Suzaku Results on the Obscured Low-Luminosity Active Galactic Nucleus in NGC 4258

Shin’ya Yamada, Takeshi Itoh, Kazuo Makishima, and Kazuhiro Nakazawa
1 Department of Physics, University of Tokyo 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033
2 Cosmic Radiation Laboratory, Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako-shi, Saitama, 351-0198

(Received 2008 October 9; accepted 2008 November 27)

Abstract

In 2006 June, the obscured low-luminosity active galactic nucleus in the nearby Seyfert 1.9 galaxy NGC 4258 was observed with Suzaku for ~100 ks. Utilizing the XIS and the HXD, the nucleus emission was detected over a ~2 to ~40 keV range, with an unabsorbed 2–10 keV luminosity of ~8 × 10^{40} erg s⁻¹; it varied by a factor of ~2 during the observation. Its 2–40 keV spectrum is reproduced by a single power law with a photon index of Γ ~ 2.0, absorbed by an equivalent hydrogen column of ~1.0 × 10^{23} cm². The spectrum within 4’ of the nucleus also required a softer thin-thermal emission, as well as an intermediate hardness component, attributable to integrated point sources. A weak neutral Fe-Kα florescence line was detected at an equivalent width of ~40 eV. A cold reflection component was not required by the data, with the reflector solid angle Ω seen from the nucleus constrained as Ω/2π ≤ 0.3, assuming a general case of 60° inclination. The results suggest that the cold reflecting material around the nucleus is localized along our line of sight, rather than forming a thick torus.

Key words: galaxies: active — galaxies: individual (NGC 4945) — galaxies: Seyfert — X-rays: galaxies

1. Introduction

Although active galactic nuclei (AGNs) exhibit a wide variety of spectral properties, a comprehensive classification of them, called “Unified Scheme” (e.g., Antonucci 1993), has been developed. In addition to the black-hole mass and the mass accretion rate, which are obvious parameters, this scheme employs two more fundamental parameters: radio loudness and our viewing direction to the accretion plane. A “type 1” AGN refers to an object with a nearly pole-on viewing angle, while a “type 2” AGN concerns a roughly edge-on aspect. The spectrum differs between the two classes, depending on whether our line of sight is blocked by some part of the accreting material or not. The blocking material is often assumed to have the shape of an inflated torus around the nucleus, a so-called molecular torus, or simply torus. This scheme can explain much of the observational differences among various kinds of AGNs. Nevertheless, the validity of the Unified Scheme and the nature of the putative torus are still open questions.

X-ray observations of type-2 AGNs provide a powerful tool in these attempts, because the strength of photoelectric absorption affecting the nuclear hard X-rays provides the most direct information on the column density of the obscuring material. Indeed, X-ray observations with Ginga (e.g., Koyama et al. 1989; Awaki et al. 1991), and ASCA (Ueno et al. 1996) of typical type-2 AGNs demonstrated that their nuclei are heavily obscured with a column density of 10^{23} to 10^{24} cm⁻². Subsequently, BeppoSAX investigators introduced a new concept, called “Compton thick AGNs” (Maiolino et al. 1998; Matt et al. 2000), as the most extreme class of type-2 AGNs, wherein the absorber is opaque not only to photoelectric absorption, but also to Compton scattering. Because of a strong suppression of the direct component, these objects are expected to provide further clues to the circumnuclear matter distribution, via the detection of various secondary components, including in particular the Compton reflection hump, and fluorescent Fe-K lines.

Using Suzaku, we observed a Compton-thick AGN, NGC 4945, which is one of the brightest AGNs above 20 keV. Analyzing the data, Itoh et al. (2008) found the reflection features to be unusually weak, as judged from both the Fe-K edge feature in the XIS spectra and the Compton hump in the data from the HXD. Reinforced by the detection of clear hard X-ray variations, Itoh et al. (2008) thus constrained the reflection fraction, f_{refl} ≡ Ω/2π, to be less than a few percent, where Ω is the solid angle of the reflector as seen from the nucleus. This makes a significant contrast to many other Compton-thick Seyfert 2 AGNs, where we usually find f_{refl} ~ 1–2 (e.g., De Rosa et al. 2008). Therefore, the reflector in NGC 4945 is suggested to have a geometrically-thin, disk-like structure rather than that of a thick torus, and the reflector, absorber, and the water maser source are thought to be provided by the same structure, namely a flat accretion disk (Madejski et al. 2000, 2006). Although this means a clear deviation from the Unified Scheme, it is not yet clear whether such a property is specific to NGC 4945, or more or less common to a certain class of AGNs. One of effective ways to examine this issue is to study AGNs with low mass-accretion rates, namely low-luminosity AGNs (LLAGNs), because NGC 4945 has a rather low intrinsic (absorption corrected) luminosity of ~1 × 10^{42} erg s⁻¹ in 2–10 keV.

