabsorbed, while that of NGC 4941 is subject to heavy absorption. Conspicuous iron-Kα emission lines are noted at the rest-frame 6.4 keV in both targets.

We simultaneously fit the Suzaku and Swift/BAT spectra, which cover the wide energy range of 0.5–195 keV altogether. To absorb the cross-calibration error in absolute fluxes between the XISs and the HXD, the relative normalization of the HXD/PIN to FI-XISs is fixed to be 1.16 according to the result based on the Crab Nebula observations (Maeda et al. 2008), while that between BI-XIS and FI-XISs is set free because they cover the similar energy bands and even a small systematic error in their relative flux calibration would affect the fit significantly. We do not apply such correction for instrumental calibration between the Suzaku and Swift/BAT data, although time variability between the two periods is taken into account, as detailed below.

We follow previous work by Tazaki et al. (2013), who constrain the torus structures of two very luminous radio-loud AGNs, 3C 206 and PKS 0707–35, by applying a physically motivated spectral model to the data of Suzaku and Swift/BAT. In this paper we basically adopt the same model as in Tazaki et al. (2013), which is composed of four components for the nucleus emission: (1) the primary transmitted component from the nucleus, (2) reflection component from the accretion disk, (3) that from the torus, and (4) scattered component from
surrounding gas in the case of absorbed AGN (NGC 4941). In addition, we also consider emission from an optically thin thermal plasma in the host galaxy, which is often observed from LLAGNs as “soft excess” below ~1 keV (Terashima et al. 2002). It is modeled with the apec model (Smith et al. 2001) on XSPEC.

We approximate the shape of the primary continuum with an exponential cutoff power-law model, \( E^{-\gamma} \exp(-E/E_{\text{cut}}) \). Since it is not possible to set a meaningful limit on \( E_{\text{cut}} \) from our data, we fix it at 360 keV for consistency with the torus model by Ikeda et al. (2009). Even if we instead set \( E_{\text{cut}} \) at 300 keV, an averaged value in nearby AGNs reported by Dadina (2008), the results of our spectral fits are little affected.

Time variability of the direct component flux is expected between the short (2 days) Suzaku observation and the long (70 months) Swift/BAT observations. To reflect it, we introduce a normalization factor of Suzaku (FI-XISs) relative to the Swift/BAT, NormXIS, as a free parameter, assuming that the continuum shapes (i.e., \( \Gamma \) and \( E_{\text{cut}} \)) are constant. The same factor is also applied to the reflection component from the accretion disk, while we do not apply it to that from the torus, the scattered component, and the thin thermal emission, assuming that their fluxes do not change over years because of their large spatial scales.

For calculation of the reflection components, we utilize the pexmon model (Nandra et al. 2007), which consists of the continuum of the pexrav model (Magdziarz & Zdziarski 1995) from cold matter and fluorescence lines of iron-K\( \alpha \), iron-K\( \beta \), and nickel-K\( \alpha \) self-consistently calculated with the continuum. The only free parameter of the model is the reflection strength \( R \equiv \Omega/2\pi r_s \), where \( \Omega \) is the solid angle of the reflector covering the X-ray source. As for the reflection component from the accretion disk, we apply blurring due to Kepler motion and relativistic effects around a non-rotating black hole with the convolution model rdblur.

