X-ray spectral variability of the Seyfert galaxy NGC 4051
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ABSTRACT

We report on the X-ray spectral variability of the Seyfert 1 galaxy NGC 4051 observed with the Rossi X-ray Timing Explorer (RXTE) during a 1000 day period between May 1996 and March 1999. The spectra were obtained as part of monitoring observations and from two long observations using the RXTE Proportional Counter Array (PCA). During the monitoring period the 2-10 keV flux of NGC 4051 varied between $10^{-12}$ and $7 \cdot 10^{-11}$ erg/(cm$^2$ s). We re-analysed RXTE PCA observations from a distinct low state in May 1998 using the latest background and detector response models. The RXTE and BeppoSAX observations of NGC 4051 during the low state show a very hard spectrum with a strong unresolved fluorescence line. This emission, probably due to reflection from a molecular torus, is likely to be constant over long time-scales and is therefore assumed as an underlying component at all flux states. By subtracting the torus component we are able to determine the spectral variability of the primary continuum. In the variable component we observe a strong anti-correlation of X-ray flux and spectral hardness in the PCA energy band. We show that the changes in hardness are caused by slope variability of the primary power law spectrum rather than by changing reflection or variable photoelectric absorption. The primary spectral index varies between $\Gamma = 1.6$ for the faintest states and $\Gamma = 2.3$ during the brightest states, at which level the spectral index approaches an asymptotic value. We find that the response of the flux of the 6.4 keV iron fluorescence line to changes in the continuum flux depends on the timescale of the observation. The profile of the line is very broad and indicates an origin in the innermost regions of the accretion disk.

Key words: Galaxies: individual: NGC 4051 – X-rays: galaxies – Galaxies: Seyferts

1 INTRODUCTION

It is thought that the central engines of active galactic nuclei (AGN) are powered by the infall of matter onto a supermassive black hole. Theoretical arguments suggest the formation of an accretion disk which extends from the innermost stable orbit to an outer radius on the scale of light days. The popular unified scheme for Seyfert galaxies (e.g. Antonucci 1993) requires a dusty torus, probably coplanar with the accretion disk, which is opaque to radiation from the near infrared to soft X-rays. According to the unified scheme Seyfert type 1 and Seyfert type 2 AGN are intrinsically identical object classes with the only difference being that in Seyfert type 2 galaxies, due to their different orientation relative to the observer, the central source and the broad line region (BLR) are obscured by a dusty torus. The first probable direct detection of a torus was shown in our earlier SAX (Guainazzi et al. 1998) and RXTE (Uttley et al. 1999) observations of NGC 4051. However, in general, detection of the torus and the determination of its geometry has not been possible.

X-ray observations have shed some light on the structure of the innermost regions of AGN. The soft X-ray spectrum often has a relatively steep slope, which has been explained by thermal emission from an accretion disk. However, there are alternative theoretical interpretations and due to the limited spectral resolution in this energy range the soft X-ray spectra are poorly understood.

At higher energies, a hard power law spectrum dominates the emission. This component is probably due to Comptonization of the thermal UV photons in a hot corona surrounding the disk.

The averaged Ginga medium energy X-ray spectrum of several Seyfert galaxies showed the presence of an emission line at 6.4 keV, an absorption feature at 7-8 keV, and a further flattening of the spectrum beyond $\sim 10$ keV. These features are interpreted as iron K$_\alpha$ emission, iron K edge absorption and Compton reflection and therefore are evidence for reprocessing of X-rays by relatively cold matter. The discovery of broadening due to gravitational redshift and Doppler shifts of the iron K$_\alpha$ fluorescence lines in Seyfert X-ray spectra suggests that at least part of the reprocessing takes place in the inner parts of the accretion disk (Tanaka et al. 1995, Nandra

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et al. 1997, Reynolds & Begelman 1997). However, the detection of narrow components to the Fe Kα line with ASCA (eg Weaver et al. 1997) and recently Chandra (Yaqoob et al. 2001, Kaspi et al. 2002) and XMM-Newton (Reeves et al. 2001) suggests reprocessing of X-rays in matter at a larger distance from the black hole, eg in the BLR or in the molecular torus.

The analysis of X-ray variability is a powerful tool for the investigation of the inner regions of the AGN central engine, since the time-scales of the variability can give an indication of the geometrical sizes of the regions involved. Yaqoob et al. (1996) reported a rapid (< 3·10^4 s) response of the Fe fluorescence line flux to the continuum flux in NGC 7314. From the resulting maximum distance of the reflecting material from the primary X-ray source they derive an upper limit on the mass of the black hole. However, the analysis of fluorescence line variability in a number of other Seyfert galaxies has led to confusing and partly contradictory results. While in some sources a positive correlation of line and continuum flux has been observed, averaged over long timescales, (eg NGC 5506, Lamer, Uttley & M'Hardy 2000), other studies found no evidence for a close relationship between continuum and fluorescence line (Weaver, Gelbord & Yaqoob 2001, Vaughan & Edelson 2001).

