

Long-term optical and X-ray variability of the Seyfert galaxy Markarian 79

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ABSTRACT

We present the results of concurrent X-ray and optical monitoring of the Seyfert 1 galaxy Mrk 79 over a period of more than 5 yr. We find that on short to medium time-scales (days to a few tens of days) the 2–10 keV X-ray and optical *u*- and *V*-band fluxes are significantly correlated, with a delay between the bands consistent with 0 d. We show that most of these variations may be well reproduced by a model where the short-term optical variations originate from reprocessing of X-rays by an optically thick accretion disc. The optical light curves, however, also display long time-scale variations over thousands of days, which are not present in the X-ray light curve. These optical variations must originate from an independent variability mechanism and we show that they can be produced by variations in the (geometrically) thin disc accretion rate as well as by varying reprocessed fractions through changes in the location of the X-ray corona.

Key words: galaxies: active – galaxies: individual: Mrk 79 – galaxies: Seyfert.

1 INTRODUCTION

Active galactic nuclei (AGN) emit across almost the entire electromagnetic spectrum. In most AGN, the bulk of the emission is radiated in the ultraviolet (UV)/optical region in what is known as the ‘big blue bump’. The blue bump is generally accepted to be thermal emission, originating in an optically thick accretion disc surrounding the central black hole. For a review, see Koratkar & Blaes (1999). AGN have been known to exhibit optical variability since shortly after their discovery (e.g. Smith & Hoffleit 1963) but the origin of the variability is still unclear. The two main possibilities are that either the optical variations arise from intrinsic variations of the disc emission, perhaps due to accretion rate variations, or that the variations arise from reprocessing of the variable X-ray emission, boosting the intrinsic thermal emission from the disc.

If the optical variations arise from reprocessing of X-rays, we expect them to lag behind the X-ray variations. As the X-rays originate

from close to the central black hole and the longer wavelength emission comes from further out in the disc, light travel time arguments for a standard optically thick disc predict that the lag will increase with wavelength as $\tau \propto \lambda^{4/3}$ (Collier et al. 1999). For a typical AGN, we expect short delays, of order a day or less, between adjacent photometric bands. Such wavelength-dependent delays have been seen in many AGN (Wanders et al. 1997; Collier et al. 1998; Kriss et al. 2000; Collier et al. 2001; Oknyanskij et al. 2003; Sergeev et al. 2005; Doroshenko et al. 2006). For a detailed discussion of the disc reprocessing model, see Cackett, Horne & Winkler (2007). Gaskell (2007) suggested that the wavelength-dependent delays in the UV-optical may also be due to a contribution from reprocessing material much further out in the torus.

On the other hand, if the optical variations arise from variations in the intrinsic disc emission as accretion rate perturbations propagate inwards, we expect the optical variations to precede the X-ray variations. By the same argument, the longer wavelength optical emission will also lead those at shorter wavelengths. The variations will propagate through the disc on a viscous, rather than light-travel time-scale, so we expect much longer delays (\sim months–years) between wavebands than in the reprocessing scenario.

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Coordinated X-ray and optical monitoring observations provide a method for determining the sign of the delay between the optical and X-ray variations and hence for determining the dominant process underlying optical variability. However, previous studies have yielded varied and confusing results, with some sources showing well-correlated emission and others no correlation at all. For example, Mason et al. (2002) report a 0.14 d lag of the UV emission relative to the X-rays in NGC 4051, but on longer time-scales Shemmer et al. (2003) find a 2.4 d optical lead. Peterson et al. (2000) find a correlation between the X-rays and optical on time-scales of a few weeks in the same source, but little agreement on time-scales of days. For NGC 3516, Maoz, Edelson & Nandra (2000) reported a possible 100 d X-ray to optical lag after their 1.5 yr monitoring of this source. However, with the addition of 3.5 yr more data (Maoz et al. 2002), they were unable to confirm this lag or measure any other statistically significant correlation at any lag in the light curves. For 3C 390.3, the relationship between passbands is also complicated: X-ray flares sometime lead and sometimes follow optical/UV events (Gaskell 2008). Uttley et al. (2003) found the X-ray and optical continuum in NGC 5548 to be well correlated on month time-scales, and also that the amplitude of the optical variations was larger than that of the X-rays on these long time-scales. On short time-scales, Suganuma et al. (2006) report a clear 1.6 d optical lag to the X-ray variations and an optical amplitude much smaller than the X-ray amplitude, suggesting that, unlike on the longer time-scales, reprocessing is the main driver of the optical variability on time-scales of days. Intensive monitoring by Gaskell (2006), however, fails to show this short time-scale correlation.

Besides simply measuring the optical-X-ray lag, coordinated X-ray and optical monitoring observations enable us to put other useful constraints on the X-ray and optical emission processes and on the geometry of the emitting regions. For example, the greater fractional variability of the X-rays on short (\sim day) time-scales indicates that, in a Compton scattering scenario for the X-ray production, at least part of the X-ray variability is not produced by variable up-scattered seed photons, but by variations in the scattering corona itself. The relative amplitude of optical and X-ray variability is also important because if the optical variations, which represent variations in the bolometrically dominant blue bump, exceed those in the X-rays, it is hard to explain the optical variations as purely due to reprocessing, e.g. as in NGC 5548 (Uttley et al. 2003) and MR2251-178 (Arévalo et al. 2008). In these AGN, the large amplitude optical variations occur on time-scales of years and may represent accretion rate fluctuations propagating through the emission region.

It has been suggested (e.g. Uttley et al. 2003) that the strength of the correlation may be dependent on the mass of the central black hole. Scaled in terms of the gravitational radius, AGN of higher black hole mass or lower accretion rate, with cooler discs, will have the thermal optical emitting region closer to the black hole than the less massive/high accretion rate objects. We may expect stronger correlations in the high-mass systems, as the accretion rate variations will be better connected between the X-ray and optical emitting regions. Conversely, in the low mass/high accretion rate systems, the very different local viscous time-scales will allow the emission regions to vary independently, causing poorer correlations on long time-scales.