One important goal is to constrain the torus structure through its reflection component \( R_{\text{torus}} \). Since the two reflection components from the torus and accretion disk are strongly coupled with each other in spectral fit, we need to fix the reflection strength from the accretion disk on the basis of reasonable assumptions. Following Tazaki et al. (2013), we estimate a value of \( R \) from the disk (\( R_{\text{disk}} \)) by combining a theoretical equivalent width of an iron-K\( \alpha \) line given by George & Fabian (1991) and the pexmon reflection code. George & Fabian (1991) calculates the iron-K\( \alpha \) equivalent width from an optically thick plane irradiated by a primary X-ray source above it for three parameters, (1) ratio between the height of the source \( h_s \) and the inner radius of the disk \( r_s \), (2) inclination, and (3) photon index. We assume \( h_s = 10r_s \) \( (r_s \equiv GM/c^2 \) is the gravitational radius where \( G, M \), and \( c \) are the gravitational constant, black hole mass, and light velocity, respectively). Some works suggest that the accretion disk of LLAGNs with \( L_{2-10} < 10^{42} \text{ erg s}^{-1} \) is not extending down to the innermost stable circular orbit, but likely to be truncated at much larger radii, \( \sim 10^3 r_s \) (e.g., Quataert et al. 1999 for M81 and NGC 4579; Ptak et al. 2004 for NGC 3998; Nemmen et al. 2006 for NGC 1097). We thus adopt the inner radius to be \( 100r_s \) in our models.

The inclination is assumed to be \( 30^\circ \) for NGC 1566 (unobscured AGN) and \( 70^\circ \) for NGC 4941 (obscured AGN). We consider a range of photon index of \( \Gamma = 1.9-2.1 \) as obtained from our data. The expected equivalent width of the iron-K\( \alpha \) line is then calculated to be \( 15-21 \text{ eV} \) (NGC 1566) and \( 14-16 \text{ eV} \) (NGC 4941). We find that the corresponding reflection strength of the pexmon model that produces these values becomes \( R_{\text{disk}} \approx 0.1 \) in both targets. We confirm that the spectral parameters obtained from the broadband fits are not changed over the 90% confidence errors even if we assume different inclination angles within a range of \( 20^\circ-60^\circ \) for NGC 1566 and \( 30^\circ-80^\circ \) for NGC 4941. Effects by changing \( r_{\text{in}} \) or \( h_s \) (and hence \( R_{\text{disk}} \)) will be examined in the following subsections, which do not affect our conclusions, either.

### 3.1.1. NGC 1566

We first apply a simple model without any intrinsic absorption composed of the transmitted emission and torus reflection component to the spectra of NGC 1566, which is optically classified as a type 1.5 AGN. The latter is required to explain the strong narrow iron-K line. The model is represented as

\[
\text{constant} \ast \text{zpowlerw} \ast \text{zhihect} \ast \text{pexmon}
\]

in XSPEC terminology. The constant term takes into account flux variability of the direct component between the observation epochs of Suzaku and Swift/BAT, and the power-law normalizations in the two terms are tied together. The inclination angle in the pexmon model is set to \( 60^\circ \) as a representative value, since the code assumes reflection from a half-infinite plane, which is too simple to be applied for a complex torus-like geometry. Changing it to \( 30^\circ \), however, does not affect our fitting results within the errors. Since a majority of the torus reflection in type-1 AGNs can arise from its inner wall without self obscuration (see, e.g., Ikeda et al. 2009 for an example of torus geometry), we do not apply any absorption to this component. The resultant \( \chi^2 \) value is not acceptable, \( \chi^2/\text{dof} = 279.6/186 \).

To improve the fit, we add a partial covering model to the first component, which is known to sometimes give a good description of AGN spectra. The likely interpretation is that there is patchy material in the line of sight. This model composition is represented as

\[
\text{constant} \ast \text{zpfcabs} \ast \text{zpowlerw} \ast \text{zhihect} \ast \text{pexmon} \ast \text{apex}.
\]

where zpfcabs represents an absorption by cold matter with a column density \( N_H \) and a covering fraction of \( f \). The addition of zpfcabs significantly improves the fit, yielding a \( \chi^2 \) value of \( \chi^2/\text{dof} = 220.4/184 \). Note that the fit is considerably worse when a full covering model (i.e., \( f = 1 \)) is applied (\( \chi^2/\text{dof} = 279.7/185 \)). Next, we add emission from an optically thin thermal plasma. This model, represented as

\[
\text{constant} \ast \text{zpfcabs} \ast \text{zpowlerw} \ast \text{zhihect} \ast \text{pexmon} \ast \text{apec},
\]

better explains the spectra with \( \chi^2/\text{dof} = 214.0/182 \), and the improvement is confirmed at >95% confidence level on the basis of an F-test. We obtain \( \Gamma = 2.03^{+0.10}_{-0.09}, R_{\text{torus}} = 0.45^{+0.13}_{-0.10}, \) and the variability factor (constant) NormXIS = 0.26±0.06.