NGC 4258 (M 106), one of the typical LLAGNs, is a highly inclined (72°, Tully 1988) SABbc spiral galaxy located at
a nearby distance of 7.2 Mpc (Herrenstein et al. 1999), where 1" suggested by strong polarization of the relatively broad optical emission lines (Wilkes et al. 1995), and Hα and X-ray emitting “anomalous arms” (Cecil et al. 1995). Observation with ASCA up to 10 keV (Makishima et al. 1994) clearly demonstrated the “anomalous arms” (Cecil et al. 1995). Observation with ASCA the two instruments were screened using version 2.2.7.18 of the Suzaku pipeline processing. We used “cleaned events” files, the source was detected significantly with the XIS (subsection 2.2), and HXD-PIN (subsection 2.3), but not with HXD-GSO.

2.2. XIS Data Selection and Background Subtraction

XIS events with grades 0, 2, 3, 4, and 6 were selected, and then hot and flickering pixels in each CCD chip were removed using cleansis software. Using aextcor software (Uchiyama et al. 2007), we corrected the event positions for attitude fluctuations due to thermal spacecraft wobbling. Then, we extracted those events that satisfy the criteria described in subsection 2.1. A net exposure of ~99 ks was obtained in total from each XIS sensor.

Figure 1 shows XIS0 images of the NGC 4258 region, in two energy ranges of 0.3–3 keV and 3–10 keV. The soft-band image is dominated by complex extended emission with an extent of at least ~4′, while the hard-band image is dominated by the bright nucleus, as first revealed with ASCA (Makishima et al. 1994). In addition, several fainter point-like sources are distributed over the NGC 4258 disk. As indicated in figure 1, we accumulated XIS events from a circular region of radius 4′.8 (8.4 kpc at the distance of 7.2 Mpc) centered on the nucleus. Since the nuclear emission is confused in this region with the extended galaxy emission, we restrict the following spectral studies mainly to energies above 1.9 keV.

At ~2′/2 south of the nucleus, figure 2 reveals a faint point source which has not been reported previously. We excluded a circular region centered on the source, with a radius of 1′.0 (indicated by a black dashed circle). Besides, the 4′-radius region for the nuclear signal accumulation contains a Chandra point source, J121857.3+471812 (Yang et al. 2007), located at ~1′′.5 off the nucleus, of which the contribution is estimated to be ~3% at 3 keV and ~1% at 5 keV of the nucleus. We consider its contribution in subsection 3.1, together with those from other fainter point sources that can contaminate their own spectra.

The background spectra were extracted from a source free region of the same field of view, as indicated by a black solid circle in figure 1. The background count rates in 3–9 keV were found to be ~7% of the total event rate in the same energy range detected with each FI CCD from the on-source region, and ~10% of those with the BI CCD. The response matrices and ancillary response files were created utilizing xismarfgen and xissimarfgen (Ishisaki et al. 2007), respectively. In the spectral analysis described below, we coadded the spectra and responses of the three FI chips (XIS0, 2, and 3).

2.3. HXD Data Selection and Background Subtraction

Table 1 summarizes the count rate of HXD-PIN averaged over the whole observation. To subtract the non X-ray background (NXB), we used an NXB model, called LCPITDPT or “tuned” method (Fukazawa et al. 2009), which accurately takes
Fig. 1. Background-inclusive Suzaku XIS0 images of NGC 4258, in the 0.3–3.0 keV (panel a) and 3–10.0 keV (panel b) band. Dashed and solid circles, both of radius 4", indicate the on-source and background accumulation regions. A dotted small circle of radius 1" is a region used to eliminate a possible point source.

Fig. 2. (a) Raw HXD-PIN spectra (open circles) observed during the Earth-occultation periods, compared with the NXB model predictions (filled squares). (b) The model to data ratio.

Table 1. HXD count rates during Earth occultation periods, compared with the NXB model.

| Component     | 12–40 keV       | 40–60 keV       |
|---------------|-----------------|-----------------|
| Earth event   | 0.4367±0.0069   | 0.0492±0.0023   |
| NXB*          | 0.4504±0.0021   | 0.0464±0.0007   |
| ratio         | 1.03 ± 0.02     | 0.94 ± 0.05     |

* Modeled with LCFITDT (Fukazawa et al. 2009).

into account various variations of the NXB. The model also includes slight differences caused by the different bias voltages imposed on the 64 HXD-PIN diodes. This is because a quarter of the whole HXD-PIN diodes have been operated with a bias voltage of 400 V since 2006 May 24 (to suppress anomalous noise behavior seen in some of the diodes) while the others were operated at 500 V. Systematic errors of the NXB model in the 15–40 keV and 40–70 keV bands were estimated to be 1.4% and 2.8% (1σ level), respectively, when night Earth was observed for an exposure of 10 ks (Fukazawa et al. 2008). Since our observation was longer than 10 ks, the NXB model is expected to have a reproducibility no worse than these estimates. Therefore, we used these values as an approximation to the systematic errors involved in the NXB subtraction.

To further evaluate the systematic error of the NXB, we accumulated the HXD-PIN spectrum while the satellite was pointing to Earth, with an exposure of 9.3 ks, and compare the results in figure 2 with the NXB model prediction. Thus, the modeled NXB spectrum is slightly higher than the Earth spectrum, especially around 12–20 keV. A more quantitative result of this comparison is given in table 1, where we find that the NXB is overestimated by ~3% in the 12–40 keV range, even though this is within the guaranteed accuracy of the present model (Fukazawa et al. 2009).

