Suzaku Discovery of a Hard Component
Varying Independently of the Power-Law Emission in MCG–6-30-15

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Abstract

Focusing on hard X-ray variability, we reanalyzed Suzaku data of Type I Seyfert galaxy MCG–6-30-15 obtained in 2006. Intensity-sorted spectroscopy and a principal component analysis consistently revealed a very hard component that varies independently of the dominant power-law emission. Although the exact nature of this hard component is not yet identified, it can be modeled as a power-law with a photon index \( \sim 2 \) affected by a partial covering absorption, or as a thermal Comptonization emission with a relatively large optical depth. When this component is included in the fitting model, the time-averaged 2.5–55 keV spectrum of MCG–6-30-15 can be reproduced successfully by invoking a mildly broadened iron line with large optical depth. When this component is included in the fitting model, the time-averaged 2.5–55 keV spectrum of MCG–6-30-15 can be reproduced successfully by invoking a mildly broadened iron line with large optical depth. When this component is included in the fitting model, the time-averaged 2.5–55 keV spectrum of MCG–6-30-15 can be reproduced successfully by invoking a mildly broadened iron line with large optical depth.

Key words: galaxies: active – galaxies: individual (MCG–6-30-15) – galaxies: Seyfert – X-rays: galaxies

1. Introduction

Investigations of spectral and temporal characteristics of X-ray emission from an Active Galactic Nuclei (AGN) provides one of the most direct ways to detect general relativistic effects around a black hole (BH). Among various types of AGNs, Seyfert galaxies are known to exhibit an X-ray spectrum which can be decomposed mainly into a variable power-law continuum, iron lines, and a reflection component. Using ASCA, Tanaka et al. (1995) detected a broad iron line feature from the Type I Seyfert galaxy MCG–6-30-15, and interpreted its extreme broadening as a result of special and general relativistic effects near the BH residing in this AGN. Later, this result was strengthened by other satellites, including XMM-Newton and Chandra, followed by reports of the detections of similar features from other Seyfert galaxies (for reviews, Reynolds & Nowak 2003; Nandra et al. 2007).

Utilizing the broad-band coverage of Suzaku, Miniutti et al. (2007) succeeded in reproducing the ASCA results on MCG–6-30-15. Specifically, they detected an apparently broad Fe-K line using the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007), and a strong reflection hump over an energy range of 20–40 keV using the Hard X-ray Detector (HXD; Takahashi et al. 2007). The large equivalent width of the former, \( \sim 320 \) eV, is consistent with the large reflection fraction, \( f_{\text{rel}} \equiv \Omega / 2\pi \sim 4 \), of the latter (with \( \Omega \) being the reflector’s solid angle).

A quantitative modeling of these reprocessed components by Miniutti et al. (2007) indicated that they are emitted from an accretion disk with an inner radius of \( R_{\text{in}} \sim 2 R_g \). Here, \( R_g \) is the gravitational radius, and is \( \sim 15 \) \( \text{lt s} \) in the present case assuming a BH mass of \( 3 \times 10^6 M_\odot \) (McHardy et al. 2005). Because the derived \( R_{\text{in}} \) is significantly smaller than the radius of the last stable circular orbit (6 \( R_g \)) around a non-spinning BH, the BH in this Seyfert galaxy was concluded to be rapidly spinning (Miniutti et al. 2007).

During these Suzaku observations, the iron line flux and the reflection-component intensity were both approximately constant on time scales of 45 ks (Miniutti et al. 2007), while the power-law emission did vary. Although this behavior apparently contradicts the idea that the iron line and the reflection component are emitted from a close vicinity of the black hole, Miniutti et al. (2007) introduced the “light-bending” model as a possible explanation to the phenomena: when the power-law emitting region is located at particular positions above the accretion plane, and gets closer to the BH, the power-law component becomes dimmer because more photons are swallowed into the black hole, while the strength of the reflected component is kept rather constant. In addition, this geometry can explain the unusually large value of \( f_{\text{rel}} \).

The light-bending model, however, requires the specific geometry with fine tuning, in order to explain the varying power-law continuum and the non-varying reprocessed components (Niedźwiecki & Życki 2008). In addition, some other works showed that the same Suzaku spectrum

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of MCG–6-30-15 can be reproduced with alternative spectral modelings, invoking ionized absorbers and partial covering, but using neither the broad iron line nor the strong reflection (e.g., Miller et al. 2009; Miyakawa et al. 2009). Thus, the same data allow degenerate interpretations with different physical implications, one requiring a rapid BH rotation whereas the others not.