Flux-dependent variability of the continuum spectral shape itself can be used to constrain models of the Comptonising accretion disk corona (eg Haardt, Maraschi & Ghisellini 1997). In general, the continuum slope appears to be correlated with flux (eg Leighly et al. 1996; M'Hardy, Papadakis & Uttley 1998; Lamer, Uttley & M'Hardy 2000), as predicted by most simple Comptonisation models. However, it is important to determine whether the degree of slope variability, and the form of the correlation with flux (eg does the continuum slope saturate at some maximum value?) are in agreement with existing models.

NGC 4051 is a nearby (z=0.0023) low luminosity Seyfert 1 galaxy, which is among the most variable AGN in the X-ray band (Green, M'Hardy & Letoho 1993). We have been monitoring NGC 4051 with RXTE since 1996. Since our monitoring commenced, the 2-10 keV flux from the object has varied by a factor of ~100. In 1998 NGC 4051 entered a state of extremely low X-ray flux that lasted for ~ 150 days (Guainazzi et al. 1998, Uttley et al. 1999). Here we report on the spectral changes that accompanied the dramatic flux variability. In section 2 we describe the observations and the reduction of the RXTE data. Results from observations in May 1998, during the extreme low state, are re-analysed in a consistent manner with the other observations and are discussed in section 3. In section 4 we present the analysis of the continuum and fluorescence line variations observed during the long term monitoring and during an RXTE long look in December 1996.

2 OBSERVATIONS AND DATA REDUCTION

We have been monitoring NGC 4051 with RXTE since May 1996. The observations were separated by a range of time intervals. For the first 6 months the observations took place weekly with periods of twice-daily observations in May 1996 and daily observations in October 1996. Since November 1996 the source has been observed at fortnightly intervals. RXTE observed NGC 4051 with the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE). The PCA (Zhang et al. 1993) consists of 5 Xenon-filled Proportional Counter Units (PCUs), sensitive to X-ray energies from 2-60 keV. The maximum effective area of the PCA is 6500 cm^2. As the signal to noise ratios of the higher energy HEXTE spectra on NGC 4051 are low, we only present the results from the PCA. For technical reasons the high voltage settings of the PCA units have been adjusted several times during their lifetime. In this paper we only present data taken during the PCA gain epoch 3, which lasted from April 1996 to March 1999. The total exposure time of the 130 individual monitoring observations during gain epoch 3 is 85 ksec. Apart from the monitoring observations RXTE performed two long-look observations of NGC 4051 in December 1996 with a total on-source time of 36.4 ksec within 3 days and in May 1998 for 84.4 ksec (on-source) within 2 days.

We have used FTOOLS V4.2 for the reduction of the PCA and HEXTE data. PCA “good times” have been selected from the Standard 2 mode data sets using the following criteria: target elevation > 10°, pointing offset < 0.01°, time since SAA passage > 30 min, standard threshold for electron contamination. Occasionally one or more of the 5 Proportional Counter Units (PCUs) of the PCA were switched off during the observations. In order to maximise the signal to noise ratio of the spectra, we used the data from all PCUs that were switched on during each individual pointing and used only PCU layer 1. We calculated the background in the PCA with the tool PCABACKEST V2.1 using the L7 model for faint sources, which is suitable for determining the PCA background for energies ≤ 24 keV. From a series of ~ 100 blank field observations from the public archive (proposal ID P30801) we determined the uncertainties in the estimated background rates as a function of energy. At energies below 24 keV the 1σ uncertainty of the background is of the order 0.01cts s^-1 keV^-1 (see Lamer, Uttley & M'Hardy 2000 for details). The PCA response matrices were calculated invidividually for each observation using PCARSP V2.37, taking into account temporal variation of the detector gain and the changing numbers of detectors used.

3 THE LOW STATE SPECTRUM

Our monitoring with the RXTE PCA revealed that during a 150 day period from January 1998 to May 1998 NGC 4051 was in a state of unusually low X-ray flux (Uttley et al. 1999, see Fig. 1). Near the end of this period NGC 4051 was observed simultaneously by RXTE (Uttley et al. 1999) and BeppoSAX (Guainazzi et al. 1998). We derived a 2-10 keV flux of 2.0 · 10^-12 ergs^-1 cm^-2 from the RXTE PCA spectrum and 1.4 · 10^-12 ergs^-1 cm^-2 from the BeppoSAX MECS data. Both observations showed a very hard X-ray spectrum and unresolved 6.4 keV iron line emission with a very high equivalent width (~ 1000 eV). This spectrum was interpreted as a pure reflection component with the central source being virtually switched off. Since the reflected emission was still present after the source had been in a low state for 150 days, the distance of the reflector from the central source must be ≥ 10^17 cm. It is likely that the Compton reflection and iron line fluorescence from the distant reflector is a constant contribution to the X-ray spectrum of NGC 4051. For the investigation of the variability of the primary X-ray source in NGC 4051 it is necessary to take this underlying component into account.