The counts remaining after subtracting the NXB still include the contribution of the cosmic X-ray background (CXB: Boldt 1987), which must be subtracted as well. The CXB contribution was estimated using the HXD-PIN response to diffuse sources, assuming the spectral CXB surface brightness model determined by HEAO 1 (Gruber et al. 1999): $9.0 \times 10^{-9} \, (E/3\, \text{keV})^{-0.29} \exp(-E/40\, \text{keV}) \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{str}^{-1} \, \text{keV}^{-1}$, where $E$ is the photon energy. The estimated CXB count rate is 5% of the NXB signals. The actual CXB normalization has recently been found (Revnivtsev et al. 2003; Churazov et al. 2007) to be higher by 10–15% at 10–100 keV than that of Gruber et al. (1999), but the difference is negligible because it is within the systematic uncertainty of the NXB subtraction. As indicated by table 2, the source has been
Table 2. Signal and background count rates from HXD-PIN during the on-source exposure.

| Component | 12–25 keV | 25–40 keV | 40–60 keV |
|-----------|-----------|-----------|-----------|
| On-source | 0.3944 ± 0.0021 | 0.0925 ± 0.0010 | 0.0463 ± 0.0007 |
| NXB*  | 0.3445 ± 0.0048 | 0.0832 ± 0.0004 | 0.0425 ± 0.0012 |
| CXB†  | 0.0225 | 0.0040 | 0.0005 |
| Net signal‡ | 0.0274 ± 0.0022 | 0.0053 ± 0.0010 | 0.0035 ± 0.0007 |

* Modeled with LCFITDT (Fukazawa et al. 2008). The systematic errors are described in subsection 2.4.
† Predicted from the HEAO-1 measurement (Gruber et al. 1999).
‡ Net count rate obtained by subtracting the NXB and CXB from the on-source count rate.
The first and the second uncertainties represent the statistical and systematic errors, respectively.

The dominant emission in this energy range is thermal diffuse emission. Interestingly, some variations are suggested in the 1–2 keV band. Although the HXD-PIN light curve has rather poor photon statistics, it is inconsistent with being constant, because fitting it with a constant yields $\chi^2$ < 79 for 24 d.o.f.

2.4. Light Curves

Figure 3 shows XIS-FI and HXD-PIN light curves of NGC 4258 from the present observation. In the 3–10 keV band, the source is gradually increasing and then decreasing by $\pm 10\%$ on time scales of $\sim 100\,$ks. In contrast, the light curves below 3 keV are much closer to being constant. These agree with previous reports (e.g., Makishima et al. 1994) that significantly detected, at least up to $\sim 40\,$keV with a significance level of $> 5\sigma$.

In contrast to the detections with HXD-PIN, the source was not detected with HXD-GSO. The estimated upper limit, $\sim 1\,$mCrab at $\sim 50\,$keV, is consistent with an extrapolation from the HXD-PIN signals, which indicate a source intensity of $\sim 0.6\,$mCrab at 30 keV.

2.5. Time-Averaged Spectra

Figure 4 shows time-averaged Suzaku spectra of NGC 4258. The HXD-PIN spectrum was corrected for the dead time, and was presented after subtracting the backgrounds (NXB + CXB), as described in subsection 2.2. As revealed with ASCA (Makishima et al. 1994) and BeppoSAX (Fiore et al. 2001), the XIS spectrum thus consists of at least two components: a soft thermal and the absorbed hard ones, dominant in energies below and above $\sim 2\,$keV, respectively. To grasp the overall features of the spectra, we divided them by those of the Crab Nebula, and show the results in figure 5. The ratio clearly reveals the two components mentioned above. However, the flux decrease from $\sim 4\,$keV to $\sim 2\,$keV is less steep than is described with a single-valued photoelectric absorption. This suggests that another component of medium
3. Spectral Analysis

3.1. Analysis of the Time-Averaged 0.9–40keV Spectra

To quantify the spectrum, we assign the PIN data points with a systematic error of 20%, which corresponds to an NXB uncertainty of \(~1.4\%\). At each spectral bin, this systematic error is added in quadrature to the statistical error. In the following spectral analysis, we constrain each spectral model parameter to be the same among XIS-FI, XIS-BI, and HXD-PIN. The overall model normalization is set to be identical between XIS-FI and XIS-BI, while 13% higher for HXD-PIN (Suzaku memo 2008-06). Furthermore, we ignored the 1.84–1.86keV range due to the XIS response uncertainty around the Si edge.