To disentangle the model degeneracy, identifying the underlying spectral components in a model independent manner is critically important. For this purpose, many works, such as statistical and timing analyses, have been performed so far (e.g., Taylor et al. 2003; Vaughan et al. 2004; Miller et al. 2009). However, due to lack of sensitivity in the energy band in > 15 keV, few of them focused on the hard X-ray variability. In the present paper, we hence studied the variability of MCG–6-30-15 in the hard X-ray band, where the putative large reflection is dominant. As a result, we have successfully identified a very hard component that may be distinct from the usually assumed reflection. Taking this component into account, we have succeeded in reproducing the time-averaged 2.5–55 keV spectrum without invoking the extremely broad iron line or the strong reflection.

2. Observation and Data Reduction

The present work uses the same Suzaku data of MCG–6-30-15 as Miniutti et al. (2007) did. They were obtained with the XIS and the HXD on three occasions, 9–14, 23–26, and 27–30 of January 2006. After standard data screening process of Suzaku, the exposures achieved with the XIS are 143 ks, 98 ks, and 97 ks in the three observations, while those with HXD-PIN are 126 ks, 82 ks, and 90 ks, respectively. We analyze on-source and background data processed via version 2 pipeline processing, together with the corresponding software and calibration data.

On-source events of each XIS camera were extracted from a circular region of 6′ radius centered on the source, while background XIS events were taken from a surrounding annular region of the same camera with the inner and outer radii of 6′ and 10′, respectively. We added events from XIS0, XIS2, and XIS3, because these three front-illuminated (FI) CCDs have almost identical responses. The response matrices and ancillary response files were created utilizing xisrmgen and xissimgen (Ishisaki et al. 2007), respectively. The data from XIS1 (back-illuminated CCD) are not utilized in the present work.

In a similar way, events from HXD-PIN were accumulated. Non X-ray background (NXB), included in the on-source data, is estimated by analyzing the set of fake events which are created by a standard NXB model (Fukazawa et al. 2009). By analyzing the on-source and the NXB event sets in the same way, we can subtract the NXB contribution from the HXD-PIN data. The events remaining after the NXB subtraction still include contributions from the cosmic X-ray background (CXB; Bold et al. 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.

3. Timing Analysis

3.1. Light curves

Figure 1 shows light curves of MCG-6-30-15, obtained on the three occasions with the XIS and HXD-PIN. All of them are shown after subtracting the backgrounds (both NXB and CXB) as described in section 2, and corrected for dead times. In addition to clear variations by a factor of 2 in the XIS light curves, those of HXD-PIN also vary significantly with a typical amplitude of $\sim \pm 30\%$ ($\sim \pm 0.03 \text{ cnt s}^{-1}$). Since the HXD-PIN NXB is modeled within a systematic uncertainty of 1–2% (Fukazawa et al. 2009), or 0.003 – 0.006 cnt s$^{-1}$ in the present case, the HXD-PIN variations are real rather than instrumental. Although the hard X-ray variations generally follow those in the soft X-rays, the two bands sometimes appear to be varying in rather uncorrelated manner. This issue is discussed in the next subsection.

3.2. Count-Count Plots

In order to examine to what extent the XIS and HXD intensities are correlated, we made scatter plots between the 3–10 keV XIS count rates and those of HXD-PIN in 15–45 keV, and show them in figure 2. We hereafter call them Count-Count Plots (CCPs). There, the time bin size is chosen to be 10 ks, which is a minimum integration time needed to achieve sufficient photon statistics. These CCPs employ the XIS count rates with background subtraction. The HXD data are used in figure 2 with the NXB also subtracted, but with the CXB inclusive, because the CXB should be constant with time, and only gives a positive offset by $\sim 0.02 \text{ cnt s}^{-1}$. The errors associated with the HXD data points are quadratic sum of the statistical errors and the systematic NXB error by $\sim 1.4\%$ (Fukazawa et al. 2009). In all CCPs, the XIS and HXD count rates both vary by a factor of $\sim 2$, generally in positive correlations.