In order to try and understand the optical variability of AGN, and the relative importance of the two proposed variability mechanisms, we have set up a long-term monitoring programme of a sample of AGN of differing mass and fractional accretion rate $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$. Previously (Uttley et al. 2003), we have reported on observations of NGC 5548 [$M \sim 7 \times 10^7 M_{\odot}$; $\dot{m} \sim 0.08$ (Woo & Urry 2002;

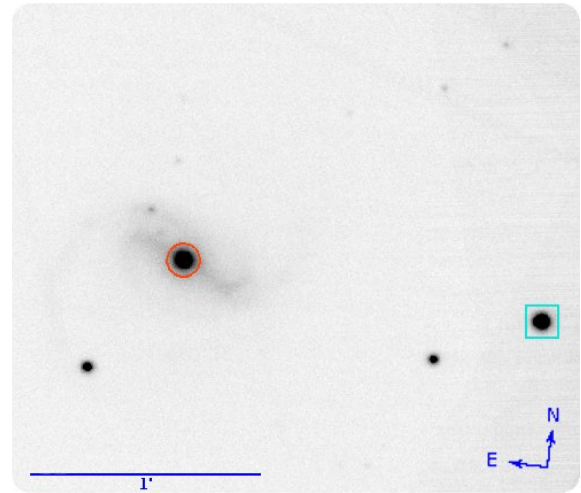


Figure 1. A combined V-band image of the Seyfert galaxy Markarian 79 (marked with a red circle) as obtained with the LT. The bar at the bottom of the image represents a scale of 1 arcmin. The comparison star used for the optical photometry is marked with a blue square, and the summed flux from the other two bright stars in the image was used to confirm that the comparison star did not vary.

Peterson et al. 2004)] and MR2251-178 [$M \sim 10^9 M_{\odot}$; $\dot{m} \sim 0.04$] (Arévalo et al. 2008) and here we report on the observations of Mrk 79.

Mrk 79 (UGC 3973, MCG+08-14-033) is a nearby ($z = 0.022$) Seyfert 1.2 galaxy with a black hole mass of $(5.24 \pm 1.44) \times 10^7 M_{\odot}$ (Peterson et al. 2004) and an average \dot{M} of ~ 6 per cent of its Eddington accretion rate (Kaspi et al. 2000). A V-band image of the galaxy is shown in Fig. 1. It is a well-known X-ray source and its optical variability is well established (Peterson et al. 1998a; Webb & Malkan 2000). We present the combined optical light curves from four independent monitoring programs, together spanning more than 5 yr, as well as the X-ray monitoring light curve as obtained by the *RXTE* satellite for the same time. Data collection, construction of the light curves and basic variability properties are discussed in Section 2. We present the cross-correlation analysis in Section 3, and in Section 4, we show that the medium term fluctuations are well reproduced by a reprocessing model and that the long time-scale trends can be accounted for by allowing the disc and/or corona geometry to vary over these time-scales. We conclude in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

2.1 X-ray observations

We used the Proportional Counter Array (PCA) on board *RXTE* to obtain a long-term X-ray light curve of Mrk 79. From 2003 March 23 to 2008 January 30, we took snapshots of ~ 1 ks exposure time each, at 2 d intervals. During a period of intensive monitoring, 2005 November 17 to 2006 January 19, four observations per day were made. Only data from Proportional Counter Unit (PCU) 2 were used, as PCUs 1, 3 and 4 were regularly switched off during our observations and PCU 0 has known problems with high background since the loss of its propane layer. The data were reduced and analysed with *FTOOLS* v.6.4, using standard extraction methods and acceptance criteria. The background was calculated from the most recent background models which corrects for the recent problems

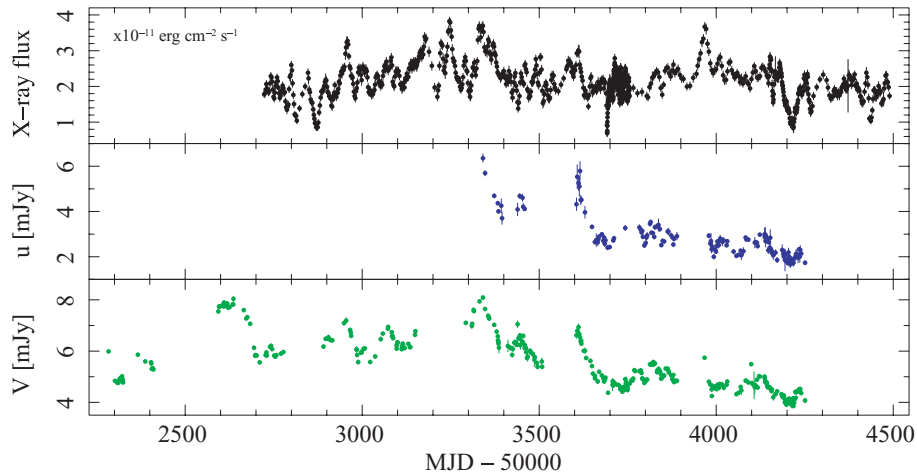


Figure 2. 2–10 keV X-ray (top panel), u (middle panel) and V -band (bottom panel) light curves of Mrk 79. The X-ray light curve is smoothed with a 4 point (~ 8 d) boxcar, to highlight the variations on time-scales similar to that of the optical light curves. The X-ray light curve is in units of 10^{-11} ergs $\text{cm}^{-2} \text{s}^{-1}$, the optical light curves are in mJy. The u -band flux is scaled to a comparison star in the field but no colour correction has been applied. V flux calculated as described in the text. No host galaxy contribution has been subtracted.

with the *RXTE* SAA (South Atlantic Anomaly) history file. The final 2–10 keV fluxes were calculated by fitting a power law to the observed spectra. This allows one to take account of changes in the instrumental gain over the duration of the monitoring.

The X-ray light curve shown in Fig. 2 is smoothed with a 4 point (approximately 8 d) running average to show the variations on time-scales of days more clearly. However, the unsmoothed light curve was used in all calculations.