Although our main interest is in the absorbed nuclear emission, its low-energy end (\(<4\)keV) is confused with other softer spectral components. To disentangle this effect, we start from a relatively wide energy range of 0.9–40keV, while discarding the softer ranges so as to avoid any complexity due to the very soft components. Employing the procedure described above, we hence simultaneously fitted the XIS (FI and BI) and HXD-PIN spectra, in the 0.9–9.0keV, 0.9–8.0keV, and 12.0–40keV energy ranges, respectively. Figure 7a shows the case when we employed the simplest fitting model, which consisted of an absorbed power-law component and a single-temperature plasma emission model, representing the absorbed nuclear emission and the extended soft thermal emission, respectively. The plasma emission was modeled using the xspec code with a free temperature and a free overall metallicity (but keeping the solar abundance ratios), and was subjected to a Galactic absorption column of $1.2 \times 10^{20}$ cm$^{-2}$. The fit then gave, as the best estimates, a power-law photon index of $\Gamma \sim 1.93$, an absorbing column of $N_H \sim 1.1 \times 10^{23}$ cm$^{-2}$, and a plasma temperature and an abundance of 0.58keV and 0.47 solar, respectively. However, as evident in figure 7a, the fit was not acceptable, leaving significant residuals in the energy range of 1.5–2.5keV, where the two model components cross over. In addition, the fit residuals reveal a weak Fe-K line at \(\sim6.4\)keV.

As already mentioned in subsection 2.5, referring to figure 5, the 1.5–2.5keV residuals indicate the presence of another spectral component with an intermediate hardness; Makishima et al. (1994) already noticed the same component, and attributed it to the integrated emission from point sources. Our results support this interpretation, because the very strong He-like Si Kα line (at 1.86keV) and the weakness of its H-like counterpart (at 2.01keV) imply that any hotter thin-thermal emission is unlikely to contribute significantly to our spectrum at energies above \(\sim2\)keV.

To improve the fit, we added a thermal bremsstrahlung model and a single Gaussian. The former is an empirical modeling of point sources (mostly thought to be low-mass X-ray binaries) after Makishima et al. (1994); we left its temperature and normalization both free, and fixed its absorption artificially at a value of $2 \times 10^{22}$ cm$^{-2}$ (Makishima et al. 1989) for a better approximation of integrated point-sources. The latter was allowed to have a free centroid and free intensity, but was assumed to be narrow ($\sigma = 0.001$ eV). Then, as shown in figure 7b, the fit was significantly improved. As summarized in table 3, the temperature of the thermal bremsstrahlung

![Fig. 5. Same spectrum as figure 3, normalized to those of the Crab Nebula acquired on 2005 September 15. The inset shows details around the Fe-K lines and edges.](https://example.com/handle/10.1093/pasj/61.2.309)

![Fig. 6. Suzuki spectra of NGC 4388 (Shirai et al. 2008), divided by those of NGC 4258 presented in figure 4. The inset shows details around the Fe-K lines and edges.](https://example.com/handle/10.1093/pasj/61.2.309)
1.0 solar, we obtain $kT_{\text{pl}}$ of the soft thermal component is fixed at the continuum attributable to the plasma emission. If, e.g., the $kT_{\text{pl}}$ was obtained with large errors of $314$ S. Yamada et al. [Vol. 61, 

The power-law normalization at 1 keV, in units of $10^{-5}$ photons keV$^{-1}$cm$^{-2}$s$^{-1}$ at 1 keV.

The equivalent hydrogen column density in $10^{22}$ cm$^{-2}$.

Center energy in keV.

Photon number flux in $10^{-6}$ photons cm$^{-2}$s$^{-1}$.

Integrated 2–20 keV luminosity at 7.2 Mpc in units of $10^{39}$ erg s$^{-1}$.

as a summed point-source spectrum from a spiral galaxy (Makishima et al. 1989). In addition, the 2.0–20 keV luminosity of this component, $5.8^{+2.9}_{-1.3} \times 10^{39}$ erg s$^{-1}$, is consistent with that interpretation (Makishima et al. 1989). We therefore choose the 1.0 solar abundance and $kT_{\text{br}} = 5.0$ keV as our baseline modeling. The model parameters obtained under these conditions are also given in table 3.
be broad, but this did not significantly improve the fit.

Although the data have already been reproduced successfully with this simple model, an AGN spectrum generally bears a feature due to “reflection” from circum-nuclear cold materials. To evaluate its possible contribution to the NGC 4258 spectrum, we tentatively added a reflected continuum component (pexrav in XSPEC) to our fitting model. The input to pexrav was assumed to be a power-law with the same photon index as the intrinsic power-law, without a cutoff. The reflector was assumed to have solar abundances, and an inclination of \(i = 60^\circ\) as a representative case. The inclusion of this additional component did not improve the fit, and its strength was constrained as \(f_{\text{refl}} < 0.3\) at the 90% confidence limit (the best-fit being at \(f_{\text{refl}} = 0.063\) with \(\chi^2/\nu = 494.5/448\)). In order to understand how the data constrain \(f_{\text{refl}}\), we repeated the fitting with \(f_{\text{refl}}\) purposely fixed at 1.0, simulating a reflector with an infinite slab geometry. Then, as shown in figure 7e, the HXD-PIN data became rather discrepant with the model, yielding \(\chi^2/\nu = 527.4/449\). In other words, HXD-PIN would have to be measuring higher fluxes if the nuclear emission were accompanied by a reflection component with \(f_{\text{refl}} \sim 1\). Thus, the HXD data play an essential role in constraining the reflection.