As shown in figure 2, we fitted the data points in each CCP with a straight line. The fits in the first and the second observations were both acceptable, with $\chi^2/\text{d.o.f.} = 33.38/34$ and $\chi^2/\text{d.o.f.} = 18.69/20$, respectively. Therefore, the soft and hard intensities in these data sets are consistent with being fully correlated, without evidence of any hard-band variations that is independent of those in the soft X-ray band. In other words, the variability in these data sets is “one-dimenstional”. The obtained linear fits are described as

$$y = (0.019 \pm 0.003)x + (0.068 \pm 0.010) \quad (1\text{st obs.}),$$
$$y = (0.021 \pm 0.005)x + (0.076 \pm 0.012) \quad (2\text{nd obs.}),$$

where $x$ and $y$ denotes the XIS and HXD-PIN counts, respectively. Thus, the hard counts have a positive offset that is larger than is predicted by the CXB contribution.
3.3. Examination of the NXB reproducibility

There would be an immediate suspect that the two-dimensional data scatter in figure 2c simply reflects variations in the HXD-PIN background that have not been accurately subtracted out by the NXB model. To investigate this issue, we compare in figure 3 light curves (with 10 ks binning) of four relevant quantities (see caption for the explanation). If the effect seen in figure 2c were due to residual NXB variations, the purple light curve in figure 3c should show some (anti-) correlations to the NXB model (green), because the NXB model reproducibility is limited mainly by the accuracy to account for orbit-related semi-periodic NXB changes (Fukazawa et al. 2009). However, we do not find such correlations in figure 3c.

Figure 4 shows an occurrence distribution of the purple light curve in figure 3c. (This is identical to the distribution of data deviations in figure 2c from the corre-
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Fig. 3. Detailed 15–45 keV HXD-PIN light curves of the three observations with a 10 ks binning. The raw count rate is in red, the modeled NXB is in green, and the NXB-subtracted signal is in blue. Purple in panel (c) shows the hard X-ray deviation in figure 2c from the correlation line.

Fig. 4. A histogram of the hard X-ray deviation from the best-fit line in the CCP of the 3rd observation (figure 2c).

lution line). This histogram exhibits an rms scatter by 0.017 ± 0.003 cnt s⁻¹ which corresponds to 5.2% of the average NXB rate, around the mean of 0.0018 cnt s⁻¹. This is significantly larger than the typical rms scatter of the NXB modeling residuals at the 10 ks binning, 2.3%, as reported by Fukazawa et al. (2009). Therefore, the 21 data points, constituting the HXD-PIN count rate in figure 3c purple, are found to exhibit a standard deviation which is 2.3 times larger than that of the population formed by the residual NXB rate at 10 ks binning. According to F-tests, we find a chance probability of less than 1% for the former sample to be derived from the latter population. We hence conclude that the effect observed in figure 3c is difficult to explain in terms of residual NXB fluctuations.

There would still remain a concern that the NXB behavior was not normal during the 3rd observation. To examine this possibility, we accumulated the HXD-PIN spectrum over Earth occultation periods in the three observations, with an exposure of 94 ks, 52 ks, and 42 ks, and normalized them to those predicted by the NXB model. As shown in figure 5, the three spectral ratios behave in very similar ways, all close to unity, without any indication that the 3rd observation was unusual. In particular, the 3rd ratio (as well as the other two) is very flat towards the highest and lowest energy limits, where any anomalous NXB behavior would appear preferentially.

From these examinations, we conclude that the secondary hard component in the 3rd data set is not an artifact caused by uncertainties in the NXB reproducibility. In addition, this component is not due either to slow spectral variations associated, e.g., with long-term changes in the accretion geometry, because the purple light curve in figure 3c varies on a typical time scale of several tens kiloseconds.

3.4. A Variable Hard Component

Having confirmed that the secondary hard X-ray variation in the 3rd observation is real rather than instrumental, let us examine how the wide-band spectrum changes as the hard X-rays vary independently of the soft X-rays.
To see this, we defined “High” and “Low” phases, wherein the data points are above and below the straight line in the CCP, respectively. We then subtracted the spectrum accumulated over the “Low” phase, from that summed over the “High” phase. As a result of this subtraction, positive signals have remained in both the XIS and PIN bands. Figure 6 shows “difference spectrum” obtained in this way, normalized to the prediction of a power-law model of photon index $\Gamma = 2.0$. The ratio, though approximately constant in the XIS band, increases by an order of magnitude in the HXD-PIN band. We interpret that the data points in the CCP of the 3rd observation (figure 2c) exhibit the vertical scatter, because this hard spectral component varied, on time scales of 10–50 ks, independently of the primary power-law component.

In figure 6, we also show the HXD-PIN NXB spectrum, reduced in normalization to 5% of its average. Although it is thus similar in shape to the difference spectrum, the latter does not increase to lower energies where the NXB uncertainty is largest (Fukazawa et al. 2009). Furthermore, the NXB spectrum rises toward higher energies, while the other does not. Therefore, it is hard to explain the difference spectrum in terms of insufficient NXB subtraction. This reinforces our conclusion made in subsection 3.3.