We have therefore re-analysed the PCA data from the low state using the latest response matrices, appropriate to gain epoch 3, and background models. We fitted two models to the PCA and BeppoSAX MECS spectra: a simple power law model with a Gaussian emission line and a pure reflection model, also with a Gaussian emission line. The model for a pure reflection component was calculated by using the XSPEC PEXRAV model (Magdziarz & Zdziarski 1995) with a fixed reflected fraction R = 100. With this
setting the contribution of the intrinsic power law emission is negligible. See Table 1 for the results of the spectral fits. Throughout the paper 1 σ confidence limits are given as error values. The error of the fit parameters in Table 1 were calculated for 4 interesting parameters. Due to the relatively low signal-to-noise ratios of the data a clear cut decision between these two models is not possible. For both the PCA and MECS spectra the power law model yields a slightly better χ² value than the pure reflection fit. However, the power law fit requires a photon index of Γ ∼ 0.5, a value that is unlikely for standard Comptonization models but which might be applicable to an advective flow. If the low state X-ray emission solely arises from reflection, the PEXRAV model fit to the PCA spectrum results in a photon index Γ ∼ 2.0 for the primary emission. Assuming that the reflecting matter subtends a solid angle of 2π steradians or less, the required incident radiation corresponds to a 2-10 keV flux level of ≥ 2 · 10⁻¹¹ ergs⁻¹ cm⁻². This is in good agreement with the flux range of ∼ 1 · 10⁻¹¹ to ∼ 6 · 10⁻¹¹ ergs⁻¹ cm⁻² found during the monitoring of NGC 4051 before the 150 day low state period.

The strong iron Kα fluorescence line supports the interpretation that the low state spectrum is a pure reflection component. The very low level of the continuum in these observations of NGC 4051 allows a more detailed analysis of any fluorescence or emission lines. When fitting a power law or PEXRAV model with a single Gaussian line to the PCA spectrum, the resulting source frame line energy of ∼ 6.6 ± 0.1 keV is slightly higher than the nominal value of 6.4 keV for fluorescence from cold iron. The best fit model to the BeppoSAX MECS spectrum includes a narrow line at 6.47 ± 0.06 keV, consistent with 6.4 keV. The fit residuals, however, show some excess flux at ∼ 7 keV. When fixing the energy of the fluorescence line to 6.4 keV, excess flux at ∼ 7 keV is evident in all spectra. We therefore included narrow (0.05 keV) iron Kβ and nickel Kα fluorescence lines at 7.058 keV and 7.477 keV into the spectral model. The fluxes of these additional lines were set to Fe Kα/Fe Kα = 0.11 as theoretically expected for neutral iron (Kikoin 1976) and Ni Kα/Fe Kα = 0.07 as expected for solar abundances (Nandra et al. 1999). Taking these lines into account slightly improves the χ²

Figure 1. 2-10 keV lightcurve of NGC 4051 during the long term monitoring campaign (filled circles with error bars). The diamonds show the lightcurve from the December 1996 observation, the open circle indicates the flux level during the May 1998 observation at the end of the 150 day long low state.

### Table 1. Fit parameters for the May 1998 low state spectrum

<table>
<thead>
<tr>
<th>model</th>
<th>Γ</th>
<th>f₆.₄ 10⁻⁵ ph s⁻¹ cm⁻²</th>
<th>EW₆.₄ [keV]</th>
<th>EW₇.₄₇ [keV]</th>
<th>EW₇.₄₇ [keV]</th>
<th>χ² (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXTE PCA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWL+ZGAUSS</td>
<td>0.56 ± 0.11</td>
<td>2.80 ± 0.70</td>
<td>1.40 ± 0.35</td>
<td>-</td>
<td>-</td>
<td>38.8 (42)</td>
</tr>
<tr>
<td>PWL+3 ZGAUSS</td>
<td>0.52 ± 0.11</td>
<td>2.57 ± 0.53</td>
<td>1.40 ± 0.34</td>
<td>0.16</td>
<td>0.10</td>
<td>36.8 (42)</td>
</tr>
<tr>
<td>PEXRAV+ZGAUSS</td>
<td>2.02 ± 0.10</td>
<td>2.16 ± 0.75</td>
<td>0.79 ± 0.35</td>
<td>-</td>
<td>-</td>
<td>39.8 (42)</td>
</tr>
<tr>
<td>PEXRAV+3 ZGAUSS</td>
<td>2.01 ± 0.10</td>
<td>2.35 ± 0.66</td>
<td>0.88 ± 0.27</td>
<td>0.12</td>
<td>0.11</td>
<td>38.0 (42)</td>
</tr>
<tr>
<td>BeppoSAX MECS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWL+ZGAUSS</td>
<td>0.37 ± 0.17</td>
<td>1.88 ± 0.60</td>
<td>1.16 ± 0.37</td>
<td>-</td>
<td>-</td>
<td>28.4 (29)</td>
</tr>
<tr>
<td>PWL+3 ZGAUSS</td>
<td>0.52 ± 0.18</td>
<td>2.04 ± 0.64</td>
<td>1.26 ± 0.39</td>
<td>0.14</td>
<td>0.09</td>
<td>25.5 (29)</td>
</tr>
<tr>
<td>PEXRAV+ZGAUSS</td>
<td>1.75 ± 0.18</td>
<td>1.85 ± 0.64</td>
<td>0.87 ± 0.30</td>
<td>-</td>
<td>-</td>
<td>33.9 (29)</td>
</tr>
<tr>
<td>PEXRAV+3 ZGAUSS</td>
<td>1.83 ± 0.20</td>
<td>1.12 ± 0.63</td>
<td>0.50 ± 0.28</td>
<td>0.07</td>
<td>0.06</td>
<td>29.6 (29)</td>
</tr>
</tbody>
</table>
of both the PCA and the MECS fits without increasing the number of free parameters (see Table 1).