To confirm that these results are not affected by the uncertainty in \(kT_{br}\), we changed them to 2.0 keV and 10.0 keV, but both yielded \(f_{\text{refl}} < 0.3\). For a further confirmation, we used the nominal NXB model instead of the 2% reduced one, but the upper limit on \(f_{\text{refl}}\) remained unchanged.

The above choice of \(i = 60^\circ\) is considered to be appropriate for a general case, where reflecting materials assume the shape of an inflated torus, as dictated by the Unified Scheme. However, the strong constraint on \(f_{\text{refl}}\) derived under this assumption suggests that the material is in reality localized in a limited solid angle containing our line of sight, like in the case of NGC 4945 (Itoh et al. 2008). To examine the consistency of this alternative configuration, we repeated the fitting while assuming the reflector to have \(i = 83^\circ\), which is the same as the inclination of the water-maser emitter (Miyoshi et al. 1995). Then, the constraint was relaxed to \(f_{\text{refl}} < 2.0\), and the case of \(f_{\text{refl}} = 1.0\) (a flat infinite slab) became acceptable with \(\chi^2/\nu = 498.7\). In other words, the data are consistent with the presence of a slab-like reflector viewed nearly sideways. This result is reasonable, because signals from such a flat reflector will scale as \(\sim \cos i\) in the observed spectra. Finally, we let \(i\) and \(f_{\text{refl}}\) both float, and found that the data favor \(i \sim 30^\circ\), but the fit does not improve \((\chi^2/\nu = 494.5/447)\).

3.3. Analysis of Time Variations

During the present observation, the absorbed nuclear X-rays exhibited mild intensity variations (figure 3). In order to search the spectra for intensity-correlated changes, we divided the entire observation period into two subsets, namely “high-flux” and “low-flux” phases, when the 2–10 keV count rate is higher and lower than 0.5 counts s\(^{-1}\), respectively. The two dotted lines in figure 3 separate them; the high-flux phase between the lines and the low-flux phase outside. The net exposure is 42.9 ks (XIS) and 38.7 ks (HXD) for the high-flux phase, and 42.9 ks (XIS) and 38.7 ks (HXD) for the low-flux phase.

Figure 9 shows the spectra from these two phases, divided by the time averaged spectrum. Thus, the variation is evident at
energies above $\sim 2.5$ keV, in agreement with a simple idea that only the absorbed nucleus should vary. Interestingly, however, we observed small, but significant, variations in the 1.0–2.0 keV range, apparently in an anti-phase with the dominant hard X-ray variations. This is also suggested by figure 3.

To quantify the intensity-correlated spectral changes, we simultaneously fitted the intensity-sorted spectra with the same model, as employed in subsection 3.1. The normalization and temperature of the thermal plasma component was fixed to those obtained with the time averaged spectra, because such extended plasmas would not vary. Furthermore, we constrained the bremsstrahlung normalization and the Fe-K line flux to be the same between the two data sets. This is because the former is thought to be an assembly of many faint point sources, and the latter is considered to arise at too large distances to vary significantly on $\sim 100$ ks. We retained the constraint of $kT_{br} = 5$ keV. The results became fully acceptable with $\chi^2/\nu = 435.8/436$, as presented in table 4 and figure 10. Thus, the nuclear emission became softer by $\Delta \Gamma \sim 0.3$ as the intensity increased, with marginal evidence of an increase in $N_H$.

This spectral steepening is most clearly visible in figure 9 over the 5–9 keV range of the XIS data. As a cross confirmation, we tentatively constrained $\Gamma$ to be the same between the two data sets, to find that the fit worsens by $\Delta \chi^2 = 29.8$. The fit degradation is smaller ($\Delta \chi^2 = 6.5$) when we tie $N_H$ instead of $\Gamma$.

In figures 3 and 9, the 1–2 keV signals exhibit a hint of a weak variation. To examine this effect, we tentatively allowed the bremsstrahlung normalization to take separate values between the two phases, while keeping $kT_{br}$ the same between them. Then, the bremsstrahlung normalization became $\sim 10\%$ lower in the high-flux phase than in the other, with a fit improvement by $\Delta \chi^2 = -4.6$ for $\Delta \nu = -1$. The 2–20 keV bremsstrahlung luminosity was obtained as $3.9 \pm 0.4$ and $4.5 \pm 0.4$ in the high-flux and low-flux phases, respectively, both in units of $10^{39}$ erg s$^{-1}$. Therefore, the small (anti-phased) variation seen in the 1–2 keV band of figure 3 is consistent with changes in the medium-hardness component. Further examination of this issue is presented in section 4.