To quantify the difference spectrum, we fitted it with several models. Figure 7a shows the simplest case of fitting it with an unabsorbed power-law model. The fit was in fact acceptable with $\chi^2$/d.o.f. $= 44.47/41$, and gave $\Gamma = 1.03^{+0.49}_{-0.23}$. Thus, the difference spectrum indeed has a much harder average slope than the primary $\Gamma \sim 2$ power-law which dominates the average spectrum of MCG–6–30–15. However, this $\Gamma = 1$ fit is not necessarily successful if the HXD data only are considered. This urges us to look for better modeling. This hard slope may be a result of absorption of a certain fraction of the primary component, and changes of this fraction may be responsible for the independent hard X-ray variation. To examine this possibility, we refitted the difference spectrum with a $\Gamma = 2.0$ (fixed) power-law, absorbed by an ionized medium with a free column density $N_H$ and free ionization parameter $\xi$. 

**Fig. 5.** The ratios between the HXD-PIN spectrum accumulated over Earth occultation periods and the modeled NXB spectrum on (a) 2006 January 9, (b) 2006 January 23, and (c) 2006 January 27.

**Fig. 6.** The difference spectrum from the 3rd observation, divided by the prediction of a $\Gamma = 2.0$ power-law model. A green curve shows 5% of the HXD-PIN NXB.
Fig. 7. The difference spectrum in the $\nu F_\nu$ form from the 3rd observation, fitted with (a) an unabsorbed power-law with a free slope, (b) a power-law with $\Gamma = 2.0$ absorbed by an ionized medium, (c) a partially absorbed power-law with $\Gamma = 2.0$, (d) a thermal Comptonization spectrum with an electron temperature of 13.4 keV, seed photon temperature of 0.1 keV, and an optical depth of 12.0, and (e) reflection plus a broad Fe-K line.

The chemical abundance of the ionized absorber was fixed at 1.0 solar. This modeling gave a column density of $10^{23}$ cm$^{-2}$ and $\log \xi = 0.70$ as the best estimates, but the fit was unsuccessful with $\chi^2$/d.o.f. = 50.24/41, because the model fell much short of the HXD-PIN data as presented in figure 7b. Therefore, a simple ionized absorber interpretation is not appropriate: when assuming a $\Gamma = 2.0$ power-law as the incident spectrum, it cannot explain the slope hardening in the 10–20 keV interval.

A simple and promising way to improve the above two unsuccessful modelings, and to create an apparently very hard continuum with low-energy flattening, is to assume “partial covering” of the primary power-law. When a thick material absorbs a certain fraction of the emission while the rest reaches us without absorption, a spectrum like figure 6 will emerge. Indeed, the presence of such a partially-covering absorber (with possible ionization) is supported by various observations (e.g., Miller et al. 2009, Miyakawa et al. 2009). We have fitted the different spectrum with a partial covering model, wabs * power + wabs * power. The photon indices of the two power laws were both fixed at 2.0, and one wabs was fixed at the Galactic line-of-sight value toward this AGN, $4.0 \times 10^{20}$ cm$^{-2}$. As a result, the fit was very successful with $\chi^2$/d.o.f = 33.35/41; the thicker column density became $N_H = 2.5^{+0.3}_{-0.7} \times 10^{24}$ cm$^{-2}$, and the ratio between the strongly absorbed power-law to the other one was $0.89 \pm 0.06$. As shown in figure 7c, the dominant strongly-absorbed signals explain the HXD data, while the minor “leak through” signals mainly account for the XIS data.

This variable hard component must originate in regions near the central BH, because its variational time scale
of \( \sim 10 \) ks translates to a distance of \( \sim 700 R_g \). Then, thermal Comptonization is one of alternative production processes of such a hard continuum in such regions, as evidenced by the most recent Suzaku results on Cyg X-1 which revealed the Compton corona to have multiple optical depths (Makishima et al. 2008). We therefore fitted the difference spectrum with a thermal Comptonization model, \texttt{comptt} in Xspec12, with the seed photon temperature fixed at 0.1 keV and the coronal geometry assumed to be disk. As presented in figure 7d, the fit has been successful with \( \chi^2/\text{d.o.f.} = 40.69/41 \), yielding an optical depth of \( \tau \sim 5.3^{+1.7}_{-1.8} \) and an Comptonizing electron temperature of \( T_e = 16.0^{+68.4}_{-7.1} \) keV. Therefore, this variable hard component allows an alternative interpretation as a result of thermal Comptonization in a relatively thick and cool corona. Even if this component is absorbed, e.g., by a neutral column of \( N_{\text{H}} = 1.0 \times 10^{22} \) cm\(^{-2}\), the fit parameters remain unchanged within the errors.

