Complex optical–X-ray correlations in the narrow-line Seyfert 1 galaxy NGC 4051

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ABSTRACT
This paper presents the results of a dense and intensive X-ray and optical monitoring of the narrow-line Seyfert 1 galaxy NGC 4051 carried out in 2000. Results of the optical analysis are consistent with previous measurements. The amplitude of optical emission-line variability is a factor of 2 larger than that of the underlying optical continuum, but part or all of the difference can be due to host-galaxy starlight contamination or to the lines being driven by the unseen ultraviolet continuum, which is more variable than the optical continuum. We measured the lag between optical lines and continuum and found a lower, more accurate broad-line region size of $3.0 \pm 1.5$ light-days in this object. The implied black hole mass is $M_{\text{BH}} = 5.4 \pm 1 \times 10^5 \, M_{\odot}$; this is the lowest mass found, so far, for an active nucleus. We find significant evidence for an X-ray–optical (XO) correlation with a peak lag $\sim 1$ d, although the centroid of the asymmetric correlation function reveals that part of the optical flux varies in advance of the X-ray flux by $2.4 \pm 1.0$ d. This complex XO correlation is explained as a possible combination of X-ray reprocessing and perturbations propagating from the outer (optically emitting) parts of the accretion disc into its inner (X-ray emitting) region.

Key words: galaxies: active – galaxies: individual: NGC 4051 – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION
Correlations between different parts of the spectral energy distribution in active galactic nuclei (AGN) have been utilized in the past decade as an important tool to probe and map the deepest components of the central engine’s energy source. Several attempts have aimed at finding a connection between X-ray and optical light curves, in order to follow the source and location of the X-ray emission. Such attempts have been carried out in the past decade as part of AGN multiwavelength monitoring campaigns (e.g. Done et al. 1990; Nandra et al. 1998, 2000; Edelson et al. 2000; Maoz, Edelson & Nandra 2000; Peterson et al. 2000, hereafter P00; Shemmer et al. 2001; see also Maoz et al. 2002 for a brief summary of previous campaigns). So far, reliable determinations of X-ray–optical (XO) correlations are few and far between. In most cases where a strong correlation was found, the X-ray and optical light curves appeared to vary simultaneously, i.e. practically with zero lag. For example, on long time-scales (days–months) all attempts to find XO lags have failed (e.g. Clavel et al. 1992 in NGC 5548; Done et al. 1990 and P00 in NGC 4051; Shemmer et al. 2001 in Ark 564; and Maoz et al. 2002 in NGC 3516). Even on shorter time-scales (hours) XO correlations and lags are rare (e.g. Edelson et al. 1996 in NGC 4151; but see also Edelson et al. 2000 for no XO correlation in NGC 3516).

One exception is NGC 7469 (Nandra et al. 1998, 2000), in which a significant correlation was found between the optical/ultraviolet (UV) continuum and the X-ray flux that followed it with a $\sim 4$ d lag, including periods when increasing X-ray flux led decreasing UV flux by a similar lag. This complex behaviour ruled out two possible scenarios: UV seed photons that are Compton up-scattered to produce X-rays in a putative corona (UV leading X-ray; e.g. Haardt & Maraschi 1991, 1993); or UV radiation that is produced by reprocessed X-ray photons (X-ray leading UV; e.g. Stern et al. 1995). Uttley et al. (2003) find a very strong correlation between long time-scale (months) X-ray and optical variations in NGC 5548, but constrain any lag to be less than 15 d. Another success in finding an XO correlation was during the Ark 564 campaign, when an X-ray flare was followed $\sim 2$ d later by an optical flare (Shemmer et al. 2001) and was interpreted in terms of reprocessing models.