Finally, as a physically motivated model introduced by Tazaki et al. (2013), we further include the reflection component from the accretion disk into the above model. This “final” model is expressed as

\[
\text{constant} \ast \text{zpfcabs} \ast (\text{zpowlerw} \ast \text{zhihect} \ast \text{rdblur} \ast \text{pexmon}) \ast \text{pexmon} \ast \text{apec},
\]

where the second term represents the disk reflection component whose intensity is synchronized with that of the direct component (the first term). The reflection strength from the accretion disk is fixed at \( R_{\text{disk}} = 0.1 \) (see above), while that from the torus \( R_{\text{torus}} \) is still left to be a free parameter. Note that, unlike \( R_{\text{disk}} \), \( R_{\text{torus}} \) is defined relative to the flux determined with Swift/BAT, not to that of Suzaku. The inclination in the pexmon model is set to \( 30^\circ \) for the disk reflection. In the rdblur model, we fix the inner and outer radii at \( r_{\text{in}} = 100r_s \) and \( r_{\text{out}} = 10^3r_s \), respectively, with an emissivity index of \( \beta = -3 \). This outer
The normalization ratio of the flux measured with Swift BAT. The best-fit model folded with the data. By adopting different values for the inner radius of \( r_{\text{in}} = 10^{3} \) g, as suggested from previous studies of LLAGNs (Quataert et al. 1999; Ptak et al. 2004), should be expected even though it is weak. Here we derive an upper limit for the strength of the disk reflection \( R_{\text{disk}} \) from the data. By adopting different values for the inner radius of \( r_{\text{in}} = 10^{3} \) g, 30 g, and 50 g, which corresponds to \( R_{\text{disk}} = 0.6, 0.3, \) and 0.2 for the source scale height of \( h_s = 10 g \), we obtain \( \chi^2 \) values of 224.5, 219.5, 217.5, respectively, from the broadband spectral fit. Thus, the data constrain \( R_{\text{disk}} < 0.2 \) at a 90% confidence limit, which is well consistent with our best model, \( R_{\text{disk}} = 0.1 \).
If we instead assume \( h_t = 100 r_g \), then \( R_{\text{disk}} = 0.6 \) is expected for \( r_g = 100 r_g \) and the fit results in a worse \( \chi^2 \) value of 224.3. This implies that the smaller scale height, \( h_t = 10 r_g \), is more reasonable unless the disk is truncated at a very large radius like \( r_{\text{in}} > 10 r_g \). In any case, we confirm that our conclusion on the torus structure based on the iron-K\( \alpha \) line analysis described in Section 4.3 is not affected by these uncertainties on the disk-reflection component, whose contribution to the total spectrum is rather small.

### 3.1.2. NGC 4941

We first apply the following model for the broadband spectra of NGC 4941, which is a type-2 AGN and shows clear evidence for an intrinsic absorption:

\[
\text{constant} \times \text{zphabs} \times \text{zhight} \times \text{zpowerlw} + \text{zphabs} \times \text{pexmon} + \text{constant} \times \text{zhight} \times \text{zpowerlw}.
\]