Throughout the remainder of this paper, we will assume that a narrow iron line component, whose flux is consistent with the line flux measured in May 1998, is present in the spectrum of NGC 4051 over the 3 years of our RXTE observations. Fig. 2 shows the Fe Kα line profile with a possible strong narrow component during the lowest flux states of the December 1996 observation (see first row of Table 3). This is consistent with our view that a component, which is constant on the time-scale of years is present in the X-ray spectrum of NGC 4051. In the analysis of the spectral variability in the RXTE PCA data, we therefore add the PEXRAV + 3 ZGAUSS model with the parameters derived from the PCA low state data (see Table 1) as a constant component to all model fits of the monitoring and December 1996 data.

We note that the presence of narrow line components in some other objects has been confirmed by Chandra and XMM observations. Yaqoob et al. (2001) detected a narrow line at 6.40 keV in a Chandra High-Energy Transmission Grating spectrum of NGC 5548. Since the line is slightly resolved, they assume an origin in the broad line region. Ogle et al. (2000) suggested that part of the narrow iron line observed by Chandra in NGC 4151 may originate in the narrow-line region. Reeves et al. (2001) found an unresolved component at 6.4 keV in the XMM EPIC spectrum of the low-luminosity quasar MKN 205. Kaspi et al. (2002) were able to resolve the narrow 6.4 keV line in NGC 3783 with the Chandra HETGS. The velocity dispersion of FWHM=1720 km s\(^{-1}\) suggests that the line is emitted in the outer BLR or the inner part of the molecular torus.

Although we can say little about the line width from our RXTE observations, the fact that the line remains detectable in the very low state May 1998 observations, 150 days after the continuum went into the low state, means that it could not come from the broad line region, but part of it might come from the narrow line region. However the very hard continuum is not easily explained by scattering from the narrow line region.

If the strong torus contribution to the iron fluorescence line in NGC 4051 is common in other Seyfert galaxies, some of the previous results on disk line spectroscopy will have to be revised, once high resolution spectra become available.

### Table 2. Flux bins for monitoring observations

<table>
<thead>
<tr>
<th>flux range</th>
<th>mean flux [erg s(^{-1}) cm(^{-2})]</th>
<th>exposure [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.0 (\cdot) 10(^{-11})</td>
<td>5.47 (\cdot) 10(^{-12})</td>
<td>21824</td>
</tr>
<tr>
<td>1.0 – 2.0 (\cdot) 10(^{-11})</td>
<td>1.63 (\cdot) 10(^{-11})</td>
<td>22525</td>
</tr>
<tr>
<td>2.0 – 3.0 (\cdot) 10(^{-11})</td>
<td>2.76 (\cdot) 10(^{-11})</td>
<td>15744</td>
</tr>
<tr>
<td>3.0 – 5.0 (\cdot) 10(^{-11})</td>
<td>3.36 (\cdot) 10(^{-11})</td>
<td>8288</td>
</tr>
<tr>
<td>3.5 – 4.5 (\cdot) 10(^{-11})</td>
<td>4.06 (\cdot) 10(^{-11})</td>
<td>10880</td>
</tr>
<tr>
<td>4.5 – 5.5 (\cdot) 10(^{-11})</td>
<td>5.21 (\cdot) 10(^{-11})</td>
<td>4376</td>
</tr>
<tr>
<td>&gt; 5.5 (\cdot) 10(^{-11})</td>
<td>6.66 (\cdot) 10(^{-11})</td>
<td>2016</td>
</tr>
</tbody>
</table>

### Table 3. Flux bins for December 1996 observation

<table>
<thead>
<tr>
<th>flux range</th>
<th>mean flux [erg s(^{-1}) cm(^{-2})]</th>
<th>exposure [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.0 (\cdot) 10(^{-11})</td>
<td>6.78 (\cdot) 10(^{-12})</td>
<td>20800</td>
</tr>
<tr>
<td>1.0 – 2.0 (\cdot) 10(^{-11})</td>
<td>1.53 (\cdot) 10(^{-11})</td>
<td>7792</td>
</tr>
<tr>
<td>2.0 – 3.0 (\cdot) 10(^{-11})</td>
<td>2.65 (\cdot) 10(^{-11})</td>
<td>6800</td>
</tr>
<tr>
<td>&gt; 3.0 (\cdot) 10(^{-11})</td>
<td>3.62 (\cdot) 10(^{-11})</td>
<td>1008</td>
</tr>
</tbody>
</table>