The successful detection of an optical response to an X-ray flare in Ark 564, a narrow-line Seyfert 1 (NLS1) galaxy, has motivated us to search for similar behaviour in other NLS1s that we have been monitoring as part of a larger project. Since one of the more
pronounced characteristics of NLS1s is the intense X-ray variation (e.g. Boller, Brandt & Fink 1996; Leighly 1999a,b), which is at least one order of magnitude larger in amplitude than in 'normal' Seyfert 1 galaxies, we assumed that detection of X–O connections will be more frequent and more pronounced in this subclass of AGN. One difficulty, though, appears to be the fact that the persistent large and rapid X-ray variability in NLS1s (flux variations of a factor of 2 or more on time-scales of minutes/hours) is contrasted by the very low variability exhibited by the optical band. NLS1s differ markedly from 'normal' broad-line Seyfert 1 galaxies (e.g. NGC 7469; Nandra et al. 1998, 2000) in this respect by varying strongly in the X-ray while showing little or no variability in the optical/UV band (e.g. Ark 564; Shemmer et al. 2001).

NGC 4051 is a nearby (z = 0.0023), low-luminosity (~10$^{42}$ erg s$^{-1}$), NLS1 [FWHM(H$\beta$) = 1110 km s$^{-1}$] that has been studied extensively across the spectrum (e.g. Utley et al. 1999; Collinge et al. 2001, and references therein; Lamer et al. 2003) and has shown optical variability amplitudes of up to ~10 per cent in flux (Done et al. 1990, POO). In 2000 we carried out a dense and continuous X-ray and optical monitoring campaign on NGC 4051. Our major goal aimed at finding a temporal relationship between the variations observed in the two bands. In this paper we present the results of this campaign. Section 2 presents the observational data and their reduction. In Section 3 we present the results of the time-series analysis, and in Section 4 discuss its implications. Section 5 summarizes our main conclusions.

2 OBSERVATIONS AND DATA REDUCTION

2.1 The optical band

NGC 4051 was monitored spectrophotometrically during 2000 May–July at the Tel-Aviv University Wise Observatory (WO). The observations were carried out with the Faint Object Spectrograph and Camera on top of the WO 1-m telescope. We used a 10 arcsec-wide long slit and a 600 line mm$^{-1}$ grism. A Tektronix 1024 x 1024 pixel back-illuminated CCD was used as the detector. Reduction of the data was carried out in the usual manner using IRAF$^1$ with its SPECDIR, ONEDSPEC and TWODSPEC packages. In order to reduce light contamination from the host galaxy while not lowering the signal-to-noise (S/N) ratio, we extracted the spectrum using an 8 arcsec extraction window.

Spectrophotometric calibration of the nucleus of NGC 4051 was carried out using the technique in which a nearby comparison star is observed simultaneously with the object of interest inside a wide slit. This technique of using a local comparison star is described in detail by Maoz et al. (1990, 1994) and produces high relative spectrophotometric accuracy. Each spectroscopic observation consisted of two 15-min exposures of NGC 4051 and its comparison star. The consecutive galaxy/star flux ratios were compared to test for systematic errors in the observations and to clean cosmic rays. We discarded pairs of data points with ratios larger than ~5 per cent and verified that the comparison star is non-variable to within ~2 per cent by means of differential photometry of other stars in the field, carried out before this campaign began.

As a result, 31 good-quality spectra remained. The spectra were calibrated to an absolute flux scale by multiplying each galaxy/star ratio by a spectrum of the comparison star that was flux-calibrated by applying a characteristic WO extinction curve and CCD sensitivity function, which do not change considerably from night to night. The absolute flux calibration has an uncertainty of ~10 per cent, which is not shown in the error bars of our light curves. The error bars reflect only the differential uncertainties, which are of order 2–3 per cent. By measuring the [O iii] 5007 fluxes in our spectra, we verified that the differential uncertainty level is consistent with the night-to-night scatter in this narrow emission-line light curve (which is expected to maintain a constant flux level). We measured the mean flux in narrow line-free continuum bands close to H$\alpha$ and H$\beta$ (see Fig. 1) and the integrated flux of both emission lines in each spectrum. Two of the resulting light curves (together with the X-ray light curve, see Section 2.2) are plotted in Fig. 2.