The first and second terms are the transmitted and disk reflection components, respectively. Here we consider absorptions separately for the two components, with \( N_{\text{HI}} \) for the former and with \( N_{\text{H2}} \) for the latter, because the torus reflection comes from a large volume and hence could well be subject to a different absorption in average from that for the transmitted emission. The third term represents a scattering component by a gas surrounding the nucleus. It is assumed to have the same photon index \( \Gamma \) as the transmitted component with a relative normalization of \( f_{\text{scat}} \) (to the Swift/BAT flux). Even though the \( \chi^2 \) is already acceptable with this model (\( \chi^2 / \text{dof} = 44.3 / 45 \)), we add emission from a thin thermal plasma to the above model, which is often observed in type-2 AGNs (e.g., Turner et al. 1997) including LLAGNs (Terashima et al. 2002). The model composition is then expressed as

\[
\text{constant} \times \text{zphabs} \times \text{zhight} \times \text{zpowerlw} + \text{zphabs} \times \text{pexmon} + \text{constant} \times \text{zhight} \times \text{zpowerlw} + \text{apec}.
\]

The addition of the thin thermal emission significantly improves the fit, reducing the \( \chi^2 \) value to \( \chi^2 / \text{dof} = 28.7 / 43 \). We obtain \( \Gamma = 1.91^{+0.28}_{-0.23} \), \( N_{\text{HI}} = (74^{+19}_{-15}) \times 10^{22} \) cm\(^{-2} \), \( N_{\text{H2}} = (5.1^{+24.1}_{-4.1}) \times 10^{22} \) cm\(^{-2} \), \( R_{\text{torus}} = 0.62^{+0.67}_{-0.26} \), \( f_{\text{scat}} = (0.95^{+0.70}_{-0.61}) \% \), and \( N_{\text{NormXIS}} = 0.47^{+0.34}_{-0.18} \). In the same way as the spectral analysis of NGC 1566, we finally fit the spectra with the model including the disk reflection component:

\[
\text{constant} \times \text{zphabs} \times \text{zhight} \times \text{zpowerlw} + \text{zphabs} \times \text{pexmon} + \text{constant} \times \text{zhight} \times \text{zpowerlw} + \text{apec} + \text{rdblur} \times \text{pexmon} + \text{zphabs} \times \text{pexmon} + \text{constant} \times \text{zhight} \times \text{zpowerlw} + \text{apec}.
\]

The reflection strength from the accretion disk is fixed at \( R_{\text{disk}} = 0.1 \) with an inclination of 70° (see Section 3.1), while that from the torus, \( R_{\text{torus}} \), is a free parameter defined relative to the Swift/BAT flux. Again, an inclination of 60° is assumed for the torus reflection component as a representative value so that we can more directly compare the result of NGC 1566; the best-fit parameters are not significantly changed even if when an inclination of 30° is adopted instead. We find that this model describes the observed spectra well (\( \chi^2 / \text{dof} = 28.7 / 43 \)) with the best-fit parameters of \( \Gamma = 1.91^{+0.28}_{-0.23} \), \( N_{\text{HI}} = (73^{+15}_{-16}) \times 10^{22} \) cm\(^{-2} \), \( N_{\text{H2}} = (5.1^{+24.1}_{-4.1}) \times 10^{22} \) cm\(^{-2} \), \( R_{\text{torus}} = 0.64^{+0.69}_{-0.27} \), and \( f_{\text{scat}} = (0.99^{+0.76}_{-0.18}) \% \). We obtain \( N_{\text{NormXIS}} = 0.48^{+0.35}_{-0.18} \), which indicates that the direct component flux was weaker by 52% during the Suzaku observation than the 70 month average observed with Swift/BAT. Unlike the case of NGC 1566, we cannot constrain the strength of the disk reflection from our data, mainly due to the heavy obscuration of the direct and disk-reflection components. We obtain a similar \( \chi^2 \) value of \( \chi^2 / \text{dof} = 28.0 / 43 \) even when we assume \( r_{\text{in}} = 6 r_g \) corresponding to \( R_{\text{disk}} = 0.7 \) for \( h_t = 10 r_g \) and \( \chi^2 / \text{dof} = 28.9 / 43 \) when \( r_{\text{in}} = 100 r_g \) and \( h_t = 100 r_g \) corresponding to \( R_{\text{disk}} = 0.6 \) are adopted. Nevertheless, with the same argument for NGC 1566, we adopt this model that includes the disk reflection with \( R_{\text{disk}} = 0.1 \) as the best physical model for NGC 4941. All the parameters are listed in Table 3. The best-fit folded model is plotted in Figure 2 with fitting residuals (lower panel), and the unfolded spectra in units of \( E I_E \) are shown in Figure 3.