### 4 SPECTRAL VARIABILITY

The large variations in the X-ray flux observed within the 3 years of monitoring of NGC 4051 make the RXTE observations ideally suited for an investigation of associated spectral variability. Since the signal to noise ratio in any one of the individual 1 ksec pointings is not sufficient for individual spectral analysis, we have grouped and added the spectra according to source flux. Since the data were gathered by different combinations of PCUs and the detector gains changed slightly over time, we used fitted model fluxes for the grouping of the data. In order to obtain the flux level for each spectrum we fitted a single power law model to each spectrum in the 2-10 keV range using the appropriate detector response for each spectrum. The monitoring observations were grouped into 7 flux bins, while the spectra from the December 1996 long look observation were grouped into 4 bins (see Tables 2 and 3 for the boundaries of the bins). The appropriate detector response matrices for each spectrum have been created by averaging the response matrices of the individual input spectra (using their integration times as weighting factors).

As described in section 3 we regard the emission observed during the low state in May 1998 as a constant underlying spectral component from a distant reflector. For all spectral fits in this section we have therefore included the best fit of the PEXRAV + 3 ZGAUSS model to the May 1998 PCA data as a fixed additional component.

#### 4.1 Continuum and reflection

Simple power law fits to the flux binned spectra from the monitoring observations after removal of the torus component still reveal a strong correlation of the spectral slope with the flux level of NGC 4051: the softest spectra are found when the flux is highest (see fig 7). In the context of the standard models for the X-ray emission of Seyfert galaxies three principal mechanisms can contribute to this correlation:

1. Intrinsic spectral variability of the primary continuum. During states of high luminosity the higher flux of UV/soft X-ray
photons may cool the accretion disk corona and therefore lead to a softer Compton spectrum at higher X-ray energies.

2. The fraction of reflected radiation may be higher during periods of low luminosity (eg due to an additional, non-variable reflection component).

3. Gas near the X-ray source that is usually strongly ionised by radiation from the central source might recombine to less ionised states when the luminosity of the AGN drops. The resulting increase in absorption of soft X-ray then leads to a hardening of the spectrum. Outside of the very low luminosity states NGC 4051 is observed to have a significant "warm absorber" with a column density of $5 \times 10^{22}$ cm$^{-2}$ (M'Hardy et al. 1995, Komossa & Fink 1999) which could lead to substantial absorption of soft X-rays if the warm absorbing gas recombined.

In order to distinguish between the first two possibilities we fitted PEXRAV models with a variable Gaussian line in addition to the fixed torus reflection model to the flux selected spectra of both the monitoring and December 1996 observations. We reduced the number of free parameters by fixing some of the less critical parameters of the PEXRAV model to reasonable values. The high energy cutoff of the primary power law was set to 300 keV, effectively eliminating the cutoff. The iron and metal abundances were set to the solar values and the inclination angle was fixed at $30^\circ$ as suggested by the results of disk line model fits to ASCA spectra (Nandra et al. 1997). Confidence contours of the primary photon index $\Gamma$ and the reflected fraction $R$ are shown in Figs 3 and 4. It is evident that a continuum of variable spectral index is needed to satisfy the data. The best fit photon indices range from $\Gamma = 1.6$ for the lowest flux states to $\Gamma = 2.3$ for the highest flux states of the monitoring observations. Note that the inclusion of the presumed constant torus component does not change the results qualitatively. If we omit this fixed component, the photon index of the lowest flux spectrum is $\Gamma = 1.2$; the fit to the highest flux spectrum is not affected by this change. No variability of the reflected fraction is observed and at the 90% confidence levels all spectra are consistent with zero reflection. Apart from the fact that the constant reflected (torus) component will become less prominent at higher flux levels, there is no obvious contribution of reflection to the spectral variability.

We also investigated the warm absorber as the third possible source of hardness variability. Again including the low state spectrum as a constant component, we modelled the flux-selected X-ray spectra with a power law and Gaussian emission line absorbed by a warm absorber (XSPEC ABSORI model) with a column density of $N_{HI} = 5 \times 10^{22}$ cm$^{-2}$, as suggested by Komossa & Fink (1999). The models were calculated on a grid in spectral index $\Gamma$ and ionisation parameter $\xi$ and fitted to each of the 7 flux selected spectra of the monitoring observations. As a result, the ionisation parameter appears to be poorly constrained. The spectral index is clearly correlated with flux and there is no $\Gamma$ that would be consistent with all of the 7 spectra (see Table 4). We therefore conclude that changes in the ionisation state of the warm absorber in NGC 4051 do not play a significant role in the spectral variability of the source.

To summarize, variability of primary power law continuum slope is the only viable explanation of the strong hardness variability in the 2-24 keV X-ray spectrum of NGC 4051.