The difference spectrum, though reproduced with a partial covering model or \texttt{comptt}, could still be a part of reflection, considering its resemblance in shape to the ordinary reflection component. To examine this possibility, we fitted the difference spectrum alternatively with an iron line and a reflection, modeled by \texttt{laor} (Loar 1991) and \texttt{pexrav} (Magdziarz & Zdziarski 1995), respectively. The \texttt{laor} component was assumed to have typical parameters: the center energy of 6.4 keV, the emissivity index of 3.0, \( R_{\text{in}} = 10 R_g \), and an inclination of 30\(^\circ\). Its equivalent width was set at 1500 eV with respect to \texttt{pexrav}, which we would expect when a power-law of \( \Gamma = 2 \) line) component. Changing the parameters did not help very much.

4. Reanalysis of time-averaged spectra of MCG–6-30-15

Through the CCP and difference-spectrum techniques, we have shown that the hard X-ray variation of MCG–6-30-15 during the 3rd Suzaku observation is driven not only by intensity variations of the primary (unabsorbed) power-law continuum, but also by those of a secondary component with a hard spectrum. Then, we expect to find the same secondary component in the time-averaged spectra. In figure 2, the CCPs in the 1st and 2nd observations are consistent with exhibiting one-dimensional distributions, unlike the 3rd observation. This may be understood by presuming that the secondary hard spectral component was present on all three occasions, but its intensity varied significantly only in the 3rd observation. With this in mind, we analyze in this section the 2.5–55 keV spectrum of MCG–6-30-15, summed over the three observation to increase statistics.

4.1. Fitting including the variable hard component

To look for possible contributions of the variable hard component in the persistent X-ray emission, we fitted the summed time-averaged spectra of XIS and HXD-PIN of MCG–6-30-15 with a model \texttt{wabs} * (\texttt{cutoffpl} + \texttt{pexrav} + \texttt{comptt} + \texttt{laor} + three narrow gaussians). Although the secondary component is expressed here in terms of the Comptonization scenario, this is for simplicity only, and the results to be obtained below are essentially the same if we alternative employ the partial-covering scenario. Except for this \texttt{comptt}, the model composition is almost the same as that employed by Miniutti et al. (2007). One of the three gaussians expresses the narrow Fe-K emission line around 6.4 keV, while the other two (with negative normalizations) the resonance absorption lines by ionized iron. The column density of neutral absorption was left free (see below). We fixed the emissivity index of \texttt{laor} at 3.0 again. Referring to the result obtained in section 3.4, the optical depth \( \tau \) and the electron temperature of \texttt{comptt} were fixed at 5.3 and 16.0 respectively, while its normalization was left free. The cutoff energy of \texttt{cutoffpl} was fixed at 200 keV, and its photon index \( \Gamma \) was tied to that of \texttt{pexrav}. The relative abundance of heavy elements other than Fe was fixed at 1.0, while that of Fe, \( A_{\text{Fe}} \), was left free. The other parameters were left free.

With this model, we successfully obtained an acceptable fit (\( \chi^2/\text{d.o.f.} = 172.44/157 \)). The obtained parameters are summarized in table 1 (3rd column), and the best-fit model and residuals are shown in figure 8. The column density, \( N_{\text{H}} \sim 0.8 \times 10^{22} \) cm\(^{-2}\), is considered to approximate (in the limited energy range of \( > 2.5 \) keV) the effect of warm absorber. Except for the reflection fraction \( f_{\text{refl}} \) and the inner radius \( R_{\text{in}} \), the derived parameters are consistent with those in Miniutti et al. (2007). Since \texttt{comptt} accounts for some fraction of the hard X-ray signals, the reflection intensity has decreased to \( f_{\text{refl}} \sim 1.2 \), from the solution with \( f_{\text{refl}} > 2 \) by Miniutti et al. (2007). The obtained inner radius of \texttt{laor} is \( R_{\text{in}} \sim 10 R_g \), again in contrast to the value of \( R_{\text{in}} \sim 2 R_g \) derived by Miniutti et al. (2007). This is because the inclusion of the secondary hard component has slightly changed the continuum curvature around 3–6 keV. The equivalent width of the broad iron line is \( = 145^{+93}_{-74} \) eV, which is much smaller than \( \sim 320 \) eV in Miniutti et al. (2007), but consistent with the value of \( \sim 160 \) eV expected from the reflection fraction of \( f_{\text{refl}} \sim 1.2 \) (George & Fabian 1991).