### 3.2. Analysis of Iron-K\( \alpha \) Line in Narrow-band Spectra

To verify that the above broadband fit results, we also perform spectral analysis in the narrow 3–9 keV band, focusing on the iron-K\( \alpha \) line features. This procedure enables us to derive observed equivalent widths (or their upper limits) most directly from the data, independently of the assumption of the reflection model. Here we use the spectra of the FI-XISs in the 3–9 keV band and those of BI-XIS in the 3–8 keV band. Basically, the best-fit continuum model obtained by the broadband fit is adopted by replacing the \text{pexmon} components with the \text{pexav} model, which does not contain fluorescence lines. Instead, we add a \text{diskline} component (Fabian et al. 1989) as the iron-K\( \alpha \) emission line from the accretion disk, and \text{zgauss} as that from the torus. The line energies for both components are fixed at 6.4 keV in the rest frame, and the 1σ line width of \text{zgauss} is set to be 0.1 eV, which is unresolved with the XIS. The line profile parameters in the \text{diskline} model are fixed at the same values as those in the \text{rdblur} component. Thus, only the normalizations of \text{diskline}, \text{zgauss}, and \text{zpowerlw} are set free, while the other parameters are all fixed at their best-fit values determined from the broadband spectra. Figure 4 (upper panel) shows the spectra of FI-XISs with the best-fit model of \text{zgauss}. The ratios between the data and the best-fit model are also shown in Figure 4 (lower panel).

In both targets, the \text{diskline} components are not significantly detected with 90% confidence upper limits on “observed” equivalent widths with respect to the total continuum \( E \text{W}^\text{obs}_{\text{disk}} < 32 \) eV (NGC 1566) and \( E \text{W}^\text{obs}_{\text{disk}} < 150 \) eV (NGC 4941). The error for NGC 4941 is larger than that for NGC 1566 because of the fainter continuum flux due to the heavy absorption and the large inclination assumed (70°) that produces a broader iron-K\( \alpha \) line profile. To compare these upper limits with the theoretical predictions, we need to subtract the contribution of the torus-reflection and scattered components from the total continuum. Thus we obtain “corrected” equivalent widths of \( E \text{W}^\text{cor}_{\text{disk}} < 39 \) eV (NGC 1566) and \( E \text{W}^\text{cor}_{\text{disk}} < 230 \) eV (NGC 4941). These upper limits are consistent with the calculation by George & Fabian (1991) under our assumptions on the geometry between the primary source and disk (\( h_t / r_{\text{in}} = 0.1 \)) and the inclination, 15–21° for NGC 1566 and 14–16° for NGC 4941 (see Section 3). Hence, adopting the disk-reflection strength of \( R_{\text{disk}} = 0.1 \) in the broadband spectral analysis is justified. Note that even when we adopt a smaller inner radius of \( r_{\text{in}} < 100 r_g \) in the \text{diskline} and \text{rdblur} models, the broad iron-K\( \alpha \) line is not significantly detected; for \( r_{\text{in}} = 6 r_g \), 100 \( r_g \), or 30 \( r_g \) we obtain an upper limit of \( E \text{W}^\text{cor}_{\text{disk}} < 42 \) eV in NGC 1566, although the constraint is weaker in NGC 4941.