### Table 4. Results of warm absorber fits to flux selected monitoring spectra

<table>
<thead>
<tr>
<th>mean flux [erg s$^{-1}$ cm$^{-2}$]</th>
<th>photon index 1$\sigma$ range</th>
<th>$\xi$ 1$\sigma$ limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5.47 \times 10^{-12}$</td>
<td>1.50-1.91</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>$1.63 \times 10^{-11}$</td>
<td>1.85-2.14</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>$2.76 \times 10^{-11}$</td>
<td>2.10-2.30</td>
<td>$&gt; 60$</td>
</tr>
<tr>
<td>$3.36 \times 10^{-11}$</td>
<td>2.13-2.28</td>
<td>$&gt; 120$</td>
</tr>
<tr>
<td>$4.06 \times 10^{-11}$</td>
<td>2.08-2.28</td>
<td>$&gt; 370$</td>
</tr>
<tr>
<td>$5.21 \times 10^{-11}$</td>
<td>2.28-2.43</td>
<td>$&gt; 170$</td>
</tr>
<tr>
<td>$6.66 \times 10^{-11}$</td>
<td>2.29-2.45</td>
<td>$&gt; 240$</td>
</tr>
</tbody>
</table>

Figure 3. 68% and 90% confidence contours of the parameters photon index $\Gamma$ and reflected fraction $R$ for the PEXRAV model fits to the flux selected PCA spectra. The letters 'a' to 'g' denote the spectra in the order of increasing flux levels. See section 4 for a full description of the model fits.

Figure 4. Same as Fig. 3 for the flux selected spectra of the December 1996 observation. The letters 'a' to 'd' denote the 4 flux levels in ascending order.
4.2 Fluorescence line variability

After subtraction of the low state reflection spectrum with the narrow iron fluorescence line, broad fluorescence line emission is still detectable at all flux levels. Figs. 5 and 6 show ratio plots obtained by fitting power law models to the flux selected spectra excluding the 4-8 keV spectral range. The line is broad and strongly redshifted as expected for an origin in the inner parts of an accretion disk.

We fitted each of the flux selected spectra with a model consisting of the best fit low state spectrum as discussed in section 3, a power law, and the XSPEC DISKLINE model. The DISKLINE model calculates the profile of a line originating from a Keplerian disk surrounding a Schwarzschild black hole. The rest energy of the line was fixed at 6.4 keV. The geometric origin of the fluorescence line is defined by three parameters: the inner radius \( R_i \), the outer radius \( R_o \), and the power law index \( q \) which describes the radial variation of the emissivity. We set \( R_i \) to 6 \( r_g \), the radius of the innermost stable orbit for a Schwarzschild black hole. The outer radius \( R_o \) was set to 400 \( r_g \). The emissivity index \( q \) was left free to vary.

Table 5 summarizes the results of the disk line modelling. For each spectrum we give both the equivalent widths of the narrow fluorescence lines from the fixed narrow line component and the best fit values for the broad disk line. The values for the narrow lines are derived from the total fluxes of the lines at 6.4 keV, 7.06 keV, and 7.477 keV (see section 3). Note that the narrow line fluorescence from the torus can be a major contribution to the total line flux, in particular during lower flux states. Hence the profile of the disk line can only be determined if the contribution from the torus can be reliably measured. The best fit values of the disk inclination confirm the values of \( i \sim \) 30° resulting from ASCA observations (Nandra et al. 1997). The values of \( q \) in most cases are poorly constrained, but generally the emissivity drops steeper than with \( q = -3 \). This indicates a concentration of the line emission in the innermost regions of the disk, as suggested by the broad profile of the iron line.

Since the PEXRAV model fits described in section 4 required no disk reflection (see Figs 3+4) we do not include disk reflection in the disk line model fits. However, we repeated the model fits using a PEXRAV model with reflected fraction \( R = 1 \) instead of the power law model. Including reflection to the fits did not change the line fluxes or disk line parameters significantly.

The best fit photon indices, line fluxes, and line equivalent widths are plotted in Fig. 7. The best fit values of the fluorescence line flux from the long term monitoring observations show a clear correlation with the 2-10 keV flux. However, the correlation is not linear, in the continuum flux range range \((2.0...5.5) \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}\) the line flux is nearly constant.
5 DISCUSSION

We show that the variable X-ray spectrum of NGC 4051 can be well described by a model that includes two principal components:

1. A hard, constant, component including a narrow iron fluorescence line as revealed during the extreme low state in May 1998.

2. A variable component including a power law with strongly variable slope and a very broad emission line. We find a strong correlation between the power law slope and the source flux. On the long time-scales of the monitoring observations the line flux is correlated with the continuum flux, although not in a simple manner. The reflected fraction of the disk component is less than $R = 1$ at all flux levels.

This two-component model is consistent with the model we proposed for the X-ray spectral variability of the Seyfert 2 galaxy NGC 5506 (Lamer, Uttley & M€Hardy 2000). We note that even if the constant hard component is not included in our spectral fits, the general form of our results is not significantly affected, as the assumed constant component is relatively weak. Indeed, the lack of inclusion of a hard continuum component would result in an even larger spectral index variation with flux.