2.2 X-ray observations

NGC 4051 was intensively monitored by the Rossi X-ray Timing Explorer (RXTE) in 2000 May–July, as part of an ongoing campaign to measure its broad-band X-ray variability power spectrum (McHardy et al., in preparation). The intensive monitoring programme consisted of 251 observations, each of exposure ~1 ks, obtained at roughly 6-h intervals from 2000 May 1 to July 5. We used data from the RXTE Proportional Counter Array, applying standard good time interval selection criteria and using all available Proportional Counter Units (PCUs; top layer only) to extract a spectrum for each observation. Using XSPEC, we fitted each spectrum with a simple power law plus Galactic absorption model, in order to obtain an estimate of the 2–10 keV photon flux which is robust to changes in instrument gain and number of PCUs used (see Lamer et al. 2003, for further details of data reduction and spectral fitting).

3 TIME-SERIES ANALYSIS

3.1 Variability

The fractional variability, $F_{\text{var}}$, (Rodríguez-Pascual et al. 1997) of a light curve is defined as

$$F_{\text{var}} = \frac{\sqrt{S^2 - \langle \sigma_y^2 \rangle}}{\langle X \rangle^2},$$

where $S$ is the power of the power spectral density, $\langle \sigma_y^2 \rangle$ is the variance of the light curve, and $\langle X \rangle$ is the mean flux in the light curve.
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intuitive to compare this with the optical value, it is technically incorrect
the X-ray light curve is 35.3 ± 3.1 per cent and, even though it might seem more
value of the unbinned
for each data point. This allows us to compare the ±

Even though the sampling patterns of both X-ray and optical light curves are
different, both have a similar length and a similar exposure time (~10 min)
for each data point. This allows us to compare the Fvar value of the unbinned
X-ray light curve directly with that of the optical. The Fvar of the 1-d bin
X-ray light curve is 35.3 ± 3.1 per cent and, even though it might seem more
intuitive to compare this with the optical value, it is technically incorrect
since binning the X-rays smoothes out the ±1 d variations that contribute to
the optical light curve.

Table 1. Fractional variability.

<table>
<thead>
<tr>
<th>Band</th>
<th>Fvar (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2–10 keV</td>
<td>44.9 ± 2.0</td>
</tr>
<tr>
<td>&gt;4800</td>
<td>3.4 ± 0.5</td>
</tr>
<tr>
<td>Hβ</td>
<td>7.8 ± 1.2</td>
</tr>
<tr>
<td>&gt;5100</td>
<td>3.4 ± 0.5</td>
</tr>
<tr>
<td>&gt;6400</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>Hα</td>
<td>4.0 ± 0.5</td>
</tr>
<tr>
<td>&gt;6800</td>
<td>1.9 ± 0.3</td>
</tr>
</tbody>
</table>

where $S^2$ is the total variance of the light curve, $\sigma_{\text{err}}^2$ is the mean
error squared, and $(X)^2$ is the mean flux squared. The uncertainty
on $F_{\text{var}}$ is (Edelson et al. 2002):

$$\sigma \left( F_{\text{var}} \right) = \frac{S^2}{\sqrt{2N F_{\text{var}}(X)^2}}.$$  \hspace{1cm} (2)

A list of $F_{\text{var}}$ values calculated for the optical and X-ray light
curves appears in Table 1, where it is apparent that the X-ray variability
is an order of magnitude larger than the optical variability over the same time interval.2 It is also apparent that, within the

3.2 Cross-correlations

The X-ray light curve shows strong short time-scale variations that are
not reflected in the optical light curves (as previously noted by Done et al. 1990 and P00), so to obtain a better comparison with the optical variations we smoothed out the rapid X-ray variability
by binning the X-ray light curve into 1 d bins (see Fig. 2) before
cross-correlating with the unbinned optical data (which is sampled at approximately daily intervals). To derive the cross-correlation
function (CCF) between the two light curves (the first assumed to be the
driving light curve and the second assumed to be the responding light curve), we utilized the discrete correlation function (DCF)
method (Edelson & Krolik 1988). For each pair of light curves, we
measured the DCF in the lag range 0 ± 10 d, binning in 1-d lag bins
(at larger lags there are fewer pairs of light curve points per lag bin so that spurious peaks in the CCF are much more common). Peak values
($r_{\text{max}}$) and corresponding peak lags ($\tau_{\text{peak}}$) were determined, together
with the lag centroid (\tau_{\text{cent}}), which is a measure of the 'centre of mass'
of the lag peak, and thus takes account of asymmetries in the correlation. The centroid is determined by summing the CCF values in the range either side of $\tau_{\text{peak}}$ where the CCF value $r > 0.8r_{\text{max}}$. The
uncertainties on the lags (peak and centroid) were estimated using the
flux randomization/random subset selection (FR/RSS) method
(Peterson et al. 1998). The CCFs for the most important correlations
are plotted in Fig. 3 and parameters of each correlation are shown
in Table 2.