We find that the equivalent widths of \text{zgauss} relative to the total continuum are \( E \text{W}^\text{obs}_{\text{Gauss}} = 240 \pm 40 \) eV and \( E \text{W}^\text{obs}_{\text{Gauss}} = 380 \pm 80 \) eV for NGC 1566 and NGC 4941, respectively. The observed equivalent width of a narrow iron-K\( \alpha \) line from the
torus with respect to the total continuum is subject to variability of the transmitted component, however. From the broadband spectral analysis, we know that the fluxes during the Suzaku observations were much fainter than those of Swift/BAT in both targets. This leads to an overestimate of the true (i.e., time averaged) equivalent widths of the iron-Kα line. On the basis of our assumption that the long-term Swift/BAT data give the averaged continuum flux that determines the torus reflection strength and narrow iron-Kα line flux observed with Suzaku, we calculate the true continuum level at 6.4 keV by increasing the transmitted and disk-reflection components by a factor of 1/Normxis, and then derive “corrected” equivalent width values, \( EW_{\text{cor}}^{\text{Gauss}} = 60 \pm 10 \text{ eV} \) for NGC 1566 and \( EW_{\text{cor}}^{\text{Gauss}} = 230 \pm 50 \text{ eV} \) for NGC 4941. We summarize the fitting results in Table 4.

4. SUMMARY AND DISCUSSION

4.1. Summary of Results

With Suzaku and Swift/BAT, we have obtained the broadband X-ray spectra covering the 0.5–195 keV band of the two LLAGNs NGC 1566 (type 1.5) and NGC 4941 (type 2) for the first time. The spectrum of NGC 1566 is found to be essentially unobscured, while that of NGC 4941 is subject to heavy absorption. Strong iron-Kα emission lines at the rest-frame 6.4 keV are detected in both targets. Their spectra are well reproduced by a physically motivated model consisting of a partially or fully absorbed transmitted component with its reflection from the accretion disk, a reflection component from the torus, a scattered component (in NGC 4941), and optically thin thermal plasma emission. The physical parameters of the thin thermal components (temperature of \( kT \sim 0.2–0.9 \text{ keV} \) and luminosities in the 0.3–2 keV band of diffuse X-ray emission) are consistent with the origins from star-forming activities in the host galaxies (e.g., Tüllmann et al. 2006), although it may be partially contaminated by line emission from a photoionized plasma powered by the AGN. In fact, the far-infrared luminosities calculated from the IRAS 60 \( \mu \text{m} \) and 100 \( \mu \text{m} \) fluxes by using the formula of David et al. (1992) are \( 2.9 \times 10^{33} \text{ erg s}^{-1} \) (NGC 1566) and \( 4.2 \times 10^{34} \text{ erg s}^{-1} \) (NGC 4941), suggesting the presence of significant star-forming activities. In the analysis, we carefully take into account time variability of the transmitted plus disk reflection components between the Suzaku and Swift/BAT observations, while it is assumed that the last three components are constant. During the Suzaku observations, the flux levels of both objects were significantly fainter than their 70 month average obtained by Swift/BAT.

An important result is that both NGC 1566 and NGC 4941 show moderate mount of the torus reflection, \( R_{\text{torus}} = 0.4_{-0.10}^{+0.13} \).

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**Table 4**

The Parameters in the Narrow-band Analysis

| Target | NGC 1566 | NGC 4941 |
|--------|----------|----------|
| (1) \( E_{\text{line}}^{\text{Gauss}} \) (keV) | 6.4±1 | 6.4±1 |
| (2) \( E_{\text{line}}^{\text{disk}} \) (keV) | 6.4±1 | 6.4±1 |
| (3) \( \theta_{\text{inc}} \) (degree) | 30±1 | 70±1 |
| (4) \( N_{\text{Gauss}} \) (10⁻⁶ photons cm⁻² s⁻¹) | 6.6±1.2 | 6.7±1.2 |
| (5) \( \alpha_{\text{disk}} \) (eV) | 240±40 | 380±80 |
| (6) \( \alpha_{\text{Gauss}} \) (eV) | 60±10 | 230±50 |
| (7) \( N_{\text{disk}} \) (10⁻⁵ photons cm⁻² s⁻¹) | <0.39 | <1.83 |
| (8) \( \alpha_{\text{disk}} \) (eV) | <3.2 | <150 |
| (9) \( \alpha_{\text{Gauss}} \) (eV) | <3.9 | <230 |