5.1 The Iron Line

Even on the long timescales probed by our time-averaged monitoring data, the flux-dependent behaviour of the broad iron line is complex. For these data, the line flux increases more-or-less proportionally with the continuum flux, resulting in a roughly constant equivalent width over a decade range of flux. The December 1996 long-look data also show line flux increasing with continuum flux, although the relation is not directly proportionate, so that the equivalent width decreases with flux. In fact, the line fluxes measured in December 1996 are consistently larger than the corresponding fluxes measured from the long-term monitoring data. The anti-correlation of line equivalent width and continuum flux in December 1996 timescales is also in contrast to the result of (Wang et al. 1999), who report a positive correlation during an ASCA observation in 1994.

The discrepancy between the iron line behaviour in the December 1996 and long-term monitoring data might be explained if there is additional short-term variability in the iron line which is not simply related to the continuum flux. For example, Vaughan & Edelson (2001) show that in the Seyfert 1 MCG-6-30-15, the broad iron line flux varies significantly but independently of short term continuum variations.

One possibility is that the iron line flux tracks the long-term variations in the continuum flux (which are being probed to some extent with the long-term monitoring data), but responds only weakly to the short-term variations which are observed during the December 1996 long-look observation. A number of theoretical papers have been written to explain why the iron line flux may not vary linearly with the continuum flux (eg Matt et al. 1993, Nayakshin & Kazanas 2002, Ballantyne & Ross 2002), often involving ionised discs but these models have so far been largely untroubled by data. We are acquiring more long-term monitoring data, sampling a broader range of long-term flux variations, to determine whether the iron line does follow the continuum on long timescales and to provide some constraints for theoretical models.

5.2 The Reflected Component

Our observations of NGC 4051 do not support the correlation between the photon index and the reflected fraction $R$ in the PEXRAV model as reported from ASCA spectroscopy of a sample of Seyfert galaxies (Zdziarski, Lubinski & Smith 1999). From Fig. 4 it is obvious that the reflected fraction remains below $R = 1$ even for the softest states of the source. There is also no evidence for this correlation in the RXTE spectra of NGC 5506 (Lamer, Uttley & M€Hardy 2000). We therefore suggest that the reported correlation does not apply to the variations of photon index and reflected fraction in a given object.

5.3 Continuum Spectral Variability

During our monitoring campaign the primary continuum 2-10 keV photon index, $\Gamma$, varies strongly with photon flux from 1.60 at the lowest flux levels to 2.35 at the highest fluxes. The same correlation is also observed on the shorter time-scales of the December 1996 long look. Flux-$\Gamma$ correlations have been observed before in NGC 4051 (Matsuoka et al. 1987) and other Seyfert galaxies (eg NGC 4151, Perola et al. 1986) but, as in the present paper, it has only recently been possible to disentangle the effects of reflection and variations of the primary X-ray spectrum (eg Lamer, Uttley & M€Hardy 2000, Chiang et al. 2000, Lee et al. 2000).
X-ray spectral variability of the Seyfert galaxy NGC 4051

Table 5. Disk line model fits to flux selected spectra

<table>
<thead>
<tr>
<th>mean flux [erg s⁻¹ cm⁻²]</th>
<th>photon index</th>
<th>EW_{narrow} [eV]</th>
<th>f_{disk} [10⁻⁵ ph cm⁻² s⁻¹]</th>
<th>EW_{disk} [eV]</th>
<th>i</th>
<th>(-q)</th>
<th>(\chi^2) (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long term monitoring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.46 \times 10^{-12}</td>
<td>1.60 \pm 0.10</td>
<td>397</td>
<td>1.93 \pm 0.89</td>
<td>192 \pm 80</td>
<td>0 \pm 90</td>
<td>2 - 3.3</td>
<td>18.5(44)</td>
</tr>
<tr>
<td>1.62 \times 10^{-11}</td>
<td>1.89 \pm 0.04</td>
<td>162</td>
<td>7.19 \pm 1.49</td>
<td>389 \pm 81</td>
<td>27 \pm 7</td>
<td>&gt; 3.8</td>
<td>19.1(44)</td>
</tr>
<tr>
<td>2.77 \times 10^{-11}</td>
<td>2.10 \pm 0.02</td>
<td>105</td>
<td>11.33 \pm 1.66</td>
<td>367 \pm 54</td>
<td>31 \pm 4</td>
<td>&gt; 5.7</td>
<td>29.7(44)</td>
</tr>
<tr>
<td>3.35 \times 10^{-11}</td>
<td>2.16 \pm 0.03</td>
<td>89</td>
<td>11.40 \pm 3.25</td>
<td>327 \pm 93</td>
<td>28 \pm 7</td>
<td>&gt; 2.9</td>
<td>18.0(44)</td>
</tr>
<tr>
<td>4.06 \times 10^{-11}</td>
<td>2.19 \pm 0.03</td>
<td>80</td>
<td>9.74 \pm 1.90</td>
<td>216 \pm 42</td>
<td>24 \pm 7</td>
<td>&gt; 5.2</td>
<td>22.4(44)</td>
</tr>
<tr>
<td>5.21 \times 10^{-11}</td>
<td>2.29 \pm 0.03</td>
<td>61</td>
<td>10.56 \pm 3.17</td>
<td>204 \pm 61</td>
<td>32 \pm 9</td>
<td>&gt; 4.8</td>
<td>26.1(44)</td>
</tr>
<tr>
<td>6.74 \times 10^{-11}</td>
<td>2.33 \pm 0.03</td>
<td>49</td>
<td>16.84 \pm 3.24</td>
<td>181 \pm 35</td>
<td>0 \pm 19</td>
<td>&gt; 2.8</td>
<td>23.6(44)</td>
</tr>
</tbody>
</table>