2.2 Optical observations

Since 2002, Mrk 79 has been monitored independently by several ground-based observatories. We combine the data from six different telescopes here to construct an optical light curve spanning more than 5 yr. A summary of these observations may be found in Table 1 and each is discussed briefly below.

2.2.1 Liverpool Telescope

Mrk 79 is part of our ongoing optical monitoring programme on the Liverpool Telescope (LT), a 2 m fully robotic telescope at the Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias, La Palma, Spain (Steele et al. 2004). The telescope is equipped with an optical CCD camera, RATCam, with a 2048×2048 pixel back-illuminated detector and a scale of 0.135 arcsec pixel^{-1} . Observations in the Sloan Digital Sky Survey (SDSS)- u and Bessell- V filter bands started on 2004 December 2 with a 4 d sampling period. This was increased in 2007 March to daily monitoring in V and every 2 d in u . The latest measurement in the light curve included here was taken on 2007 May 30.

The data are overscan-trimmed and flat-fielded by the LT reduction pipeline. Bias correction is based on the underscan region only, as the bias frames do not show any significant repeatable structure. Images are binned 2×2 , resulting in a 1024×1024 pixel image of the 4.6 arcmin field of view. Standard rejection criteria are applied: data from nights with poor seeing (> 3 arcsec) or a very bright moon were discarded. The median seeing over the period of monitoring was 1.3 arcsec. A few hot pixels and one bad column on the CCD were removed by linearly interpolating between adjacent pixels.

We used the IRAF¹ package DAOPHOT to perform aperture photometry on the images. We summed the flux inside a 12 arcsec diameter aperture, centred on the nucleus, and compared it to a comparison star and 2 check stars in the field. Comparison star fluxes were taken from Doroshenko et al. (2005) and Mihov & Slavcheva-Mihova (2008). The aperture size was selected to include the point spread function under seeing conditions of 3 arcsec or less. In order to exclude host galaxy flux from the background measurement, the sky background level was not measured in an annulus. Instead, we measured and averaged the background from three 12 arcsec diameter apertures, displaced in various directions around Mrk 79 and away other stars in the field. Aligning all of our images to a reference image before these measurements were taken, ensured that the same sky areas were measured in each image. Photometric errors are based on photon statistics and the readout noise of the detector. Mrk 79 showed a steady decline in brightness over the period of monitoring. The V -band light curve from the LT is shown in Fig. 3, relative to the comparison stars.

2.2.2 Faulkes Telescope

We also carried out a short multicolour monitoring program in u , B , V , R and i on the Faulkes Telescope North (Haleakala, Maui, Hawaii) from 2007 February 5 to May 17. The telescope and camera are identical in specification and design to the LT and data were reduced and analysed in the same way. The sampling is roughly every 2 d, with some gaps due to poor weather conditions. 33 useful epochs in u , 35 in B , 39 in V , 36 in R and 27 in i were obtained. The light curves are shown in Fig. 4.

2.2.3 Crimean Observatory Telescope

We supplement these light curves with V -band data from the AGN monitoring program on the 0.7-m telescope of the Crimean Astrophysical Observatory, described in Sergeev et al. (2005). The

¹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Summary of *V*-band observations.

Observation dates (MJD)	Instrument and Telescope	Aperture diameter	No. of <i>V</i> -band observations
52283.5–53987.6	AP7p camera, 0.7-m Crimean Observatory Telescope	15 arcsec	142
52890.6–53876.3	Multicolor Imaging Photometer, MAGNUM Telescope	8.3 arcsec	47
53100.6–54198.8	0.4-m telescope, Lincoln, Nebraska	16 arcsec	79
53341.0–54250.9	RATCam, LT	12 arcsec	132
54063.4–54129.3	0.6-m telescope, Mt. Maidanak Observatory	16 arcsec	22
54136.3–54237.3	HawkCam, Faulkes Telescope North	12 arcsec	39

B, V, R, R1, I filter set on the AP7p camera mounted on this telescope are non-standard filters, though the *V* filter, from which we include data here, matches the standard Bessell-*V* filter closely. The light curve is constructed from aperture photometry through a 15 arcsec diameter aperture centred on the galaxy nucleus, relative to a comparison star in the field. It covers the period 2002 January 9 to 2006 September 9 and has a sampling rate of roughly every 2 d. Data after MJD 53058 (2004 January 18) from this program were previously unpublished.

2.2.4 MAGNUM Telescope

We also include unpublished data from the MAGNUM (Multicolor Active Galactic Nuclei Monitoring) project (Yoshii, Kobayashi & Minezaki 2003). The 2 m telescope is situated at the University of Hawaii's Haleakala Observatory, on the island of Maui, Hawaii, and monitors a large sample of AGN in optical and infrared wavebands. The *V*-band light curve included here are the observations made during the period 2003 September 8 to 2006 May 2. The nuclear flux was measured within a 8.3 arcsec diameter aperture, relative to a comparison star in the field. Comparison stars were calibrated against photometric standard stars and colour corrections applied to the fluxes. Full details of the data acquisition and reduction are described in Suganuma et al. (2006).

2.2.5 0.6-m telescope, Mt. Maidanak

Mrk 79 was also observed with the 0.6-m telescope at the Mt. Maidanak Observatory, Uzbekistan from 2006 November 24 to

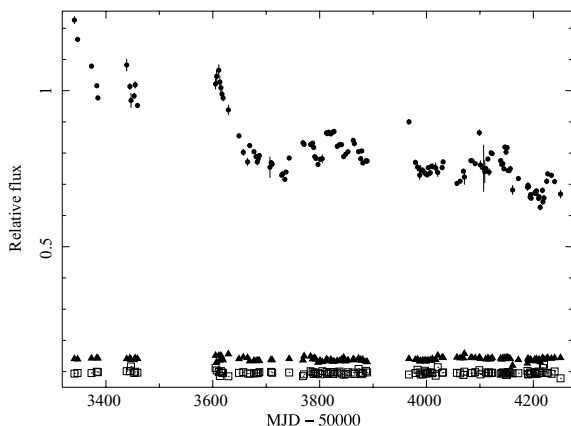


Figure 3. *V*-band light curve of Mrk 79 as obtained with the LT. The ratio of the comparison star to two check stars in the field is also shown, showing that the decrease in brightness of Mrk 79 is real and not due to a variable comparison star.