**Notes.**

(1) The line energy of iron-Kα line in the zgauss model.
(2) The line energy of iron-Kα line at the rest frame in the model diskline.
(3) The inner truncated radius of the accretion disk.
(4) The inclination angle to the accretion disk.
(5) The photon flux of the model zgauss at the line energy of (1).
(6) The observed equivalent width of the narrow iron-Kα line relative to the total continuum observed with Suzaku.
(7) The equivalent width of the narrow iron-Kα line relative to the continuum summed over the direct component and the reflection component from the dust torus.
(8) The photon flux of the model diskline at the line energy of (2).
(9) The observed equivalent width of the broad iron-Kα line relative to the total continuum observed with Suzaku.
(10) The equivalent width of the broad iron-Kα line derived from the photon flux of (9) relative to the continuum summed over the direct component and the reflection component from the accretion disk.

* The parameters are fixed in the fitting.
and 0.64$^{+0.69}_{-0.27}$, respectively, relative to the time-averaged flux of the direct component measured by Swift/BAT. They are slightly smaller as a typical total reflection strength observed in Seyfert galaxies, $R \sim 1$ (e.g., Dadina 2008). The torus structure inferred from this result is quantitatively discussed in Section 4.3.

We compare our results on NGC 4941 with previous results obtained by ASCA in 1996 July and 1997 January (Terashima et al. 2002) and BeppoSAX in 1997 January (Maiolino et al. 1998), although much simpler spectral models are adopted there due to the limited statistics in the spectra. The equivalent width of the narrow iron-Kα line is reported to be 570 ± 230 eV (ASCA) and 1600$^{+200}_{-900}$ eV (BeppoSAX). The Suzaku result of $EW_{\text{Gauss}} = 380 \pm 80$ eV may be slightly smaller than these. If we compare the iron-Kα line flux instead of equivalent width, however, we find that they are all consistent within the statistical errors; 1.0 ± 0.4, 1.2$^{+0.4}_{-0.6}$, and 0.67 ± 0.12 × 10$^{-5}$ photons cm$^{-2}$ s$^{-1}$ in the ASCA, BeppoSAX, and Suzaku observations, respectively. This supports our hypothesis that the absolute flux of the reflection component originating from the torus is nearly constant as its variability is smeared out.

The incident spectrum is assumed to be a power law with an photon index of $\Gamma = 2.0$ (see the text of NGC 1566 are shown by the two horizontal lines (magenta). (A color version of this figure is available in the online journal.)

4.2. Reflection Component from the Accretion Disk

The XIS spectra in the 3–9 keV band suggest that a broad iron-Kα line feature arising from the inner accretion disk is very weak in NGC 1566, although it is more difficult to constrain its intensity in NGC 4941 due to the heavy absorption and high inclination. Applying a relativistic line profile with an inner radius of $r_{\text{in}} \lesssim 100 r_g$, we obtain an upper limit on the corrected equivalent width of 42 eV for NGC 1566. This result constrains the reflection strength from a cold accretion disk to be $R_{\text{disk}} < 0.3$ as defined in the pexmon model. In fact, when we adopt a larger value of $R_{\text{disk}} = 0.6$ expected from the case of $h_l/r_o = 1$ (where $h_l$ is the height of the irradiating source) according to George & Fabian (1991), the broadband fit of NGC 1566 becomes significantly worse ($\chi^2$/dof = 224.5/182) compared with that for $R = 0.1$ ($\chi^2$/dof = 215.5/182). The small reflection suggests that the inner disk is likely to be truncated at relatively large radius, although it is difficult to unambiguously determine the truncation radius, which depends on the assumed corona geometry. The weak disk reflection is consistent with the result by Ptak et al. (2004), who found $R_{\text{disk}} < 0.1$ for the LLAGN NGC 3998 ($L_{2–10} \sim 10^{41}$ erg s$^{-1}$) from the X-ray spectrum. We do not rule out, however, the possibility that there is a very highly ionized disk that produces almost featureless continuum around the iron-Kα band.

