XMM-Newton Observations of NGC 4051: Temporal Flux and Spectral Variability during Transition to the Faintest Phase in NGC 4051

Yoshito HABA,1 Andrew C. LIEBMANN,2 Keigo FUKUMURA,3 Hideyo KUNIEDA,1 and Sachiko TSURUTA2

1Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602
2Department of Physics, Montana State University, PO Box 173840, Bozeman, MT 59717-3840, USA
3NASA Goddard Space Flight Center, Gravitational Astrophysics Laboratory, Code 663, Greenbelt, MD 20771, USA

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Abstract

We report on the results from temporal and spectral analyses of NGC 4051 observed with XMM-Newton. The X-ray variabilities in the higher-flux states are well explained by the combination of a variable, direct power law and a temporally stable, absorbed component. In low-flux states, however, spectral variations are mainly due to flux changes of the absorbed component. Furthermore, when the source enters into the lowest-flux state, the absorbed component no longer appears. One promising interpretation is that part of the central emission region is covered by a temporally stable material, while the size of the emission region varies so as to produce a flux variation predominantly in direct power-law component. Once the emission region becomes smaller than the size of the absorber, however, the absorbed flux also begins to decrease. Finally, when the emission region is reduced sufficiently, both the direct and absorbed components disappear (i.e., “switched off” state). In this state, we found the signature of thermal emission, whose temperature of 0.8 keV is in agreement with the average value obtained from statistical analyses of Seyfert 2 galaxies with starburst activity. This could suggest that NGC 4051 possesses a nuclear starburst region.

Key words: galaxies: active — galaxies: individual (NGC 4051) — galaxies: Seyfert — X-rays: galaxies

1. Introduction

NGC 4051 lies at a low-luminosity end of narrow-line Seyfert 1 galaxies (NLS1s). Its typical luminosity is about a few \( \times 10^{41} \) erg s\(^{-1}\). It has also been well-known that the source exhibits an extreme X-ray flux variability and an associated strong spectral variability on both long (~1 year) and short (~1000 s) time scales (e.g., Papadakis et al. 2002; Lamer et al. 2003).

In order to explain such rapid intensity and spectral changes, Kunieda et al. (1992) proposed a “blob” model, where optically thick (~10\(^2\) cm\(^{-2}\)) blobs are moving around the central emission region, and flux and spectral variations result from a change of the blob number in the line of sight. This blob model successfully explained various flux and spectral states observed by GINGA. Furthermore, this model predicted that the observed spectral change may not be intrinsic behavior, but may arise from a modification of the intrinsically constant spectrum by a change of the covering fraction of the blobs. By analyzing the same XMM-Newton data that are adopted in our current analyses, Pounds et al. (2004) also reported the existence of a partially absorbed power-law component. Especially, these authors found a drastic change in the soft energy spectrum taken with reflection grating spectrometers (RGSs), where many absorption lines from photoionized C, N, O, and Ne were seen in a high-flux state, while the absorption lines were replaced by emission lines in a low-flux state. Since the emission-line spectrum is very similar to that of type-2 Seyfert galaxies, they concluded that the enhanced visibility of the emission lines is due to an increase of opacity in a column of the line-of-sight gas responsible for the hard continuum in the low-flux state. In order to investigate the spectral variability in a model-independent way, Uttley et al. (2004) performed a flux–flux plot analysis (Churazov et al. 2001), and showed that the relationship between the soft and hard counts was well explained by a power-law model that corresponds to a pivoting model, where the power-law continuum pivots so as to become softer (harder) at high (low) fluxes. Recently, Ponti et al. (2006) proposed an alternative interpretation of the spectral variability of NGC 4051. These authors applied a “two-component” model (Fabian et al. 2002; Fabian & Vaughan 2003; Taylor et al. 2003), which consists of a variable power law with a constant slope and a relatively stable relativistically blurred (Laor 1991), ionized reflection (Ross & Fabian 2005). The model well explains the observed spectral shape and the rms variability.

Another interesting flux-variation behavior is that the source sometimes enters into an extremely low-activity state. The X-ray spectrum during the period of this low state was measured simultaneously by BeppoSAX and RXTE in 1998 May (Guainazzi et al. 1998; Uttley et al. 1999), and was found to have an extremely flat (\( \Gamma \sim 0.8 \)) shape. A recent Chandra observation also caught the source with a very hard (\( \Gamma \sim 1 \)) power-law continuum (Uttley et al. 2003). This interesting behavior in the low-flux state will give us a unique opportunity to examine the low-flux, steady spectral component, which could be scattered/reflected emission from matter surrounding the central region and/or radiation from optically thin thermal plasmas further away from the central engine.
which are usually buried under the stronger central emission.

In this paper we present the results from XMM-Newton observations of NGC 4051 performed in 2001 and 2002. In the 2001 observation, the source showed rapid and large amplitude flux variability with a historical mean intensity. On the other hand, the source entered into a low-flux state in 2002. Accompanying these changes of states, we also found drastic spectral changes, especially in the hard X-ray continuum. In the same way as Ponti et al. (2006), our results also support the “two-component” basis of the spectral variability. However, we would present an alternative interpretation of the relatively stable component, which is explained by a partial covering model.