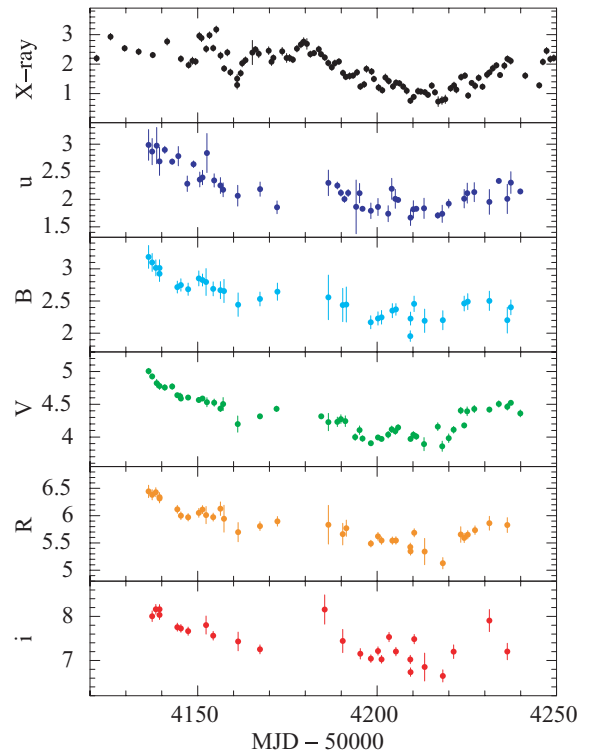


Figure 4. *uBVRI* light curves of Mrk 79 as obtained with the Faulkes Telescope, shown with the corresponding section of the X-ray light curve. The X-ray light curve is in units of 10^{-11} ergs cm^{-2} s^{-1} , the optical light curves are in mJy.

2007 January 29. Aperture photometry was performed on these data using a 16 arcsec diameter aperture and a background annulus between 24 and 40 arcsec. The measurements were calibrated using the Doroshenko et al. (2005) comparison star magnitudes.

2.2.6 0.4-m telescope, Lincoln, Nebraska

Finally, we include *V*-band CCD observations obtained with the 0.4-m telescope of the University of Nebraska. Details of these observations and reduction procedures are as given in Klimek, Gaskell & Hedrick (2004). The photometric aperture, sky annulus and comparison stars were as for the Mt. Maidanak observations.

2.3 Relative calibration

In order to account for the differences in the calibration and photometry aperture with which the individual light curves were constructed, we select the MAGNUM flux calibrated light curve as the

reference data set and scale all the other light curves to match it. We extracted pairs of measurements, taken within 1 d of each other, from overlapping light curves, and performed a least-squares fit of the equation

$$F_1 = aF_2 + b \quad (1)$$

to the flux pairs. F_1 and F_2 are the flux measurements from the two data sets and a and b the parameters of the fit. The best-fitting parameters from each pair of overlapping light curves were then used to scale that data set to the 8.3 arcsec diameter aperture MAGNUM light curve.

The total combined V -band light curve spans 1967 d (approximately 5 yr and 5 months) and contains 461 epochs. It is shown in Fig. 2 along with the X-ray and u -band light curves. Throughout the rest of this paper, we will use this combined light curve when we refer to the V -band light curve.

2.4 Variability properties

The flux measured within the aperture contains the nuclear flux as well as starlight from the part of the host galaxy falling inside the aperture. This host galaxy flux is a constant contribution to the total measured flux, so although it does not affect the results of the cross-correlation analysis (Section 3), it dilutes the variability of the nucleus. We estimate the host galaxy contribution as follows. We obtained an archival *Hubble Space Telescope* (*HST*) image of Mrk 79 from the online MAST archive, taken on 2006 November 8 (MJD 54048) with the Advanced Camera for Surveys through the F550M filter. This is a medium width continuum V -band filter, centred on 5580 Å with a full width at half-maximum of approximately 540 Å. We compared the flux measured through an 8.3 arcsec aperture (to match the total V -band light curve) with the flux measured through a 0.25 arcsec aperture centred on the nucleus. We measure a 43.5 per cent nuclear contribution to the total optical emission in the 8.3 arcsec aperture. We linearly interpolate our V -band light curve to estimate the flux at the time of the *HST* observation and take 56.5 per cent of this value to be the host galaxy contribution. This equated to a 2.54 mJy correction, which was subtracted from the whole V -band light curve for the purposes of the variability calculations below. No colour correction factor has been applied to transform this flux to the flux through the broader Bessell- V filter. However, assuming the spectrum to be flat over the width of the filter, the correction to the flux ratio as calculated here, will be very small.

In order to compare the amount of intrinsic variability in each light curve, we calculate the error-corrected flux variance, as a fraction of the mean flux. This quantity is known as the fractional

variability,

$$F_{\text{var}} = \frac{\sqrt{\sigma^2 - \varepsilon^2}}{\langle f \rangle}, \quad (2)$$

where the flux variance has the standard definition,

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (f_i - \langle f \rangle)^2, \quad (3)$$

and ε^2 is the sum of the squared measurement errors

$$\varepsilon^2 = \frac{1}{N} \sum_{i=1}^N \varepsilon_i^2. \quad (4)$$

The sampling statistics and variability properties of each light curve are summarized in Table 2.

The X-ray and total optical light curves are both highly variable. The unsmoothed X-ray light curve contains much more variability power at high frequencies than the optical light curve, but due to the large amplitude of the long-term optical variations, there is more variability power in the optical light curve when corrected for host galaxy flux. In the much shorter Faulkes Telescope colour light curves, the fractional variability is seen to decrease with wavelength. If the variability is intrinsic to the accretion disc, this behaviour is expected, as the longer wavelength emission originates from further out in the disc, where the natural time-scales are longer. This is also expected from reprocessing models: the disc response function broadens for longer wavelengths, smoothing out the variability at longer wavelengths (see, e.g. Cackett et al. 2007). We note, however, that no correction for host galaxy flux has been made to these light curves, so the variability amplitude we measure is reduced by this constant offset. Thus, the fractional variability quoted in Table 2 should be viewed as a lower limit.