4.3. Torus Structure

The equivalent width of narrow iron-Kα line from an AGN is very useful to constrain the torus structure such as the opening angle. For this purpose, we utilize the Monte-Carlo based numerical model by Ikeda et al. (2009), which calculates absorbed direct component and the reflected continuum with fluorescence lines from an AGN surrounded by a torus. In this model, the geometry of the torus is close to be a spherical shape defined by three parameters (for details, see Figure 2 of Ikeda et al. 2009): hydrogen column density at the equatorial plane $N_H^{\text{eq}}$, half-opening angle $\theta_{\text{oa}}$, and inclination $\theta_{\text{inc}}$. Hence, $\theta_{\text{inc}} < \theta_{\text{oa}}$ for type 1 AGN and $\theta_{\text{inc}} > \theta_{\text{oa}}$ for type 2 AGN. The incident spectrum is assumed to be a power law with an exponential cutoff at 360 keV. As done in Tazaki et al. (2013), we plot the predicted equivalent width of the iron-Kα line as a function of half-opening angle with several different inclinations in Figure 5 for type-1 AGNs and Figure 6 for type-2 AGNs. We consider two cases of $N_H^{\text{eq}} = 10^{23}$ cm$^{-2}$ or $10^{24}$ cm$^{-2}$ with $\Gamma = 2.0$ (the best-fit value of NGC 1566) in Figure 5, while $N_H^{\text{eq}} = 7 \times 10^{23}$ cm$^{-2}$ and $\Gamma = 1.9$, the best-fit line-of-sight column density and photon index of NGC 4941, are assumed in Figure 6. Above $\theta_{\text{oa}} > 70^\circ$ where the Ikeda model is not available, we extrapolate the data by assuming that the equivalent width is proportional to the volume of the torus.

The dashed horizontal lines (magenta) in Figures 5 and 6 represent the error region of the corrected equivalent width $EW_{\text{Gauss}}$ for NGC 1566 and NGC 4941, respectively. Although the result of NGC 1566 does not constrain the half-opening angle within the range of $N_H^{\text{eq}} = 10^{23}–10^{24}$ cm$^{-2}$, the reflection strength $R_{\text{torus}} = 0.45^{+0.13}_{-0.10}$ implies $\theta_{\text{oa}} \simeq 50^\circ–70^\circ$ by assuming $R_{\text{torus}} \simeq \text{cost}(\theta_{\text{oa}})$. For NGC 4941, the half-opening angle is estimated to be $\theta_{\text{oa}} \simeq 60^\circ–70^\circ$ from the iron-Kα equivalent width, which is consistent with $R_{\text{torus}} = 0.64^{+0.69}_{-0.27}$. Thus, in both targets, modest covering factors of the tori are suggested.

According to the unified scheme, the torus covering fraction determines the fraction of obscured AGNs. Thus, it is quite interesting to compare with the result on the type-2 fraction derived from unbiased AGN surveys. On the basis of the Swift/BAT survey performed in the 15–55 keV band, Burlon et al. (2011) suggest that the fraction has a peak of $\approx 0.6–0.8$ around
explain the observed trend. Further studies of a larger sample of LLAGNs covering a wide range of luminosity and Eddington ratio would be useful to confirm our results and to understand the origin.

We acknowledge the usage of the HyperLeda database (http://leda.univ-lyon1.fr). Part of this work was financially supported by the Grant-in-Aid for JSPS Fellows for young researchers (F.T.) and for Scientific Research 23540265 (Y.U.) and 21244017 (Y.T.), and by the Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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