After the introduction in this section, observations and data reduction methods are presented in section 2, and our results are reported in section 3. After a discussion in section 4, a summary and conclusions are given in section 5.

2. Observations and Data Reductions

NGC 4051 was observed with XMM-Newton in 2001 May and 2002 November. XMM-Newton reformatted telemetry is organized in the Observation Data Files (ODFs). The ODFs were processed to produce calibrated-event lists by using the XMM-Newton Science Analysis System (SAS) version 6.5.0. The event lists of European Photon Imaging Camera (EPIC) were generated by the tasks “emchain” and “epchain”, and cleaned by removing hot, dead, and flickering pixels. We used X-ray events corresponding to pattern 0–12 (single, double, triplet, and quadruple pixel events) for the MOS cameras and pattern 0–4 (single and double) for the PN camera.

Source spectra and light curves were extracted from a circular region with a radius of 45″, and the background was taken from an offset position close to the source with the same radius, except for the 2001 MOS data. In the case of the 2001 MOS2 data, we could not extract the background from the same CCD chip as the source, because the MOS2 camera was operated in the small-window mode. We therefore derived the background spectra and light curves from an annular region with an inner radius of 6″ and an outer radius of 9″. Since the MOS1 camera was operated in the timing mode in the 2001 observation, we did not use it.

Since the last ~10 ks of the 2001 observation was affected by significant background flares, such periods were excluded throughout the analyses. We also checked for a pile-up effect by using the XMMSAS task “epatplot”, and found that it was negligible throughout the observation.

Spectral fits were performed with the X-ray spectral fitting package XSPEC version 12.3.0 (Arnaud 1996). All of the source spectra were grouped in such a way that each bin contained at least 30 counts in order to perform the $\chi^2$ minimization technique. All fit parameters are given in the source rest frame ($z = 0.0023$), and errors are quoted at the 90% confidence level for one interesting parameter ($\Delta \chi^2 = 2.7$), unless otherwise stated. The Galactic column density, $N_H$, toward NGC 4051 was fixed at $1.31 \times 10^{20}$ cm$^{-2}$ (Elvis et al. 1989). Throughout this paper, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is assumed.

3. Results

3.1. Light Curves

Figure 1 shows the 0.3–12 keV EPIC PN light curves in 200 s bins. The left and right panels indicate the light curves obtained from the 2001 and 2002 observations, respectively. The inner panel in the right panel is an enlarged version of the light curve in the 2002 observation to see any time variation in detail. A difference in behavior between these observations is clearly seen. In the 2001 observation, the source was in a high-flux state, and exhibited rapid and large-amplitude variability, while in the 2002 observation, the source counts dropped off and showed a relatively stable variation at ~4 counts s$^{-1}$. The source entered into a minimum state at $3.5 \times 10^4$ s in the 2002 observation. Hereafter, we define this state as “dim 3” (see figure 1, right inner panel).

In order to investigate any spectral variability accompanied by a flux variation, we made a correlation of counts between different energy bands. Figure 2 shows the relationship between the 0.8–2.0 keV and 4.0–12.0 keV count rates. This is almost the same plot as figure 7 of Ponti et al. (2006).
The open squares and filled circles are the 2001 and 2002 observations, respectively. In the 2001 data, we found a clear positive correlation between them. In the 2002 data, however, the relation becomes much steeper as the count rate decreases. When the 0.8–2 keV count rate in 2002 is above 1.5 counts s$^{-1}$, the correlation is very similar to the 2001 data. This implies that the spectral behavior is dominated by a similar physical mechanism in both the 2001 data and the bright state of the 2002 data. On the other hand, once the count rate in the soft energy band falls below 1.5 counts s$^{-1}$, the 4–12 keV count rate suddenly decreases without a large drop in the soft-energy counts. This flux change may suggest that a spectral component that dominates in the high-energy band disappears when the source falls into a minimum flux (dim 3) state. We discuss the possibility of such a spectral component in the following subsection.

The variability amplitude is also an important parameter in the quantification of the light-curve property. In order to investigate a flux-dependent variability amplitude, we divided the total light curve into 5 ks durations, and calculated the rms variability (e.g., Nandra et al. 1997) with a bin size of 50.0 s in each segment. The result is shown in figure 3. The horizontal axis indicates the average count rate in each segment, while the vertical axis shows the rms variability. Most rms data points distribute from 0.1 to 0.4. However, we could only constrain the upper limit when the source falls into the “dim 3” state. This suggests that there is no significant flux variation in such a state. If it is naively assumed that the degree of the variability amplitude reflects the size of the emission region, then a lack of variation might imply that the X-ray spectrum in the “dim 3” state is dominated by emission coming from relatively extended regions.