4.2. Fitting with a relativistically burred reflection

Although we succeeded in obtaining an acceptable model in section 3.1, it is physically still incomplete and self-inconsistent in the sense that the relativistic effects are applied only to the Fe-K line, but not to the reflection component which is expected to arise from almost the same locations as the Fe-K line. Therefore, we further included the relativistic effect in \texttt{pexrav}. The model is now \texttt{wabs} * (\texttt{cutoffpl} + \texttt{kdblur} * \texttt{pexrav} + \texttt{comptt} + \texttt{laor} + three narrow gaussians). Here,
parameters are shown in Table 1 (4th column). The fit result of this fitting is shown in Figure 9, and the obtained thermal Comptonization component normalization in units of $10^5$.

As a result of this model improvement, we obtained a significantly better fit ($\chi^2$/d.o.f. = 150.84/157). The fit parameters have remained, within errors, mostly the same as before. In particular, the inner disk radius was again found at $R_{in} \sim 10 R_g$ as before. Although $f_{ref}$ somewhat increased, it is still small enough to allow straightforward interpretation. Thus, the spectrum can be interpreted invoking neither the extremely broad Fe-K line, nor the too strong reflection. Since this solution does not require the accretion disk to intrude inside the 6 $R_g$ limit for a Schwarzschild BH, the Suzaku data of MCG–6-30-15 can

**Table 1.** The best fit parameters of MCG–6-30-15 with the model $\text{wabs} \ast (\text{cutoffpl} + \text{pexrav} + \text{comptt} + \text{laor} + \text{three narrow gaussians})$ (3rd column), or by further convolving pexrav with kdblur (4th column).

| Component | Parameter | W/o kdblur | With kdblur |
|-----------|-----------|------------|-------------|
| wabs      | $N_H^*$   | $0.78^{+0.04}_{-0.05}$ | $0.95^{+0.05}_{-0.05}$ |
| powerlaw  | $\Gamma$  | $2.13^{+0.06}_{-0.09}$  | $2.24^{+0.11}_{-0.12}$ |
|           | $N_{PL}^\dagger$ | $1.87^{+0.01}_{-0.03}$ | $2.12^{+0.02}_{-0.02}$ |
| reflection| $f_{ref}$ | $1.2^{+0.2}_{-0.1}$ | $1.7^{+0.3}_{-0.2}$ |
|           | $A_{Fe}$  | $1.21^{+0.28}_{-0.2}$ | $0.98^{+0.08}_{-0.13}$ |
| comptt    | $T_c$ (keV) | $16.0$ (fix) | $16.0$ (fix) |
|           | $\tau$   | $5.3$ (fix) | $5.3$ (fix) |
|           | $N_C^\#$ | $4.07^{+5.08}_{-4.07}$ | $7.42^{+3.64}_{-4.10}$ |
| Fe I Kα   | $E_{\alpha}^g$ | $6.38^{+0.17}_{-0.17}$ | $6.35^{+0.08}_{-0.13}$ |
|           | $R_{in}(R_g)$ | $8.24^{+2.83}_{-2.27}$ | $9.47^{+1.65}_{-1.93}$ |
|           | $\theta$  | $33.5^{+12.3}_{-7.9}$ | $35.9^{+4.1}_{-1.7}$ |
|           | $N_{Fe}^b$ | $5.56^{+0.92}_{-0.92}$ | $6.86^{+1.09}_{-0.89}$ |
|           | $EW$ (eV) | $145^{+93}_{-74}$ | $196^{+65}_{-57}$ |

$^*$ Equivalent hydrogen column density in $10^{22}$ cm$^{-2}$
$^\dagger$ The power-law normalization at 1 keV, in units of $10^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV
$^\|$ Center energy in keV
$^\dagger$ The broad iron line normalization in units of $10^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$
$^\#$ The thermal Comptonization component normalization in units of $10^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$.

**kdblur,** implemented in xspec12, works as a convolution model to blur a spectrum by relativistic effects in the same way as laor. The parameters of kdblur are all linked to those of laor. With the other parameters kept in the same condition as in section 4.1, we refitted the spectrum.

As a result of this model improvement, we obtained a significantly better fit ($\chi^2$/d.o.f. = 150.84/157). The result of this fitting is shown in Figure 9, and the obtained parameters are shown in Table 1 (4th column).
be interpreted without invoking a rapidly spinning BH.