At face value, the correlations shown in Table 2 appear to be sig-
nificant, with correlation coefficients larger than one would expect
Table 2. NGC 4051 cross-correlation results.

<table>
<thead>
<tr>
<th>Band</th>
<th>$r_{\text{max}}$</th>
<th>Significance of $r_{\text{max}}$</th>
<th>$r_{\text{peak}}$ (d)</th>
<th>$r_{\text{cent}}$ (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5100–6800 Å</td>
<td>0.74</td>
<td>0.96</td>
<td>0 ± 1</td>
<td>0.4 ± 0.9</td>
</tr>
<tr>
<td>6800 Å–Hα</td>
<td>0.60</td>
<td>0.85</td>
<td>3.0 ± 1.5</td>
<td>3.1 ± 1.6</td>
</tr>
<tr>
<td>X–6800 Å</td>
<td>0.65</td>
<td>0.96</td>
<td>0 ± 1</td>
<td>−2.4 ± 1.0</td>
</tr>
<tr>
<td>X–Hα</td>
<td>0.67</td>
<td>0.97</td>
<td>−2 ± 3</td>
<td>−0.9 ± 1.7</td>
</tr>
<tr>
<td>6800 Å–Hβ</td>
<td>0.51</td>
<td>0.69</td>
<td>2.0 ± 2.6</td>
<td>2.0 ± 2.3</td>
</tr>
<tr>
<td>Hα–Hβ</td>
<td>0.79</td>
<td>0.98</td>
<td>0 ± 2</td>
<td>−0.9 ± 1.7</td>
</tr>
</tbody>
</table>

if the data were randomly distributed and uncorrelated. However, the light curves presented here are not random (white-noise) data sets: adjacent data points are correlated with one another to produce variations on a range of time-scales and are consistent with red-noise processes. As such, the correlations between two light curves are driven by only a few events (flares or dips) in each light curve, and it is possible that apparent correlations could be seen even where none exist, simply because the events in two uncorrelated light curves happen to match up by chance. To assign a reliable significance to the correlations, we must simulate uncorrelated red-noise light curves with similar variability properties to the observed light curves, and determine the frequency of spurious correlations. A similar Monte Carlo method to assess the significance of the XO correlation in NGC 5548 has been applied by Uttley et al. (2003). We outline the method here:

(i) Simulate two continuous red-noise light curves, of time resolution 0.01 d and length 16384 bins (i.e. 163 d, much larger than the 60-d observed duration) using the method of Timmer & Koenig (1995), with different random number sequences to generate each light curve so they are uncorrelated. We assume broken power-law shapes for both optical and X-ray power spectra, with break frequencies at 1 d$^{-1}$ and power-law slopes above the break of −1.5 and −2 for X-ray and optical power spectra respectively and identical slopes of −1 below the break. The X-ray power spectral shape is chosen to approximate that measured by much more extensive RXTE and XMM data sets (McHardy et al., in preparation), while the optical power spectral shape (which is assumed to be the same for continuum and lines) is chosen to reproduce the relatively low variability on short time-scales and to mimic the finding in NGC 5548 that the optical and X-ray power spectral shapes differ only at high frequencies (Uttley et al.)
below. Our main observational results are discussed below.

(ii) Apply observational noise to the simulated light curves, by adding to each simulated data point a random deviate of mean zero and variance equal to the average squared error of the corresponding light curve.

(iii) Resample the simulated light curves to the observed sampling patterns and rebin the simulated, resampled X-ray light curve to 1-d bins.