### 3.2. Spectral Analysis

NGC 4051 has been known to show spectral variations as well as intensity variations. In figure 4, we show the X-ray spectra in the different flux states. Hereafter, we refer to these states as the flare, dim 1, dim 2, and dim 3 states from the top to the bottom spectra. Corresponding periods are represented in figure 1. These spectra were chosen because of their characteristic flux behaviors. The “flare” state is identified with the largest flare event throughout the observations. The dim 1 and dim 3 states correspond to the minimum flux states during the 2001 and 2002 observations, respectively. On the other hand, the dim 2 state is just around the knee point of the count–count relation in figure 2. As mentioned in the previous subsection, the slope of the relation becomes much steeper when the 0.8–2.0 keV count rate is falling below this point. Therefore, the spectrum in the dim 2 state is very useful for revealing the reason for a sudden slope change in the count–count plot.

In the following sub-subsections, we first investigate the spectral properties of the dim 3 and dim 1 states. Based
on these lowest flux spectra, we attempted to perform the subtracted spectrum method, in which the lowest flux spectra were subtracted from other brighter state spectra in order to reveal the variable spectral component, which may cause a flux-dependent spectral variability.

3.2.1. Spectrum in the “dim 3” state

The lowest spectrum in figure 4 was obtained during the period of the “dim 3” state, where the source intensity became minimum throughout the observation. A prominent line feature is clearly seen ~ 6 keV. The continuum is very steep below 2 keV, while it becomes flatter in shape above 3 keV.

We first fitted the 2–12 keV spectrum with a power law, Gaussian, and a cold reflection model ("pexrav" in XSPEC: Magdziarz & Zdziarski 1995). We fixed the abundance at the solar value, and the disk inclination angle was assumed to be 30°. The cutoff energy of the power law was set to 0, which implies that there is no cutoff in the continuum. We also assumed that the reflecting matter subtended 2π steradians of the sky seen from the central source (i.e., the reflection scaling factor R is set to 1). The fitting results are summarized in the second column of table 1. Within the error, the photon index, Γ, the line properties, and the intensity of the reflected continuum, which might arise from the same medium as the iron line, seem to be consistent with those derived from 1998 observations of BeppoSAX and RXTE (Uttley et al. 1999), where NGC 4051 entered into the historical lowest flux state. The constancy of the narrow iron-line flux and the intensity of the reflected continuum on a time scale of ~ a year might suggest that the reflecting material is located far away from the central source, so as to smear the variability of the incident primary power law.

In our model fitting, the spectrum in the 4–12 keV band is dominated by the reflected component. However, other components might contribute to this energy band. As mentioned in the following section, there exists an absorbed component, which is also dominant in the high-energy band. If such a spectral component is really contained in the “dim 3” spectrum, we can expect a smaller contribution from the reflected emission. Therefore, we added a power law absorbed by neutral matter with a fixed column density, $N_{\text{H}}$, of 1.8 × 10$^{23}$ cm$^{-2}$ (see sub-subsection 3.2.3 in detail). In this case, we only obtained the upper limit for the normalization of the absorbed component ($A_{\text{abs}} < 0.001$), although the $\chi^2$ value was not improved by the addition of the absorbed component. Unfortunately, low statistics and a lack of observations in higher (> 10 keV) energy bands prevented us from disentangling complex spectral components. We expect that Suzaku can strictly constrain the normalization of the reflected continuum.

When the power-law continuum is extrapolated to the low-energy band, we found a prominent soft excess, which is commonly seen in the NLS1s (e.g., Leighly 1999). In order to parametrize the soft-excess component, for the sake of simplicity a blackbody spectrum was adopted. As a possible physical origin of this soft excess, several models have been proposed (e.g., Ponti et al. 2006; Brinkmann et al. 2004; Kawaguchi 2003; Ohsuga et al. 2003). After adding the blackbody component, emission-line-like residuals appear at ~0.5 and ~0.9 keV. As reported by Pounds et al. (2004), many emission lines have been detected, and hence we included two narrow (i.e., the line width = 0) Gaussian models in the spectrum. In terms of the 0.5 keV feature, the line energy and the flux were determined to be 0.56 ± 0.01 keV and 1.7 ± 0.3 × 10$^{-4}$ photons cm$^{-2}$ s$^{-1}$. These are in agreement with the OV II triplet derived from the RGS data (see table 1 of Pounds et al. 2004). On the other hand, the 0.9 keV feature is not reproduced by a narrow Gaussian, but requires a much broader line width. When the line width is free to vary, the 0.9 keV structure is represented by a Gaussian with a center energy of 0.93 keV, a width of 0.05 keV, and a flux of 1.2 × 10$^{-4}$ photons cm$^{-2}$ s$^{-1}$. The line energy is consistent with the Ne IX triplet. The intensity, however, is significantly larger than that estimated from the RGS data.