5. Discussion and Summary

Using the Suzaku XIS and HXD data acquired on three occasions in 2006 January, we studied broad-band X-ray spectra and variations of MCG–6-30-15. On the first two occasions, the hard X-ray (15.0–45.0 keV) intensity variations at 10 ks binning were consistent with being fully correlated with those in the 3.0–10.0 keV energy band. This means that the overall source variability can be explained solely by intensity changes of the dominant power-law continuum in these periods. The constant offsets in equation (1) and (2), or equivalently, the positive y-intercepts in figure 3, are interpreted as the non-varying reflection component. In the 3rd observation, in contrast, the hard X-ray variations on the 10–50 ks time scales were partially uncorrelated with those in the soft X-ray band. In other words, the overall variability in this case involved at least two independent parameters.

In the previous studies of MCG–6-30-15, the hard X-ray spectral bump (entirely attributed to reflection) was reported to remain rather constant while the main power-law varied. These results, however, were obtained mainly by taking a difference spectrum between two time phases, wherein the overall intensity is high and low (e.g., figure 11 of Miniutti et al. 2007). In our figure 2, this means taking a difference between the right and left halves of each panel. By doing so, the newly discovered secondary variability would approximately cancel out, because of its independent nature, and would not appear in the difference spectrum. In that sense, the CCPs have played an essential role.

The source behavior in the 3rd observation has been explained successfully by considering that the spectrum involves a very hard spectral component that is prominent in the HXD-PIN band and varies independently of the power-law. In the 3–45 keV energy range, this “variable hard component” could be approximated by a power-law with \( \Gamma \sim 1.0 \). More physically, this component can be interpreted in terms of a partial covering model. We may then envisage that a thick absorber covers a fraction of the entire power-law emission region. Although such a strongly absorbed continuum must be accompanied by a strong fluorescent Fe–K line with an equivalent width of \( \sim 2 \times (\alpha/4\pi) \) keV (Makishima et al. 1986), where \( \alpha \) is the solid angle of the absorption, the absorbed continuum itself carries only \( \sim 1/30 \) of the overall continuum at \( \sim 7 \) keV (figure 7). Therefore, the associated Fe–K line is expected to have an equivalent width of \( \sim 70 \times (\alpha/4\pi) \) eV. Because the equivalent width of the narrow Gaussian was obtained as \( 23^{+5}_{-4} \) eV, we infer \( \alpha/4\pi \sim 0.3 \). When the power-law intensity varies with the covering fraction kept constant, the source will move on the CCP along the correlation line. When, instead, the covering fraction varies under a constant power-law intensity, only the soft X-ray intensity will change, and hence the source will move horizontally on the CCP. Thus, in this interpretation, the covering fraction slightly changed only in the 3rd observation while little in the first two.

An alternative idea of interest is to regard the variable hard emission as a thermal Comptonization component with an optical depth of \( \tau \sim 5.3 \) and an electron temperature of \( T_e \sim 16.0 \) keV. In this case, variations of this component is expected to cause the source to move almost vertically on a CCP. Although it is not obvious whether such a relatively cool and dense Comptonization plasma can exist in an AGN, an ingredient like this is not necessarily alien to the general view of accreting black holes. Using the Suzaku data, Makishima et al. (2008) in fact showed that the Comptonizing corona in Cyg X-1 is highly inhomogeneous, requiring at least two optical depths for Comptonization. One possible candidate for a large value of \( \tau \) is a kind of transition zone between the disk and the surrounding corona.

Taking the newly identified hard X-ray variation into account, the time-averaged 2.5–55 keV spectra of MCG–6-30-15 have been reproduced successfully using 7 components: \texttt{comptt} (or equivalently, a partially-absorbed \( \Gamma = 2.0 \) power-law), a power-law with \( \Gamma = 2.24 \), a reflec-
tion with $f_{\text{refl}} \sim 1.7$, a mildly broadened Fe-K line emitted from a disk with $R_{\text{in}} \sim 10 R_g$, and three Gaussians. This result does not change even if we apply relativistic smearing to the reflection component. This condition implies a case wherein the AGN in MCG–6-30-15 is a Schwarzschild black hole.

As originally pointed by Inoue and Matsumoto (2003) with ASCA, photo-ionized warm absorbers can reduce the need for the extreme Fe-K line broadening. This has recently been demonstrated by Miller et al. (2008) and Miyakawa et al. (2009) with the same Suzaku data as we used. They have shown that the inclusion of warm absorbers can increase the inner disk radius derived from the Fe-K line shape. It is our future task to more solidly combine the present results with the warm absorber scenario, and hence to improve our understanding of the underlying continuum shape of this important AGN.