The Fe-K line photon flux, when allowed to differ between the two phases, was obtained as $5.83 \pm 2.35$ and $5.95 \pm 1.82$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{Spectra from the “high-flux” (open) and “low-flux” (filled) phases, shown as their ratios to the time averaged spectrum. The XIS and PIN data points are shown in circles and triangles, respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10.png}
\caption{Background-subtracted spectra from the high-flux (red) and low-flux (black) phases, fitted with the same model as figure 7d. The XIS-BI spectrum, though employed in the fitting, is omitted from the plot for clarity.}
\end{figure}

\begin{table}[h]
\centering
\caption{The best-fit parameters to the high-flux and low-flux phase spectra over 1.7–40 keV of NGC 4258.}
\begin{tabular}{|c|c|c|c|}
\hline
Component & Parameter & High & Low & Difference \\
\hline
Intrinsic PL & $\Gamma$ & $1.96_{-0.02}^{+0.03}$ & $1.70 \pm 0.02$ & $2.8_{-0.61}^{+0.74}$ \\
 & $N_{PL}$ & $5.95_{-0.07}^{+0.09}$ & $2.73 \pm 0.04$ & $7.5_{-2.8}^{+23.5}$ \\
 & $N_H$ & $11.3 \pm 0.3$ & $9.4 \pm 0.3$ & $18.1_{-4.2}^{+5.3}$ \\
Fe I K$\alpha$ & $E_c$ & $6.39 \pm 0.05$ & & \\
 & $I$ & $5.93 \pm 1.45$ & & \\
brems & $kT$ (keV) & 5.0 (fix) & & \\
 & $L$ & $4.3 \pm 0.3$ & & \\
apec & $kT$ (keV) & 0.76 (fix) & & \\
 & Abundance & 1.0 (fix) & & \\
 & $L$ & 0.39 (fix) & & \\
\hline
$\chi^2$/d.o.f. & & $435.8/436$ & $45.2/42$ & \\
\hline
\end{tabular}
\* All physical quantities and their units are the same as in table 3.
\end{table}
4. Discussion

4.1. Summary of the Results

In 2006 June, we observed NGC 4258 for ~100 ks with Suzaku. In addition to the soft thermal plasma emission, and a medium-hardness component presumably due to point sources, the absorbed hard emission from its LLAGN was detected with the XIS and HXD-PIN over a ~2 keV to ~40 keV band altogether. The acquired wide-band spectra of the nucleus have been successfully described in terms of a power-law with $\Gamma = 1.88$, absorbed by $N_H = 1.1 \times 10^{23} \text{cm}^{-2}$. The absorption-corrected 2–10 keV luminosity of the nucleus, estimated as $\sim 8 \times 10^{40} \text{erg s}^{-1}$, is typical of this LLAGN (e.g., Makishima et al. 1994; Reynolds et al. 2000; Pietsch et al. 2002; Yang et al. 2007). A narrow Fe-K line at 6.4 keV was detected at a relatively low $EW$ of $\sim 50$ eV. The reflection component was insignificant, with an upper limit of $f_{\text{refl}} < 0.3$ if the reflector was assumed to have $i = 60^\circ$, although it is relaxed to $f_{\text{refl}} < 2.0$ if a water-maser configuration of $i = 83^\circ$ was adopted (Miyoshi et al. 1995).

On a time scale of ~100 ks, we detected a clear hard X-ray variation by 20%, which can be explained by a change in the nuclear component. As the hard X-ray flux increased, the power-law component steepened by $\Delta \Gamma \sim 0.3$ with marginal evidence for an increase in $N_H$. The varying component was described by a relatively steep power-law with $\Gamma \sim 2.8$.

4.2. Implications of the Time-Averaged Spectrum

Being a prototypical LLAGN, the most outstanding feature of the NGC 4258 nucleus is of no doubt its very low X-ray luminosity, both in the absolute and relative sense. Hence, one of the most intriguing questions is whether it exhibits any X-ray signatures (other than its low luminosity) that are considered specific to LLAGNs. When trying to answer this question, the wide-band spectral coverage of Suzaku, with its good energy resolution, is considered to be essential. As part of such attempts, we may quote X-ray photon indices of the intrinsic nuclear component of several representative Seyferts, determined with Suzaku through a careful separation of the reflection component. The results include $\Gamma \sim 1.6$ in NGC 4945 (Itoh et al. 2008), $\Gamma \sim 1.7$ in NGC 4388 (Shirai et al. 2008), $\Gamma \sim 1.8$ in MCG -5–23–16 (Reeves et al. 2007), and $\Gamma \sim 1.9$ in NGC 3516 (Markowitz et al. 2008). Thus, our results on NGC 4258, $\Gamma \sim 1.9$, do not distinguish this LLAGN from other Seyferts.

Then, what do we find about the circum-nuclear matter distribution in NGC 4258? Generally, this can be probed using reprocessed signals, including in particular the fluorescence iron lines and the reflection component. The measured $EW$ ($\sim 50$ eV) of the former component, which agrees with previous measurements from this LLAGN (Makishima et al. 1994; Fiore et al. 2001), is significantly smaller than those generally found among Seyfert galaxies of both type 1 (typically $\sim 150$ eV) and type 2 [up to $\sim 1$ keV; Ueda et al. (2007)]. The latter component, i.e., reflection, consists of three spectral features; a deep Fe-K edge at $\sim 7$ keV, a Compton hump above 10 keV, and a hard continuum approximated by $\Gamma \sim -0.3$ (rising with the energy; figure 7e) below the Fe-K edge. While the last feature is confirmed in our spectrum with the point-source contribution, the iron edge is clearly very weak (figures 5 and 6). Furthermore, the HXD-PIN data, combined with the XIS flux points, rule out the presence of a strong Compton hump. Assuming a general configuration of $i = 60^\circ$, we have thus obtained a tight constraint of $f_{\text{refl}} < 0.3$, which falls much below those typically found with Seyferts ($f_{\text{refl}} \sim 1$–2; De Rosa et al. 2008).