Such a broad line feature around 0.9 keV is expected from Fe L lines emitted by thin thermal plasmas. We therefore included a thermal-emission model ("MEKAL" in XSPEC). Figure 5 shows the unfolded spectrum, and the third column of table 1 indicates the resultant fitting parameters. The thin thermal-plasma model is presented by a red dotted curve in the figure. The derived plasma temperature, $kT = 0.80$ keV, is in agreement with the mean value ($kT = 0.82$ keV) of

<table>
<thead>
<tr>
<th>Table 1. Fitting results for the “dim 3” and “dim 1” spectra.</th>
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<tr>
<td></td>
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<tr>
<td>2–12 keV</td>
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<tr>
<td>10$^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
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<tr>
<td>$A_{\text{p1}}$</td>
</tr>
<tr>
<td>$N_{\text{H}}$</td>
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<tr>
<td>$A_{\text{p2}}$</td>
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<tr>
<td>$kT_{\text{bb}}$</td>
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<tr>
<td>$I_{\text{FS}}$</td>
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<td>$kT_{\text{th}}$</td>
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<tr>
<td>$A_{\text{th}}$</td>
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<td>$E_{\text{FS}}$</td>
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<td>$\sigma_{\text{FS}}$</td>
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<td>$L_{\text{FS}}$</td>
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<td>$E_{\text{OVII}}$</td>
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<tr>
<td>$E_{\text{OVII}}$</td>
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<tr>
<td>$E_{\text{edge}}$</td>
</tr>
<tr>
<td>$\chi^2_\nu$ (d.o.f)</td>
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</table>

* Photon flux at 1 keV of the incident power law in units of 10$^{-2}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$.
† Column density of the absorber in units of 10$^{22}$ cm$^{-2}$.
‡ Photon flux at 1 keV of the absorbed power law in units of 10$^{-4}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$.
§ Blackbody temperature in units of eV.
‖ Blackbody normalization in units of 10$^{-5}$.
¶ Temperature of thin thermal emission in units of keV.
** Normalization of thin thermal emission in units of 10$^{-4}$.
†† Emission line energy in units of keV.
‡‡ Line width in units of keV.
§§ Line flux in units of 10$^{-5}$ photons cm$^{-2}$ s$^{-1}$.
|| Edge energy in units of keV.
### Edge optical depth.
Seyfert 2 galaxies with starburst activity, based on the ASCA results (Levenson et al. 2001). Interestingly, a similar 0.9 keV feature was reported by Grupe, Mathur, and Komossa (2004) in their spectral analysis of NLS1 Mrk 1239, which also exhibits a partial absorbed power-law spectrum. A possibility of starburst activity in NGC 4051 is discussed in section 4.

3.2.2. Spectrum in the “dim 1” state

Next, we consider the spectral properties in the “dim 1” state, where the source flux became minimum during the 2001 observation. A single power law over the 0.3–12 keV band yielded a significantly poor fit, with strong positive residuals appearing in the soft (< 1 keV) and the hard (> 3 keV) energy bands. We therefore added a blackbody spectrum (in the soft band) and an absorbed power law spectrum (in the hard band) in order to explain these residuals. The overall continuum obtained is well represented by this model.

The remaining residuals are the edgelike feature at ~0.7 keV and the narrow emission line around 6 keV. The former may be a signature of the highly ionized absorber, which has been reported by Pounds et al. (2004) in detail. Although they used a realistic plasma code to reproduce the RGS spectra, we adopted the edge model (ZEDGE in XSPEC) for the sake of simplicity. The latter is due to the emission from cold iron. The addition of these models [zedge × (blackbody + partial covered power law + zgauss)] significantly improved the fit. The edge and line energy that we derived are in agreement with those of the OV II absorption edge and the neutral iron K emission line, respectively. The iron line flux was determined to be 2.1 \times 10^{-5}\text{photons cm}^{-2}\text{s}^{-1}, which is consistent with that derived from the “dim 3” spectrum in the previous sub-section. This implies that there are no significant variations in the iron line flux on time scales of ~ one year. The existence of the narrow cold iron line may suggest that the central source is surrounded by a cold reflector, which may also produce the Compton reflection component. We therefore added a “pexrav” to the fit. The model parameters were fixed at the values determined in the “dim 3” state, because we could not find any flux variations of the iron line, which could have originated from the same material as the Compton reflection component. Figure 6 shows the observed spectrum superimposed on the best-fit model. The derived parameters are summarized in the 4th column of table 1. According to this model, 60% of the primary power law is absorbed by the material with a column density of ~ 7 \times 10^{22}\text{cm}^{-2}.

3.2.3. Subtracted spectrum

From analyses of the light curve, we found a peculiar flux behavior in the minimum flux (dim 3) state. During the period of this state, the source exhibits no significant time variation, and the substantial amount of counts in the 4–12 keV band decreases without any large flux variation in the soft (0.8–2 keV) band. These results may suggest that the spectrum in the “dim 3” state is temporally stable, and that the spectra in the other states consist of a stable component and a variable one that dominates intense flux variations.