3 CROSS-CORRELATION ANALYSIS

3.1 X-ray–optical correlation

In order to confirm and quantify the apparent correlation between the X-ray and optical emission, we use the discrete correlation function (DCF) method of Edelson & Krolik (1988).

We cross-correlate the unsmoothed, unbinned X-ray light curve with the observed u - and V -band light curves and bin the resulting DCF in uniform lag bins. Throughout this paper, we will use a positive value on the lag axis to indicate a lag of the longer wavelength emission behind the shorter wavelength (i.e. a lag of the optical variations behind the X-rays, in this case).

To account for the ~ 100 -d long solar conjunction gaps in the optical light curves, we divide them into segments defined by the

Table 2. Sampling and variability characteristics.

Light curve	Total length (d)	N	Δt_{median} (d)	F_{var}	$f_{\text{max}}/f_{\text{min}}$
X-ray	1775	975	1.89	0.2733	10.50
u (total)	910	143	2.47	0.3107	3.81
V (total)	1967	382	2.00	0.3447 ^a	4.20 ^a
<i>Multicolour monitoring:</i>					
u	103	47	1.75	0.1432	1.79
B	101	35	2.00	0.0968	1.63
V	103	51	1.73	0.0653	1.30
R	100	36	2.00	0.0504	1.26
i	99	27	2.93	0.0544	1.23

^aHost galaxy flux subtracted.

observation gaps, and calculate the DCF for each segment separately. As the strength of the correlation may be different on different time-scales, we resample the X-ray light curve to a uniform observational frequency by selecting only one point every 2 d from the intensively sampled period starting just before MJD 53700. This ensures that this segment does not dominate the combined correlation function. The final correlation function is then the combination of the individual DCFs, weighted by the number of points in each lag bin. The DCFs calculated this way, using a bin size of 4 d, are shown in Fig. 5.

The effect of calculating the DCF in segments like this is to implicitly remove the low frequency power (i.e. long-term trends) in the light curve, leading to an improved estimate of the short-term lag. The most common way of removing this low frequency power is to subtract a low-order polynomial function from the light curve prior to calculating the cross correlation function (CCF; Welsh 1999). We prefer the method of segmentation of the light curve, however, as it also eliminates the large observation gaps from the DCF calculation. We note, however, that removing a linear trend or a higher order polynomial from the light curve also result in a correlation peak of greater than 99 per cent significance, as discussed below.

The correlation function peaks at $\text{DCF}_{\text{max}} = 0.496$ for the X-ray/V-band correlation and at $\text{DCF}_{\text{max}} = 0.654$ between the X-rays and u band, with no lag between the optical bands and the X-rays. The DCF peak occurs at 0_{-4}^{+4} d for V and 0_{-4}^{+4} d for the

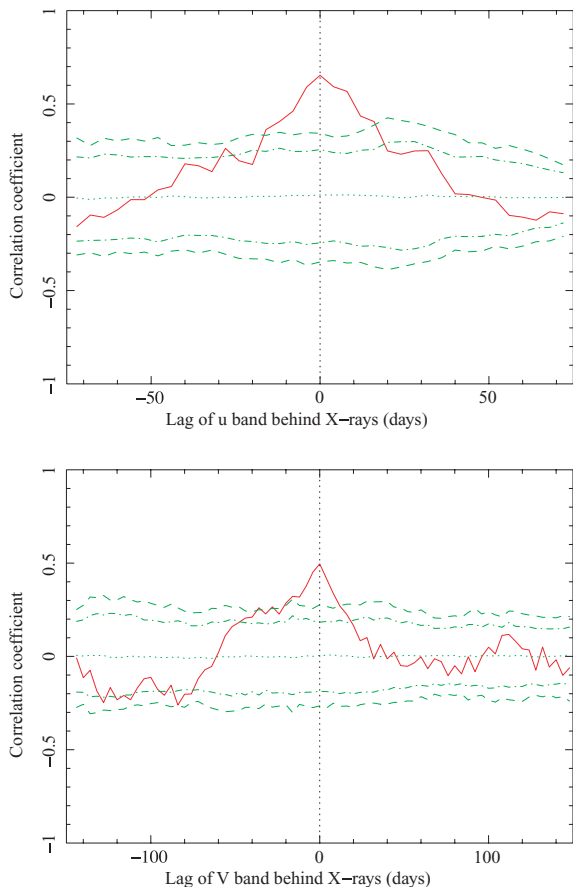


Figure 5. DCFs between the X-ray and u band (top) and X-ray and V band (bottom), binned in 4 d lag bins. The horizontal dotted, dash-dot and dashed lines are the median, 95 and 99 per cent confidence levels, based on 1000 simulations. The vertical dotted line indicates the zero lag position.

u band. (Note that, because the DCF was used, these errors will always be a multiple of the bin size.) The peak of the correlation function is thought to provide the most reliable estimate of the lag (Welsh 1999), however, when using the DCF, time resolution on time-scales shorter than the bin size is lost, so the peak position is affected by the chosen DCF binning factor. We therefore deem the measurement of the centroid lag more reliable and stable in this case. We calculate the centroid as the weighted average of all DCF points greater than 80 per cent of DCF_{max} . For the X-ray/V-band correlation, the centroid lag occurs at $0.00_{-4.00}^{+1.91}$ d and for the X-ray/ u -band at $-1.95_{-3.89}^{+1.95}$ d. The errors quoted are the 1σ errors calculated using the Flux Randomization/Random Subset Selection (FR/RSS) method of Peterson et al. (1998b) and the centroids are the median centroids from 1000 such selections.