The above results concerning the Fe-K line and reflection both mean that the nucleus of NGC 4258 is devoid of thick materials with large solid angles. As a result, an inflated torus (for which $i = 60^\circ$ is regarded as being a reasonable approximation) is unlikely to be present around it. Nevertheless, our direct view to the nucleus is obscured by a thick material with
For example, from NGC 451 with EXOSAT and Ginga (Warwick et al. 1989; Yaqoob et al. 1992), and from NGC 4051 with ASCA (Guainazzi et al. 1996). Such positive $\Gamma$ vs. flux correlations allow two alternative interpretations. One is to assume that this is an intrinsic property of the nuclear emission, possibly related to the cooling of hot electron “coronae”, which produce hard X-rays via thermal Comptonization of some soft seed photons (e.g., Sunyaev & Trümper 1979). The other is to consider the relation as being an artifact, produced by the superposition of a power-law component that varies without changing its slope, and a constant (and harder) reflection component.

As for black-hole binaries in the so-called Low-Hard state, including Cygnus X-1 in particular, Suzaku observations (Makishima et al. 2008) have revealed that the former is actually occurring at least on time scales longer than 1 s. (The latter mechanism does not work on this time scale, since the reflection catches up with the intrinsic nucleus variation). In the case of AGNs, in contrast, the latter is likely to be dominant, because their “difference” spectra can generally be expressed by a single power-law, of which the photon index is close to what is found with the time-averaged spectrum after separating the reflection component. Such examples include NGC 4945 (Itoh et al. 2008) and MCG –5–23–16 (Reeves et al. 2007). Returning to NGC 4258, our results prefer the former interpretation, because the reflection component is basically insignificant in this object. Then, the mechanism responsible for the variation of this LLAGN is suggested to be closer to that of black-hole binaries in the Low-Hard state than to those of Seyfert galaxies.

An intriguing result is a weak variation in the 1–2 keV band, apparently anti-correlated with that in the absorbed power-law. One possible interpretation is to invoke a variation of a small number of luminous point sources, as suggested by the analysis described in subsection 3.3. However, the implied luminosity change amounts to $\sim 5 \times 10^{38}$ erg s$^{-1}$, which would be too large to be explained by such a mechanism. Furthermore, we would have to invoke a chance coincidence to explain the apparent anti-correlation between the 1–2 keV and hard-band variations. Therefore, it is more natural to consider that the soft-band signals are contributed not only by point sources, but also by the nucleus at some level, and the variation therein is attributable to the nucleus contribution. Since the absorbed power-law component falls far below ($\sim 1/30$) the overall signal intensity at 1.5 keV (figure 8), this interpretation requires that a small (e.g., $\sim 1\%$) fraction of the intrinsic emission reaches us without being absorbed. Below, we construct a possible explanation based on this idea.

Let us recall that the hard X-rays from Seyfert-like objects are likely to be emitted from a hot corona with a relatively large scale height, via Compton scattering by thermal electrons (Makishima et al. 2008). If such a corona is viewed from
No. 2] Suzaku Results on the Obscured Low-Luminosity Active Galactic Nucleus in NGC 4258

sideways, its line-integrated Compton emissivity is expected to decrease rapidly as a height away from the accretion plane (like in the limb regions of solar coronae). Then, the highest part of the corona, which carries only a small fraction of the overall emissivity (but geometrically rather extended), could be rising above the grazing absorber, and hence is directly visible. If the height of this corona is time variable, the hard X-ray intensity will increase when the corona becomes less tall, because the Compton optical depth of the corona will increase due to compression. At the same time, the directly visible fraction of the coronal top region will decrease, and reduce the unabsorbed X-ray flux. Furthermore, the absorber may have a gradient in the column density, in such a way that it decreases away from the accretion plane. Then, a more compressed corona will sample on average lower heights of the absorber, leading to a slight enhancement in \( N_H \), as suggested by the data (table 4).

As a consistency check of the above scenario, a typical scale of such a corona is estimated as several tens of \( r_c \) if an analogy to Cygnus X-1 is adopted (Makishima et al. 2008). In the present case of NGC 4258, such a corona can vary just on \( \sim 50 \) ks, assuming a Keplerian time scale at such radii. Furthermore, the Comptonizing corona of Cygnus X-1 was revealed to be highly inhomogeneous (Makishima et al. 2008), and its hard X-ray intensity was suggested to increase when the corona becomes “less porous”. This is consistent with the height variation that we invoked above, because an inhomogeneous corona will naturally become less porous when it becomes vertically shorter. For a final speculation, a corona may become vertically shorter and less porous (thus leading to an increased hard X-ray intensity), as its internal magnetic pressure is released by magnetic reconnection.

The authors would like to express their thanks to the Suzaku team members. Our work was supported by Grant-in-Aid for JSPS Fellow.