In order to investigate such a variable spectral component, we compared the spectrum in the “dim 3” state with that in the “dim 2” state. Figure 7 shows the spectrum that is created by...
subtracting the “dim 3” spectrum from the “dim 2” one. This spectral subtraction method is one of the strong tools used to reveal a variable spectral component. We found a clear bump-like structure peaked at \( \sim 5 \) keV. The overall spectrum looks like a type-2 Seyfert galaxy, where the X-ray spectrum is well described by a leaked and/or scattered power law with a heavily absorbed one (e.g., Turner et al. 1997). Therefore, we fitted the spectrum with a partial covering model, which is characterized by an equivalent hydrogen column density, \( N_H \), and a covering fraction, \( f \) (0 \( \leq f \leq 1 \)). The model spectrum \( (M(E)) \) is expressed as follows:

\[
M(E) = N \times E^{-\Gamma}[(1 - f) + f \times \exp(-N_H \times \sigma(E))],
\]

where \( N \) is the normalization of a power-law continuum, \( \Gamma \) the photon index, and \( \sigma(E) \) the photoelectric cross section. We refer to this model as Model A, and the fitting results are shown in Table 2. Although the overall spectrum is well reproduced by Model A, the derived photon index is somewhat larger than the historical value (\( \sim 2.1 \)). This may imply that the spectrum in the soft (below 1 keV) band is affected not only by the power law, but also by other emission. We therefore added a blackbody component, which is sometimes used to explain the soft excess component that appeared in NLS1s (Leighly 1999), in the spectral fit. Model B in Table 2 represents the fitting results. This model also well explains the subtracted spectrum; however a significantly flat \( \Gamma \) is required. Finally, we assumed that the leaked power law is also covered by an additional absorber (Model C in Table 2). This dual-absorption model yields an excellent fit to the subtracted spectrum, and the photon index that we derived is consistent with the historical value. From the fitting results, 85% of the central emission region is covered by clouds with a column density, \( N_H \), of 1.8 \( \times 10^{23} \) cm\(^{-2} \), and the remaining power law (15%) is absorbed by material with a column density of 7.1 \( \times 10^{21} \) cm\(^{-2} \).

A significant flux decrease in 4–12 keV from the “dim 2” state to the “dim 3” is recognized as a disappearance of the partial absorbed component.

We attempted the same procedure for the 2001 observation. Figure 8 represents the spectrum where the “dim 1” state was subtracted from the “flare” state. Here, we cannot find any complex structures, and the spectrum is well reproduced by a summation of the blackbody and the power law \( (\chi^2 = 0.80) \). The temperature of the blackbody and the photon index were derived to be (115 \( \pm 2 \)) eV and 2.35 \( \pm 0.02 \), respectively. As described in sub-subsection 3.2.2, the spectrum during the period of the “dim 1” state exhibits an absorbed continuum as well as the blackbody and the unabsorbed power law. Therefore, the absence of any structures in the subtracted spectrum may suggest that the spectrum in the “flare” state also possesses the absorbed component, the intensity of which is not so different both in the “flare” and “dim 1” states.

### 3.2.4. Spectral variability

We did not detect any spectral complexity in the subtracted spectrum, where the “dim 1” data were subtracted from the “flare” data (see figure 8), although the spectrum in the “dim 1” state is well represented by the partial covering model. This may imply that the flux of the absorbed component was almost constant throughout the 2001 observation, and that the flux changes during this observation arose from the direct, unabsorbed power-law component. In order to investigate this hypothesis, we divided the 2001 observation data into 10 segments with each exposure being \( \sim 10 \) ks, and fitted the partial covering model with a fixed column density of 6.8 \( \times 10^{22} \) cm\(^{-2} \), which was obtained from the spectrum in the “dim 1” state. Each spectrum was well reproduced by this model. The open squares in Figure 9 represent the relationship between the absorbed (i.e., not corrected for the absorption) and the total (i.e., absorbed plus unabsorbed) fluxes. The absorbed flux seems to be constant, while the total flux increases by a factor of \( \sim 3 \). This implies that the covering fraction, which is defined as the ratio of the absorbed flux to the total flux.

### Table 2. Fitting results for the subtracted spectrum (“dim 2” – “dim 3”).

<table>
<thead>
<tr>
<th>Model</th>
<th>( \Gamma )</th>
<th>( kT^* )</th>
<th>( N_H )</th>
<th>( f )</th>
<th>( \chi^2 / \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.54^{+0.10}_{-0.17}</td>
<td>-3.14 ( \pm ) 0.07</td>
<td>1.55 ( \pm ) 0.38</td>
<td>95.2 ( \pm ) 1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>B</td>
<td>1.43 ( \pm ) 0.30</td>
<td>105.4 ( \pm ) 14.7</td>
<td>1.09 ( \pm ) 0.78</td>
<td>75.7 ( \pm ) 1.2</td>
<td>3.6</td>
</tr>
<tr>
<td>C</td>
<td>2.11^{+0.36}_{-0.29}</td>
<td>119.5 ( \pm ) 12.8</td>
<td>7.1 ( \pm ) 0.4</td>
<td>85.1 ( \pm ) 0.9</td>
<td>0.7</td>
</tr>
</tbody>
</table>

* Temperature of blackbody in units of eV.
† Hydrogen column density in units of \( 10^{21} \) cm\(^{-2} \).
‡ Hydrogen column density in units of \( 10^{22} \) cm\(^{-2} \).
§ Covering fraction shown in percentages.
variable absorbed component with a fixed column density of "dim 3" states. We assumed that each spectrum consists of the absorbed flux to the intrinsic unabsorbed power-law flux. A variation could be governed by other physical mechanisms (e.g., Goosmann et al. 2006 and references therein).