(iv) Measure the DCF of the pair of simulated, uncorrelated light curves, and search for a peak value, $r_{\text{max}}$, as outlined above for the observed light curves. Search within lags of $\pm 10$ d, allowing adequate overlap between the two light curves.

(v) Repeat the above four steps 1000 times, and count the number of times that the simulated $r_{\text{max}}$ exceeds the observed $r_{\text{max}}$, to yield the significance of the observed correlation.

For example, for the X-ray-Å56800 correlation, we observed a maximum correlation coefficient of $r_{\text{max}} = 0.65$. We counted 40 out of 1000 simulated, uncorrelated light curves with $r_{\text{max}} > 0.65$, implying that the observed correlation is significant at the 96 per cent confidence level (i.e. just over 2$\sigma$). The estimated significance of each correlation shown in Table 2 is based on such simulations.

We note that our Monte Carlo approach shows that the actual significance of the correlations is considerably less than would be expected from white-noise data given the same values of $r_{\text{max}}$. However, all the optical continuum-continuum and line–line correlations are significant at better than 95 per cent confidence, as are the XO correlations. The optical continuum–line correlations are not significant, but this represents a limitation of the existing data set, which contains few events in each light curve (and some additional scatter that weakens the correlation). Longer data sets confirm that the optical continuum–line correlation is real (Peterson et al. 2000). We stress however that the questions of the significance of a correlation, and the significance of lags measured between two light curves, are not the same. The significance of a correlation can be determined by testing the null hypothesis that the light curves are uncorrelated. However, in order to determine the significance of any lag, one must assume that the light curves are indeed correlated (as is implicit in the FR/RSS method of lag error estimation); in that case the quality of sampling is important to constrain the lag, rather than the number of ‘events’ in the light curve. Therefore we can still measure lags that are well constrained, even though the correlation itself is not formally significant.

### 4 DISCUSSION

We have monitored NGC 4051 in X-ray and in the optical band on a daily basis for about 60 d in order to find a possible relation between the two bands. Our main observational results are discussed below.

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3 To ensure that our significance estimates are not strongly dependent on optical power spectral shape, which is ill-defined, we also tested light curves with break frequency as low as 0.01 d$^{-1}$ and slope above the break as steep as $-2.5$, and find no significant deviation from the estimates we present here.

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4.1 Optical line–continuum lag

Cross-correlations between the two major Balmer emission lines and the optical continuum confirm the previously detected lag in this object (P00). We find that H$\alpha$ responds to the continuum variations after 3.0 ± 1.5 d, which is consistent, within the errors, with the 5.92 ± 1.96 d reported in P00 for H$\beta$. Since we do not detect any lag between H$\alpha$ and H$\beta$, our new line–continuum lag has a lower error, perhaps due to the denser sampling frequency (about once a day) compared with the previous campaign (about once every four days; P00). Moreover, as the observed average flux of NGC 4051 in this study is similar (to within ~10 per cent) to that observed during all three phases of the P00 campaign, we suggest that the lower lag we find is not a luminosity effect, but the combined effect of observations and the CCF. By incorporating our lowest error value for the lag (3.0 ± 1.5 d), and FWHM(H$\beta$) = 1110 ± 190 km s$^{-1}$ from P00 into equation (5) of Kaspi et al. (2000) for the virial black hole (BH) mass estimate, we obtain $M_{\text{BH}} = 5.6_{-1.5}^{+4.2} \times 10^5$ M$_{\odot}$. Our result is thus consistent, within the errors, with the P00 estimate. The new and lower broad-line region (BLR) size we obtained, $R_{\text{BLR}} = 3.0_{-1.5}^{+1.5}$ light-days, places NGC 4051 much closer to the best-fitting $R_{\text{BLR}}$–L$^*$ slope produced from reverberation measurements of 34 AGN (see fig. 6 of Kaspi et al. 2000).