As a separate check, we used the z -transformed DCF (ZDCF) of Alexander (1997) and the interpolation cross-correlation function (ICCF; Gaskell & Sparke 1986; White & Peterson 1994) to calculate the same correlation. The correlation functions resemble those calculated using the DCF closely and the lag results are consistent between the three methods. The short lags obtained from both the peak and the centroid measurements suggest that the reprocessor must be located near the X-ray source in this object, and not as far out as the dust torus.

To test the significance of the DCF peaks found, we used the method of Timmer & Koenig (1995) to simulate X-ray light curves based on an underlying model power spectrum. We use the single-bend power law parameters, measured by Summons et al. (in preparation), as appropriate for the power spectrum of Mrk 79. To account for long-term trends in the data, the simulated light curves were generated 10 times longer than the real light curve, and then sampled in the same way as the observed X-ray light curve. Observational noise was added at the level measured in the observed light curve. These uncorrelated, simulated X-ray light curves were then each cross-correlated with the real, observed optical light curve, to estimate the probability of obtaining equal or higher correlation peaks by chance, due to the red noise nature of the light curves. We record the mean, 95 and 99 per cent extremes of 1000 simulations and plot them in dotted, dot-dashed and dashed lines, respectively, in Fig. 5. Both the u and the V-band peaks reach higher than 99 per cent of the simulations, showing that the correlations are statistically significant at greater than 99 per cent level.

3.2 Lags between optical bands

We also present, in Fig. 6, the ZDCF between the X , u , B , R and i bands, calculated relative to the V band, for the data from the Faulkes Telescope. The u - and V-band light curves were supplemented with data from the LT covering the same period. We chose the V band as reference light curve as it is the best sampled. The X-ray and V-band autocorrelation functions are also shown. Again a positive value on the lag axis represents a lag of the variations in the longer wavelength band behind those of the shorter wavelength. The ICCF (Gaskell & Sparke 1986; White & Peterson 1994) is used as a consistency check. It is plotted as a solid line in Fig. 6 and is in close agreement with the ZDCF results.

If the optical variations are due to reprocessing of X-rays by the accretion disc, standard accretion theory for a thin viscous disc allows us to calculate the lags expected between optical bands. In a standard accretion disc model (e.g. Frank et al. 2002), the disc can be approximated by annuli at different temperatures, each emitting a blackbody spectrum. The radial temperature profile of the disc

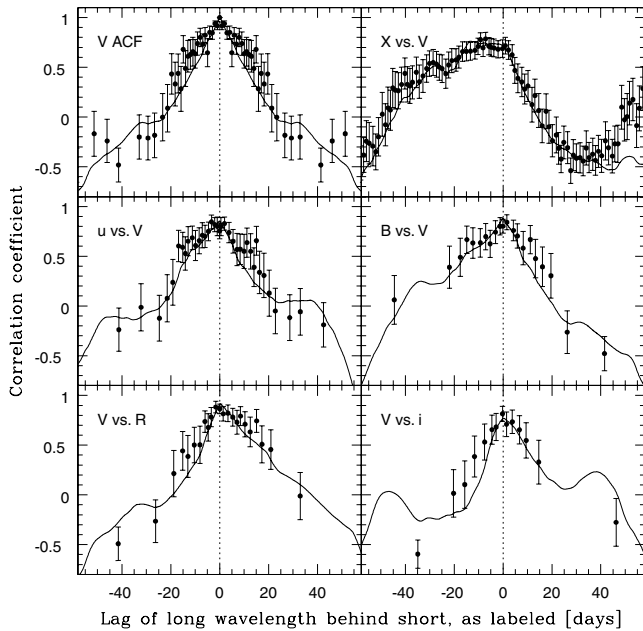


Figure 6. Cross-correlation functions relative to the V band, calculated from the three months of Faulkes monitoring. Points with error bars are calculated from the ZDCF and the solid line from the ICCF. A positive value on the lag axis indicates a lag of the long wavelength emission behind the short wavelength. The vertical dotted lines show the position of zero lag.

may then be described by

$$T(r) = 1.06 \times 10^6 \left(\frac{\dot{M}}{\dot{M}_E} \right)^{1/4} \left(\frac{M}{10^6 M_\odot} \right)^{-1/4} \left(\frac{r}{R_G} \right)^{-3/4} \text{ K}, \quad (5)$$

where $R_G = GM/c^2$ is the gravitational radius of the black hole. Using Planck's Law to calculate the peak emission, we can use (5) to calculate the radius most of this emission is coming from. In the reprocessing model, delays should exist between different wavebands, due to light travel time differences between the illuminating source (assumed to be the X-rays) and the region of the disc emitting at the given wavelength (Collier et al. 1998). Hence, variations observed at longer wavelengths should follow those at shorter wavelengths with a delay $\tau = r/c$, where r is the distance between the locations of peak emission for the relevant wavelengths. Using the reverberation mapping mass (Peterson et al. 2004) and accretion rate (Woo & Urry 2002) of Mrk 79, and assuming the X-ray source to be a point source at height $h_X = 6R_g$ above the accretion disc and on its axis of symmetry, we expect a V lag of 1.68 d behind the X-rays and lags between the optical bands of u versus $V = 0.74$, B versus $V = 0.43$, V versus $R = 0.64$ and V versus $i = 0.85$ d.

Both Figs 4 and 6 show that the variations in the optical bands are well correlated. The centroids of the correlation function, calculated at 80 per cent of the peak, were found to be u versus $V = -0.59^{+2.16}_{-1.92}$, B versus $V = -0.58^{+2.03}_{-2.29}$, V versus $R = 2.50^{+1.25}_{-1.61}$ and V versus $i = 1.23^{+1.68}_{-1.49}$ d. All except the R band are consistent with the expected lags for reprocessing to within the 1σ FR/RSS errors. The discrepancy in the R -band result is likely due to the strong, broad $H\alpha$ emission line contained within the R filter passband. The $H\alpha$ line emission originates in the broad line region, which is further from the X-ray source than the region of the disc emitting primarily at this wavelength. Hence, $H\alpha$ varies with a longer lag than the disc R -band emission and increases the average lag measured in this band.