December 1996

| 6.78 \times 10^{-12}    | 1.81 \pm 0.09 | 391              | 5.31 \pm 1.12            | 675 \pm 142   | 28 \pm 6 | > 7.0   | 45.0(44)   |
| 1.53 \times 10^{-11}    | 1.86 \pm 0.06 | 186              | 10.07 \pm 2.17           | 566 \pm 121   | 25 \pm 5 | > 5.2   | 33.3(44)   |
| 2.64 \times 10^{-11}    | 2.11 \pm 0.04 | 120              | 14.03 \pm 2.07           | 458 \pm 68    | 23 \pm 5 | > 11.2  | 28.3(44)   |
| 3.61 \times 10^{-11}    | 2.23 \pm 0.06 | 91               | 10.64 \pm 4.66           | 267 \pm 117   | 24 \pm 15 | > 3.2   | 41.8(44)   |

The slope-luminosity correlation is often explained by stronger cooling of the accretion disk corona during episodes of high thermal seed photon flux from the accretion disk itself (e.g. Pietrini & Krolik 1995, Malzac & Jourdain 2000). Haardt, Maraschi & Ghisellini (1997) have calculated luminosity – spectral index relations in Compton cooled accretion disk coronae. For a compact, pair dominated corona they predict spectral index variations of \(\Delta \Gamma \sim 0.3\) for luminosity variations by more than a factor of 20. However the variations seen here exceed their predictions and imply, in their scenario, a non-pair dominated corona. In certain regimes this model predicts a positive correlation of 2-10 keV flux and spectral hardness, which is not observed in NGC 4051. Pietrini & Krolik (1995) point out that the spectral index depends almost solely on the ratio of seed photon compactness \(l_c\) and hot plasma heating rate compactness \(l_h\) with \(\alpha = 1.6(l_c/l_h)^{3/4}\). The observed spectral indices in NGC 4051 then correspond to \(l_c/l_h = 0.02-0.4\).

Examination of fig 7 shows that the change of spectral index with flux is not linear. The rate of increase of spectral index with flux is very rapid at low fluxes but decreases at the highest fluxes where the spectral index approaches an asymptotic level. This saturation of the ‘spectral index/flux’ relationship has been known for some time; eg the saturation was clearly visible in our early RXTE monitoring observations of MCG-6-30-15 and was reported by M‘Hardy, Papadakis & Uttley (1998) where it was suggested that the relationship might derive from the combination of a constant spectrum hard component, and a steeper spectrum variable component.

Saturation of the spectral index/flux relationship was again reported in MCG-6-30-15 by Shih et al. (2002) from a long ASCA observation. In MCG-6-30-15 both the long term RXTE monitoring and short term ASCA observations agree that the saturation level of the spectral index is \(\sim 2.1\) (see fig 7 of M‘Hardy, Papadakis & Uttley 1998 and fig 8 of Shih et al. 2002). However the monitoring observations cover a wider flux and spectral range and show variation of the spectral index between 1.65 and 2.05 whereas the continuous ASCA observation only shows an index variation between 1.9 and 2.1. Similarly in NGC 4051 (fig 7) we see that the monitoring observations cover a wider flux and spectral range than the December 1996 long look and, as with MCG-6-30-15, the resultant time-averaged spectral index/flux relationship is smoother. We note, however, that although the lowest spectral index so far measured in the RXTE monitoring observations is about the same in both NGC 4051 and MCG-6-30-15, the saturation level is \(\sim 2.4\) in NGC 4051 compared to \(\sim 2.1\) in MCG-6-30-15.

In M‘Hardy, Papadakis & Uttley (1998) we suggested that the torus might be the source of the possible hard, constant, component. However the very hard spectral component found in the May 1998 very low state, which represents an upper limit to the torus contribution, was removed before producing the spectral index/flux relationship (fig 7). Thus, if we wish to retain the two-component spectral model, we require a different location for the bulk of the hard component. However any hard component produced closer to the central source by reprocessing of primary radiation is likely to vary, although probably not as rapidly as the primary continuum. Our time-averaged spectra wash out short term variability so a hard component varying slowly in line with the primary continuum could not produce the observed spectral index/flux relationship. Unless a hard component is produced by some mechanism other than reprocessing it is therefore more likely that the change of spectral index with flux is driven by some change in the physical properties of the primary continuum source, eg by changes in the seed photon populations as discussed above.

Any such physical model of the primary continuum must be able to produce different saturation levels in different sources and must be able to account for both the wide spectral range, and the very hard spectra measured at the lowest flux levels, in our monitoring observations.

References

References

Kikoin I.K., 1976, Tables of Physical Quantities (Moscow: Atomizdat)