If this scenario is applied to our NGC 4051 data, a larger size (or number) of absorbing clouds is required. With such a large cloud size, the X-ray flux becomes much weaker and the steady component, which was hidden under the stronger emission, becomes visible. This means the necessity of some special mechanisms that can naturally explain why larger clouds should appear when the observed central emission is intrinsically weaker. This requirement may not be applied to the situation where part of the central emission region is covered by a Compton-thick absorber, and hence the size of the covered region becomes smaller than the cloud region during the brighter phases. The steady component could originate from spatially extended regions. Such a scenario naturally explains the complicated, detailed spectral behavior found through both the 2001 and 2002 observations — especially the behavior during the period of dimmer states, such as the spectrum given by subtraction of the "dim 2" phase from "dim 3" one shown in figure 7. In this scenario, the time scales of the change of the emission region may be within ~ 10 ks, which is the typical exposure of our time-resolved spectra. On the other hand, it is well known that NGC 4051 exhibits a much shorter time-scale variation. Such a variation could be governed by other physical mechanisms (e.g., Goosmann et al. 2006 and references therein).

In the latter scenario (i.e., the change of the covered size), various clouds are moving around the central emission region, and the varying covering fraction is due to a variable cloud size (or number). The presence of a rapidly variable absorber was reported by Elvis et al. (2004) for NGC 4388, Risaliti et al. (2007) for NGC 1365, and Puccetti et al. (2007) for NGC 4151. If this scenario is applied to our NGC 4051 data, a larger covering fraction would be due to a larger cloud size, or an increase in the number of clouds in the line of sight. Our data indicate that an increase of the covering fraction, and hence the cloud size (or number), is accompanied by a decrease in the total intrinsic (unabsorbed) flux, because we find that the intrinsic unabsorbed fluxes in the "dim 1" and "dim 2" states are lower than in the brighter states. This means the necessity of some special mechanisms that can naturally explain why larger clouds should appear when the observed central emission is intrinsically weaker. This requirement may not be applied to the situation where part of the central emission region is covered by a Compton-thick absorber, and hence the primary intrinsic flux, even in apparently low flux states, is in fact much larger. Then, special mechanisms which link larger clouds to the observed fainter central emission are not required. The problem with this scenario, however, is, first of all, that such a heavily absorbed component is not observed.

4. Discussion

4.1. Partial Covering Scenario

The X-ray spectral behavior is generally well explained by a variable covering fraction, which is defined as the ratio of the absorbed flux to the intrinsic unabsorbed power-law flux. We found that while during the period of brighter states (the 2001 observation) the absorbed flux is almost constant as the total flux decreases, during the period of dimmer states the absorbed flux appears to decrease with a decrease of the total flux, until the source enters into the faintest "dim 3" phase (the 2002 observation)(see figure 9). This means that the covering fraction increases with a decrease of the total flux during the period of brighter states. There are two possible interpretations on this behavior. The first is due to a change of the central emission region, itself, which we prefer, and the second a change of the covered size.

In the former case (change of the emission region), we assume a situation where stable absorbing clouds cover part of the central emission region, and that the X-ray flux is proportional to the size of the emission region. When the emission region becomes smaller, the direct unabsorbed X-ray flux decreases. The absorbed flux, however, should not change, because the size of the covered region does not change. In this scenario this phase explains the constant absorbed component found in the 2001 observation. Once the size of the emission region becomes smaller than the cloud region, however, the absorbed flux also begins to decrease. The decrease of the absorbed flux in the 2002 observation was then identified with this phase. Finally, when the primary emission is no longer observed (i.e., when the primary emission becomes negligible), the partially covered component should also become negligible, as compared with the temporally stable, underlying, weaker, steady component, which was hidden under stronger fluxes from the central region during the brighter phases.

The steady component could originate from spatially extended regions. Such a scenario naturally explains the complicated, detailed spectral behavior found through both the 2001 and 2002 observations — especially the behavior during the period of dimmer states, such as the spectrum given by subtraction of the "dim 3" phase from "dim 2" one shown in figure 7. In this scenario, the time scales of the change of the emission region may be within ~ 10 ks, which is the typical exposure of our time-resolved spectra. On the other hand, it is well known that NGC 4051 exhibits a much shorter time-scale variation. Such a variation could be governed by other physical mechanisms (e.g., Goosmann et al. 2006 and references therein).
below $\sim 10\,\text{keV}$, and moreover it was also not observed in the harder BeppoSAX spectrum when the source entered into the historical minimum state (Guainazzi et al. 1998). We, therefore, conclude that the former scenario (variable central emission) is more relevant, and that the “dim 3” state is in fact a “switch-off” one. It has been reported that fluxes and spectral variations of some Seyfert 1 galaxies are similar to that of NGC 4051 (e.g., Mrk 335: Grupe et al. 2008; Mrk 766: Turner et al. 2007; IRAS 13224–3809: Boller et al. 2003). As far as such objects are concerned, we expect that a similar situation could be achieved in their nuclei.