From this short segment of the data, we measure the V -band emission to lead the X-rays by ~ 5 d (i.e. X versus $V = -5.25^{+2.55}_{-7.66}$ d),

which is not consistent with the reprocessing picture. We point out, however, that the error bars are overlapping with the X versus V correlation measurement found in Section 3.1. Since the sampling of these short light curves are not significantly better than the total V -band light curve (see Table 2), we deem the previous result of an optical lag of $0.00^{+1.91}_{-4.00}$ d behind the X-rays more robust and reliable, as it was derived from light curves almost 20 times as long. In short sections of the light curve, the long-term variations (which are present in the optical light curve but not the X-rays) can influence the lag measured, especially if there are not many peaks or troughs in that segment to constrain the lag tightly. In the longer light curves, these small shifts average out and a more reliable estimate of the true lag is obtained.

4 MODELLING REPROCESSING

A possible mechanism for the production of optical fluctuations is thermal reprocessing of variable X-rays shining on optically thick material, possibly the accretion disc. We constructed reprocessed optical light curves, using the observed X-ray light curve as input, to compare to the observed optical light curve. We assume that the X-rays are emitted by a compact source above the accretion disc and on its axis of symmetry while the optical flux arises thermally from an optically thick accretion disc. This geometry of the X-ray source may be viewed as a first order description of the centre of an X-ray corona above the inner part of the accretion disc. More realistic geometries, such as a spherical corona of radius h_X , will have a small effect on the flux calculated at the inner parts of the disc, but from further out in the disc, where most of the emission we are interested in is coming from, the corona will increasingly resemble a point source. This simplistic description is thus sufficient for our purposes here. We followed the prescription detailed by Kazanas & Nayakshin (2001) to account for light travel time effects on the reprocessed light curve, as well as geometrical considerations on the amount of flux received per unit area for different locations in the disc and X-ray source heights. We added the impinging X-ray flux to the locally dissipated flux expected for a thin disc to calculate the blackbody temperature as a function of time and radius, in order to produce flux light curves in different optical bands.

The model parameters are the height of the X-ray source h_X , thin disc accretion rate \dot{m} , inclination angle to the observer i and inner truncation radius of the thin disc R_{in} . The mass of the black hole determines the size of the gravitational radius and therefore the conversion of light crossing time to days. We left the mass fixed at the reverberation-mapped value of $5.24 \times 10^7 M_\odot$ (Peterson et al. 2004). We varied R_{in} and h_X between 6 and $50R_g$, where the gravitational radius $R_g = GM/c^2$, i between 0 and $\pi/2$ and \dot{m} between 0.001 and 0.9 times the Eddington-limit accretion rate. A distance of 94.4 Mpc was used to convert between luminosities and observed fluxes. No correction for reddening or dust extinction has been made. The calculated reprocessed light curves were resampled to match the observation epochs of the corresponding optical light curves. We subtracted the 2.54 mJy galaxy contribution (section 2.4) to the V -band flux before fitting the reprocessed light curve to the data and subsequently added the galaxy flux to the reprocessed light curve for plotting purposes.

For a standard thin disc (Shakura & Sunyaev 1973), around a black hole of mass $5.24 \times 10^7 M_\odot$ and with an average accretion rate of ~ 5 per cent of the Eddington limit, 50 per cent (100 per cent) of the V -band emission is expected to arise from within 70 (600) R_g . As the light crossing time for one R_g is $R_g/c \approx 250$ s, an edge-on disc would smooth the reprocessed V light curve on time-scales of

$\sim 2 \times 70R_g/c = 0.4$ d. We note that the inclination angle to the observer is only used to calculate the correct light travel times from different locations in the disc to the observer. As light crossing time of the optically emitting regions is shorter than the usual 2-d sampling rate of the X-rays, the smoothing of the fluctuations produced by differential light crossing time is small and the reprocessed light curve does not depend sensitively on i .

Fig. 7 shows the best-fitting reprocessed V light curve together with the observed V -band data. The corresponding parameters are $h_X = 21.5i = 24^\circ$, $\dot{m} = 0.06$ and $R_{in} = 37.6R_g$. The mean predicted optical flux is very similar to the observed flux, the ratio of mean fluxes for the light curves shown is 0.993. The normalized transfer functions for the V and u bands, calculated using these best-fitting parameters, are shown in Fig. 8. It assumes an X-ray flare of observed flux 4×10^{-11} ergs cm^{-2} s^{-1} , illuminating the disc for 0.01 d. The first peak in the transfer functions corresponds approximately to the time lag of light reprocessed at the inner edge of the thin disc on the side nearest to the observer, and the secondary peak to the light reflected at R_{in} on the far side. The two peaks merge together for smaller inner truncation radii. Varying disc parameters has a small effect on the shape of the transfer functions and we note that in all cases their median lag is less than 2 d, i.e. smaller than the X-ray sampling. Therefore, the main effect of changing model parameters on the shape of the resulting optical light curve is to change the relative amount of intrinsic to reprocessed optical flux.

As can be seen from Fig. 7, the reprocessed light curve reproduces the medium term fluctuations on the order of a 100 d moderately well, showing that it is energetically feasible to produce these optical fluctuations through reprocessing. The long-term trend in the optical, however, is not present in the X-ray band and is not reproduced by the reprocessed light curve. This trend in the optical suggests that either the geometry changes, affecting the amount of reprocessed X-rays or that the thin disc intrinsic luminosity changes, over time-scales of years. To test these possibilities, we fitted each segment separately, allowing only one parameter at the time (R_{in} , \dot{m} or h_X) to vary between the segments. This setup reproduces roughly the behaviour of a change in disc/corona geometry or accretion rate on time-scales of years, while all other parameters remain the same. These scenarios, where the long-term trends are produced by varying one model parameter, will produce different u -band long-term variations. We therefore include the u -band light curve in the fit in