References

Antonucci, R. 1993, ARA&A, 31, 473
Awaki, H., Koyama, K., Inoue, H., & Halpern, J. P. 1991, PASJ, 43, 195
Boldt, E. 1987, Phys. Rep., 146, 215
Cecil, G., Morse, J. A., & Veilleux, S. 1995, ApJ, 452, 613
Churazov, E., et al. 2007, A&A, 467, 529
De Rosa, A., Bassani, L., Ubertini, P., Panessa, F., Malizia, A., Dean, A. J., & Walter, R. 2008, A&A, 483, 749
Fiore, F., et al. 2001, ApJ, 556, 150
Fruscione, A., Greenhill, L. J., Filippenko, A. V., Moran, J. M., Herrnstein, J. R., & Galle, E. 2005, ApJ, 624, 103
Fukazawa, Y., et al. 2009, PASJ, 61, S17
Greenhill, L. J., Henkel, C., Becker, R., Wilson, T. L., & Wouterloot, J. G. A. 1995a, A&A, 304, 21
Greenhill, L. J., Jiang, D. R., Moran, J. M., Reid, M. J., Lo, K. Y., & Claussen, M. J. 1995b, ApJ, 440, 619
Greenhill, L. J., Moran, J. M., Herrnstein, J. R. 1997, ApJ, 481, L23
Gruber, D. E., Matteson, J. L., Peterson, L. E., & Jung, G. V. 1999, ApJ, 520, 124
Guainazzi, M., Mihara, T., Otani, C., & Matsuoka, M. 1996, PASJ, 48, 781
Herrnstein, J. R., et al. 1999, Nature, 400, 539
Ishisaki, Y., et al. 2007, PASJ, 59, S113
Itoh, T., et al. 2008, PASJ, 60, S251
Kokubun, M., et al. 2007, PASJ, 59, S53
Koyama, K., et al. 2007, PASJ, 59, S23
Koyama, K., Inoue, H., Tanaka, Y., Awaki, H., Takano, S., Ohashi, T., & Matsuoka, M. 1989, PASJ, 41, 731
Lasota, J.-P., Abramowicz, M. A., Chen, X., Kroll, J., Narayan, R., & Yi, I. 1996, ApJ, 462, 142
Madejski, G., Done, C., Życki, P. T., & Greenhill, L. 2006, ApJ, 636, 75
Madejski, G., Życki, P., Done, C., Valinia, A., Blanco, P., Rothschild, R., & Turek, B. 2000 ApJ, 535, L87
Maiolino, R., Salvati, M., Bassani, L., Dadina, M., Della Ceca, R., Matt, G., Risaliti, G., & Zamorani, G. 1998, A&A, 338, 781
Makishima, K., et al. 1989, PASJ, 41, 697
Makishima, K., et al. 1994, PASJ, 46, L77
Makishima, K., et al. 2008, PASJ, 60, 585
Marconi, A., Risaliti, G., Gilli, R., Hunt, L. K., Maiolino, R., & Salvati, M. 2004, MNRAS, 351, 169
Markowitz, A., et al. 2008, PASJ, 60, S277
Matt, G., Fabian, A. C., Guainazzi, M., Iwasawa, K., Bassani, L., & Malaguti, G. 2000, MNRAS, 318, 173
Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature, 373, 127
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Pietsch, W., & Read, A. M. 2002, A&A, 384, 793
Reeves, J. N., et al. 2007, PASJ, 59, S301
Revnivtsev, M., Gilfanov, M., Sunyaev, R., Jahoda, K., & Markwardt, C. 2003, A&A, 411, 329
Reynolds, C. S., Nowak, M. A., & Maloney, P. R. 2000, ApJ, 540, 143
Shirai, H. 2008, PASJ, 60, S263
Sunyaev, R. A., & Trümper, J. 1979, Nature, 279, 506
Takahashi, T., et al. 2007, PASJ, 59, S35
Terasima, Y., Iyomoto, N., Ho, L. C., & Ptak, A. F. 2002, ApJS, 139, 1
Tueller, J., Mushotzky, R. F., Barthelmy, S., Cannizzo, J. K., Gehrels, N., Markwardt, C. B., Skinner, G. K., Winter, L. M. 2008, PASJ, 60, 277
Tully, R. B. 1988, Science, 242, 310
Ueda, Y., et al. 2007, ApJ, 664, L79
Ueno, S., Koyama, K., Awaki, H., Hayashi, I., & Blanco, P. R. 1996, PASJ, 48, 389
Warwick, R. S., Yaqoob, T., Pounds, K. A., Matsuoka, M., & Yamauchi, M. 1989, PASJ, 41, 721
Wilkes, B. J., Schmidt, G. D., Smith, P. S., Mathur, S., & McLeod, K. K. 1995, ApJ, 455, L13
Wilson, A. S., Yang, Y., & Cecil, G. 2001, ApJ, 560, 689
Yang, Y., Li, B., Wilson, A. S., & Reynolds, C. S. 2007, ApJ, 660, 1106
Yaqoob, T. 1992, MNRAS, 258, 198

Downloaded from https://academic.oup.com/pasj/article-abstract/61/2/309/1591460 on 27 July 2018