4.2 Optical and X-ray relation

Inspection of Table 1 shows that the X-ray variability amplitude is about one order of magnitude larger than that of the optical and is ubiquitous in NLS1s (see e.g. Boller et al. 1996; Young et al. 1999). In particular, this result is consistent with the behaviour of NGC 4051 in two previous monitoring campaigns (Done et al. 1990, P00). The striking difference between the variability amplitudes of the X-ray and the optical bands in NLS1s is not yet understood.

Another interesting result is that each optical emission line varies about twice as much as its underlying continuum. This trend was also encountered by Peterson, Crenshaw & Meyers (1985) and by P00. One possible reason for the large $F_{\text{var}}$ of the lines might be that the UV and/or the X-ray continua, which are the likely drivers of the line flux, are varying with much larger amplitudes. However, in 1998 the H$\beta$ flux remained unchanged when the X-ray source almost completely turned off and so the highly variable X-ray continuum does not contribute significantly to the production of Balmer lines (P00). Large-amplitude UV variations do, however, remain a possibility and would be consistent with the very large extreme ultraviolet (EUV) variations observed by Uttley et al. (2000). The other remaining, and more likely, possibility is that the host-galaxy contribution to the optical continuum is larger than estimated here (~50 per cent; see e.g. the case of NGC 5548, Gilbert & Peterson 2003).

The X-ray and optical light curves are apparently correlated at >95 per cent confidence, although the light curves are not simply correlated, which would lead to a much clearer peak in the CCF (e.g. see the $\lambda 5100$–$\lambda 6800$ correlation). The relation between the X-ray and $\lambda 6800$ light curves can be seen by rescaling both light curves (after subtracting their respective means) by their rms variability (i.e. $F_{\text{var}}$ multiplied by mean flux), as shown in Fig. 4. No lag is introduced into any light curve. The X-ray and optical light curves can be seen to be generally correlated, at least on long time-scales, but there are occasional large discrepancies between the two (which are not attributable to observational noise), which reduce the strength of the observed correlation. The differences between the rescaled light curves in Fig. 4 may be attributable to the large amplitude of short
time-scale X-ray variability relative to the amplitude of long time-scale variations, which implies that the X-ray power spectrum is flatter than the optical power spectrum. Much better signal-to-noise ratio and sampling in both X-ray and optical light curves would be required in order to tell if corresponding short-term variations appear (but at a much weaker level) in the optical light curve.

We find that the peak of the XO cross-correlation is at zero lag but that the centroid of the CCF lies at an optical to X-ray lag of 2.4 ± 1.0 d. From simulations we have shown that the probability of exceeding the observed peak cross-correlation coefficient in random data from suitably constructed light curves is 4 per cent.

This result should be compared with two previous attempts to measure XO lags in NGC 4051. The first attempt (Done et al. 1990) found very little variability (F(\text{var}) < 1 per cent) in the optical band in an observational period of a week (and hence no measurable lag) and the second attempt found a good correlation on long time-scales with approximately zero lag (P00). The result of Done et al. (1990) is consistent with our observations, as we find that NGC 4051 shows only small-amplitude optical variability on time-scales of a week (see Fig. 2). Peterson et al. (2000) were unable to find any XO correlation on short time-scales, probably due to relatively poor X-ray sampling compared to the light curve we present here. On long time-scales, their light curves were smoothed by a 30-d boxcar, thus suppressing any rapid X-ray variations and rendering the detection of a short lag, such as the one we mention here, impossible.

Also of significant interest is the recent result of Mason et al. (2002). In a 130-ks observation of NGC 4051 with XMM–Newton, they found that the 0.1–12 keV X-ray continuum led the λ2000 UV continuum, measured with the XMM–Newton optical monitor, by 0.17 d. The significance of that result is similar to that found here. They interpret their observation as optical variability arising from reprocessing of X-ray photons in a region surrounding the central X-ray source.

The fact that the peak of our XO CCF is at zero lag is quite consistent with the result of Mason et al. (2002). Their short observation is not sensitive to the longer time-scales that we sample and we are not able to resolve the very short time-scales that they sample.