Throughout this paper we adopted, for convenience, a blackbody spectrum for the soft excess component, while the physical nature of the soft excess component was not specified. Several possible models, however, have already been proposed to explain the spectral shape and the temporal behavior of this soft excess component (Kawaguchi 2003; Ohsuga et al. 2003; Brinkmann et al. 2004; Gierliński & Done 2004; Ponti et al. 2006; Haba et al. 2008).

Ponti et al. (2006) applied the two-component model, which consists of a variable power law with a constant slope and a relativistically blurred, ionized reflection component, to the same data sets that we adopted in this paper. These authors found that their model well reproduces not only the soft excess component, but also the flat shape of the hard-band spectrum observed during the period of a low-flux state. This outcome suggests that some, or all, of our partially absorbed component in the hard X-ray band could be explained by their relativistic ionized reflection model. We therefore tried to fit the spectrum to their reflection model. We used the “dim 2” spectrum because it shows the most prominent absorbed component in our analysis. The continuum model that we adopted consists of a power law with a fixed slope, $\Gamma$, of 2.2, a cold reflection with the same intensity as derived from the “dim 3” spectrum, and an ionized reflection model (REFLION in XSPEC: Laor 1991). We also added three Gaussian lines in order to explain the line features around 0.6 keV, 0.9 keV, and 6.4 keV. The model reproduces the soft excess component well, and the model parameters that we derived (emissivity index, $q = 5.17$, and ionization parameter, $\xi = 88.2$) are consistent with their results. However, we found a considerable amount of positive residuals above $\sim 4\,\text{keV}$ ($\chi^2_v \sim 2.6$). This type of residual may suggest that the data indeed require a more convexly curved spectrum, such as an absorbed power law. We interpret that our worse fit resulted from an increase in the optical thickness of some Seyfert 1 galaxies (e.g., Mrk 335: Grupe et al. 2008; Mrk 766: Turner et al. 2007; IRAS 13224–3809: Boller et al. 2003). As far as such objects are concerned, we expect that a similar situation could be achieved in their nuclei.

As mentioned above, however, their ionized reflection model successfully reproduces the soft excess component and part of the hard-band spectrum. Therefore, we conclude that our studies do not deny the possibility that both the relativistic ionized reflection component and the absorbed component can coexist in the spectrum of NGC 4051.

Although our model is different from that adopted by Ponti et al. (2006), it may be noted that these models are not necessarily mutually exclusive. In fact, both models deal with somewhat similar situations, in the sense that the observed flux and spectral-variability behaviors are related mainly to phenomena within the central emission region close to the black hole. In our case the physical mechanism that results in a change of the observed primary central emission is not specified. On the other hand, according to Ponti et al. (2006) the observed-flux behavior is primarily due to an enhanced light-bending effect as the primary X-ray source moves closer to the central black hole.

4.2. Interpretation of Minimum Flux State

Since some flux variations during the period of “dim 3” state are found to be negligible, the central engine in that state may have entered into a “switched off” state, and the observed X-rays may be coming from regions distant from the central black hole. The continuum in this dimmest state, therefore, may be recognized as a combination of scattered primary emissions, the reflected component, and emissions from optically thin thermal plasmas in distant regions. Indeed, the continuum shape in the “dim 3” state seems to be similar to that of the “flare” state (see figure 4). This suggests that the stable component in the “dim 3” state could be the Thomson scattered one. In addition, we found the signature of thermal emission from an optically thin plasma. As mentioned in sub-subsection 3.2.1, this component may not be considered in the spectral analyses performed by Pounds et al. (2004), because of the low statistics of the RGS spectra at $\sim 0.9\,\text{keV}$. The thermal emissions may imply the existence of starburst activity. Since it is well known that there is a tight correlation between the far-infrared luminosity ($L_{\text{FIR}}$) and the X-ray luminosity ($L_X$) of thermal emissions in starburst galaxies (Ranalli et al. 2003), we estimate an far-infrared flux ($FIR$) of NGC 4051 defined after Helou et al. (1985):

$$FIR = 1.26 \times 10^{-11} \left( 2.58 S_{60\mu} + S_{100\mu} \right) \text{erg s}^{-1}\text{cm}^{-2},$$