Appendix 1. Principal Component Analysis

We carried out principal component analysis for the third interval. The background-subtracted light curves, with a bin width of 10 ks, were produced in 5 energy bands, 0.5–3.0 keV, 3.0–6.0 keV, 6.0–9.0 keV, 9.0–12.0 keV and 15.0–45.0 keV. Each band has an error within 4%. At the $i$-th time bin, we can define a 5-dimensional vector $\vec{v}_i = (C_{i1}, C_{i2}, \ldots, C_{i5})$, where $C_{ij}$ is the counts at this time bin in the $j$-th energy band. The ensemble $\{\vec{v}_i\}$ then forms a subset in a 5-dimensional Euclidean space. The principle component analysis is a standard procedure to find principal axes (up to 5) of $\{\vec{v}_i\}$, and to estimate elongations (or “principal values”) of $\{\vec{v}_i\}$ along those axes.

As a result of this analysis, the first and the second principal components were found to be dominant while the others are negligible. Therefore, the ensemble $\{\vec{v}_i\}$ has essentially a two-dimensional distribution, in agreement with the conclusion derived from figure 2c. Table 2 shows eigen values and eigen vectors of the 1st to 3rd principal components. Figure 10 shows the first and the second eigenvectors, divided by the corresponding principal values. Thus, the first principal component has a relatively flat spectral distribution, and can be interpreted as variations of the most dominant power-law component. In contrast, the 2nd principal component is concentrated in the highest energy range, and interpreted as representing a very hard component that is “orthogonal” to (i.e., varying independently of) the 1st component. This is approximately identified with the “variable hard component” discovered via CCP in section 3.3.

References

Boldt, E. 1987, Phys. Rep., 146, 215
Ishisaki, Y., et al. 2007, PASJ, 59, S113
Koyama, K., et al. 2007, PASJ, 59, S23
Laor, A. 1991, ApJ, 90L, 376
Magdziarz, M., & Zdziarski, A. 1995, MNRAS, 273, 837
Makishima, K., et al. 2008, PASJ 60, 585
Makishima, K. 1986, in The Physics of Accretion onto Compact Objects, ed. K. O. Mason, M. G. Watson, & N. E. White (Berlin: Springer) 249
Matsumoto, C., Inoue, H., Fabian, A. C., & Iwasawa, K. 2003, PASJ, 55, 613
McHardy, I. M., Gunn, K. F., Uttley, P., & Goad, M. R. 2005, MNRAS, 359,1469
Miller, L., Turner, T. J., & Reeves, J. N. 2008, A&A 483, 437
Miller, L., Turner, T. J., & Reeves, J. N. 2009, MNRAS, 399, L69
Miniutti, G., et al. 2007, PASJ, 59, S315
Miyakawa, T., Ebisawa, K., Terashima, Y., Tsuchihashi, F., Inoue, H., & Zycki, P. 2009, PASJ, 61, 6, 1355
Nandra, K., O’Neill, P. M., George, I. M., & Reeves, J. N. 2007, MNRAS, 382, 194
Niedźwiecki, A., & Zycki, P. T. 2008, MNRAS, 386, 2, 759
Reynolds, C., & Nowak, M., Physics Reports, 377, 6, 389
Taylor, R. D., Uttley, P., & McHardy, I. M., 2003, MARAS, 342, 2, 31
Takahashi T., et al. 2007, PASJ, 59, S35
Tanaka, Y., et al. 1995, Nature, 375, 659
Uehara, Y. Master’s thesis, University of Tokyo, 2009
Vaughan, S., Fabian, A. C., Iwasawa, K., & Turner, A. K., 2004, Nuclear Physics B Proceedings Supplements, 132, 244
Table 2. Eigen values and eigen vectors of 1st to 3rd principal component.

| Principal component | Eigen value | Eigen vector          |
|---------------------|-------------|-----------------------|
| 1st                 | 0.89        | (0.46, 0.47, 0.47, 0.46, 0.37) |
| 2nd                 | 0.09        | (-0.28, -0.18, -0.17, -0.10, 0.92) |
| 3rd                 | 0.01        | (-0.51, -0.29, 0.08, 0.80, -0.11) |

Fig. 10. The first (upper data points) and the second (lower) eigenvectors from the principal component analysis, divided by the corresponding principal values.