Interestingly, we also find that the XO CCF appears to be asymmetric, in that, although it has a zero-lag peak, it has a negative centroid lag, r_{\text{cen}} (i.e. X-rays lag optical). A negative centroid lag and zero peak lag can be reconciled if the variations on time-scales longer than a few hours have a different lag, and hence probably a different physical origin, than those on shorter time-scales. We can use Monte Carlo simulations to test whether such an observed centroid lag would be expected by chance from perfectly correlated light curves (i.e. light curves with true peak and centroid lag of zero) by counting the number of simulated CCFs with a greater XO lag than observed.4 We find that only 2 per cent of simulated pairs of perfectly correlated light curves show centroid lags of greater than 2.4 d, suggesting that the centroid lag and hence observed asymmetry in the CCF is real (as implied by the lag error estimated using the FR/RSS method). However, we caution that the significance of the centroid lag estimated by Monte Carlo simulations is model-dependent: we have only tested the significance of the centroid lag assuming perfectly correlated light curves.

Our putative lag, deduced from the offset position of the centroid of the CCF, might, at first thought, be assumed to result from Compton upscattering of UV/optical seed photons to produce X-ray photons (e.g. Haardt & Maraschi 1991, 1993). A similar argument was used by Uttley et al. (2000) for NGC 4051 to explain the very strong correlation between the X-ray and EUV emissions, whose variations are simultaneous to within 1 ks. In that case the size of the X-ray emitting region was calculated to be ≤20R_{\text{g}}. Taking account of the increased spectral difference between the optical and X-ray bands compared to that between the EUV and X-ray bands, and the greater length of the putative lag here, the implied size of the X-ray emitting region would be ~1000R_{\text{g}}, much larger than deduced previously. It is hard to reconcile such a large size with the rapid X-ray variability. It is also not easy to reconcile an accretion disc of this size (or the hot corona of such a disc) with the observed properties of this source.

An alternative explanation of an X-ray lag is that the optical emitting region is further out in the accretion disc than the X-ray emitting region (which may be a hot corona <20R_{\text{g}} in size, Uttley et al. 2000). Variations propagating inwards, perhaps at the viscous or diffusion time-scale (which in NGC 4051 can be quite short, especially if the disc is thick), would first affect the optical emitting region and, later, the X-ray emitting region. A similar explanation, based on the model for flickering in X-ray binaries suggested by Lyubarskii (1997), is used by Kotov, Churazov & Gilfanov (2001) to explain the energy dependence of the time lags in the X-ray variations in Cyg X-1. Given the many similarities in variability properties of AGN and X-ray binaries (e.g. Uttley et al. 2002; McHardy et al., in preparation), such a model might also be applicable to explain the possible X-ray lag in NGC 4051.

5 CONCLUSIONS

Our main conclusions are summarized as follows:

(i) The variability amplitudes of our X-ray and optical light curves are consistent with previous observations of NGC 4051. However, despite several good arguments made to explain the observed emission-line variability amplitudes, which are larger by a factor of 2 than the optical continuum variability amplitude, a lack of quantitative evidence remains.

(ii) Our measured R_{\text{HLR}} value is 3.0 ± 1.5 light-days, which is about a factor of 2 lower than previous measurements. This implies

4 The light curves are generated as in Section 3.2, but using identical random number sequences for light-curve generation before resampling and applying Gaussian noise.
M\(_{\text{BH}}\) = 5\(^{+3}_{-1}\) \times 10^5 M_\odot, and places NGC 4051 much closer than before to the best-fitting \(R_{\text{BLR}} - L\) slope of Kaspi et al. (2000). The apparent change in BLR distance is not a luminosity effect, but rather an observational one, since at least the optical flux of the galaxy remained practically constant during all the monitoring campaigns.

(iii) There is significant evidence for an X-ray–optical correlation close to zero lag (within one day) in NGC 4051. There is also evidence that part of the optical flux varies in advance of the X-ray flux by about 2 d. Although the amplitude of the optical variations is very low, these observations are consistent with X-ray/optical variations seen elsewhere and are probably best explained by a combination of effects including reprocessing of X-ray photons and a physical separation of the main X-ray and optical producing regions. Although Compton up-scattering of optical photons to produce X-ray photons cannot be ruled out, optical photons do not appear to be as important to the seed photon continuum as UV photons.

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