(2)

where $S_{60\mu}$ and $S_{100\mu}$ are infrared fluxes at 60 $\mu$m and 100 $\mu$m in units of Jy, respectively. We used $S_{60\mu} = 10.53\,\text{Jy}$ and $S_{100\mu} = 24.93\,\text{Jy}$ obtained from Sanders et al. (2003). $L_{\text{FIR}}$ was evaluated from

$$L_{\text{FIR}} = 4\pi d_L^2 FIR,$$

(3)

where $d_L$ is the luminosity distance. In order to ensure consistency between Ranalli et al. (2003) and our estimations, we used the cosmological parameters $H_0 = 50\,\text{km s}^{-1}\text{Mpc}^{-1}$ and $q_0 = 0.1$. Figure 10 shows the relationship between the $L_{\text{FIR}}$ and X-ray luminosity of emissions from optically thin thermal plasmas in the 0.5–2 keV range. The open circles indicate starburst galaxies listed in Ranalli et al. (2003), while the filled circle was derived from this work. It seems that a relationship of NGC 4051 is similar to that of the starburst galaxies.
Rodríguez and Viegas (2003) observed the 3.3 µm polycyclic aromatic hydrocarbon (PAH) emission, which is one of the best indicators of starburst activity of this object, and reported that only the upper limit to the PAH flux could be derived. Kohno, Nakaniishi, and Imanishi (2007) also reported the existence of nuclear starburst activity in NGC 4051 from their observations of CO(1–0), HCN(1–0), and HCO$^+$ lines with the Nobeyama Millimeter Array. Our findings strongly support these results. The starburst activity may be related to a dense molecular torus, which is considered to play an important role in the AGN unified model (Antonucci 1993). In fact, it is found that a tight and linear correlation exists between HCN(1–0) and $L_{\text{FIR}}$ over 8 orders of magnitude (Solomon et al. 1992; Gao & Solomon 2004; Carilli et al. 2005; Wu et al. 2005). Based on three-dimensional hydrodynamical simulations, Wada and Norman (2002) showed that the nuclear starburst may produce a highly inhomogeneous and turbulent torus-like structure around a central supermassive black hole. Such clouds may cover part of the central emission region. Therefore, the existence of starburst activity in NGC 4051 could be related to a partial covering absorber, suggested by our spectral analysis.

Another interesting point of view is a similarity between NLS1s and ultraluminous infrared galaxies (ULIRGs). ULIRGs are known to show intense starburst activity, and are thought to be a previous stage in quasar evolution (Sanders et al. 1988; Kormendy & Sanders 1992; Kawakatu et al. 2006). Recently, Kawakatu, Imanishi, and Nagao (2007) discovered a significant anticorrelation between the mass of a central supermassive black hole and the Eddington ratio by using a sample of ULIRGs with type 1 nuclei (type 1 ULIRGs) and an optically selected QSO sample. They found the tendency for type 1 ULIRGs to favor super-Eddington accretion flows, while QSOs tend to show sub-Eddington flows. If such an evolutionary scenario is the case, we speculate that NGC 4051 could be in the transition phase in the evolutionary sequence from ULIRGs to QSOs.

5. Summary and Conclusion

We analyzed the XMM-Newton data of the low-luminosity NLS1 galaxy NGC 4051 with major focus placed on the temporal flux and spectral variability.

In the brighter state during the 2001 observation, the hard-band (4–12 keV) flux is well correlated with the soft-band (0.8–2 keV) flux. The observed spectral variability of the X-ray continua in this state is well explained by a variable power law and a temporally stable absorbed component. On the other hand, in the dim states during the 2002 observation the hard vs. soft count–count plot (see figure 2) exhibits a much steeper slope, and the spectral variations are mainly due to flux changes of the absorbed component. Especially, when the source entered into the lowest flux state, “dim 3”, the absorbed component disappeared, and the observed spectrum was probably dominated by temporally stable components, such as scattered/reflected and/or thermal emissions.

From these results, we propose a plausible situation where the central emission region is partially obscured by dense clouds with stable size, and where the observed nuclear emission decreases as the emission region decreases. According to this model, the temporal flux and the spectral variability are interpreted as follows. When the source is in the bright state, the emission region is larger than the covered size, and the decrease in direct, unabsorbed power-law emission results from a reduction of the emission region without any significant change of the absorbed component. On the other hand, when the emission region becomes smaller than the covered size of the clouds, the flux of the absorbed component begins to decrease as the emission region decreases. Finally, when the emission region reduces sufficiently (i.e., when a “switched off” state is reached), the absorbed component no longer appears in the observed spectra, because it is overtaken by the underlying, temporally stable, spectral component, which is possibly emitted from spatially extended regions.

In fact, we found the signature of thermal emissions in the lowest flux state. Since the temperature that we derived is in agreement with the average value of type-2 Seyfert galaxies with starburst activity, NGC 4051 may possess nuclear starburst regions. This possibility has also been suggested by some infrared and radio observations. Within the frame work of the galaxy evolution scenario, ULIRGs, that exhibit intense starburst activity, are regarded as a previous evolution stage before the QSO phase. Interestingly, some authors suggest that ULIRGs could have NLS1-like nuclei (i.e., with a relatively smaller black hole plus supercritical accretion flow) in their center. If such a scenario is the case, NGC 4051 could be in a transition stage between ULIRGs and QSOs.

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