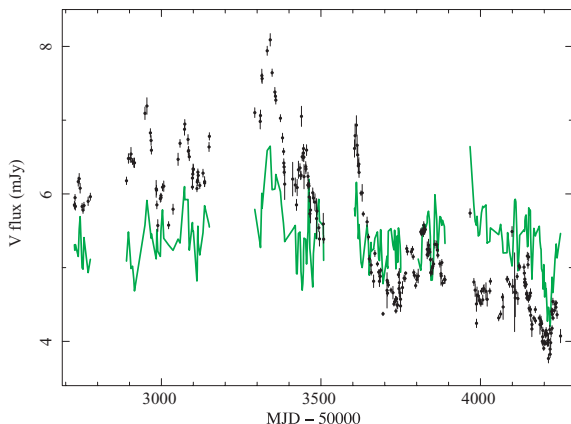


Figure 7. The fluctuations in the observed V -band flux (black markers with error bars) cannot be reproduced by reprocessing of observed X-rays in a simple scenario where the geometry and disc accretion rate remain constant. The solid line shows an X-ray to V band reprocessed light curve with disc parameters that best fit the observed V -band light curve.

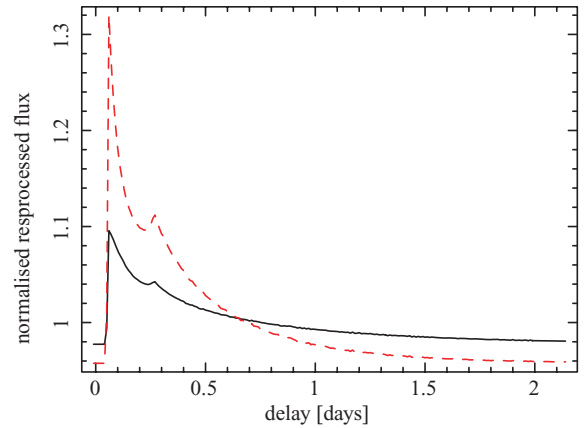


Figure 8. Disc reprocessing transfer functions for the V band (solid line) and u band (dashed line) calculated using the best-fitting parameters of Fig. 7. The first peak corresponds to the time lag of light reprocessed at the inner edge of the thin disc on the side nearest to the observer, and the second peak to the lag of the light reprocessed at the inner disc on the far side.

an attempt to reproduce simultaneously both optical bands with the same set of model parameters over the 3 yr segments where all three light curves overlap.

We start by allowing only the disc accretion rate to vary from one light curve segment to the next, while keeping the other two parameters constant between then segments. The best-fitting values of the accretion rate were 11 per cent of the Eddington limit for the first segment shown in Fig. 9, 4.8 per cent for the second segment and 0.1 per cent for the last segment, while keeping $R_{in} = 6R_g$

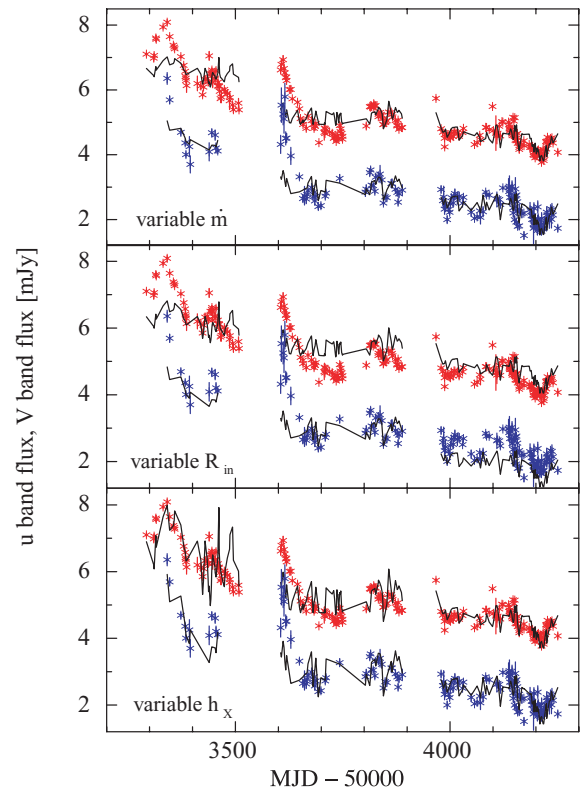


Figure 9. u (blue) and V (red) band light curves and predicted reprocessed X-ray flux (solid lines) obtained by changing only one parameter in the model between the different segments.

and $h_X = 6R_g$. The resulting reprocessed u and V light curves are shown in the top panel of Fig. 9. The large range in \dot{m} is a consequence of the small truncation radius used, and represents the case where almost all of the optical emission in the lowest flux orbit comes from reprocessing. Other solutions, where \dot{m} does not vanish, are possible, but require a larger R_{in} and results in greater contribution from the intrinsic disc emission. The middle panel on this figure shows the result of fitting the different segments with a variable R_{in} , keeping the accretion rate and source height fixed. In this case, the accretion rate was $\dot{m} = 7.7$ per cent and the source height $h_X = 7.8R_g$. The best-fitting truncation radii were $R_{in} = 6R_g$ (minimum value allowed) for the first segment, $R_{in} = 19.6R_g$ for the second and $R_{in} = 41R_g$ for the third. Finally, the bottom panel in Fig. 9 shows the result of a varying source height h_X . The best-fitting values are $R_{in} = 6R_g$, $\dot{m} = 0.01$ and $h_X = 21.3R_g$ for the first segment, $h_X = 11.8R_g$ for the second and $h_X = 6R_g$ for the third. Evidently, varying any of these model parameters can reproduce broadly the long-term trends in the V and u flux. The details of the reprocessed light curves, however, vary. In particular, varying the stable disc accretion rate adds different amounts of constant flux to the segments, while the amount of reprocessed flux remains approximately the same. Therefore, the short-term fluctuations, arising from reprocessing, are the same size at high and low average flux levels. The opposite is true when varying geometry parameters (source height or truncation radius). In these cases, the size of the short-term fluctuations scale with the mean flux. The average u and V flux levels are best reproduced by changing the accretion rate between the segments while the worst fit is obtained by varying R_{in} . Changing this parameter has a much stronger effect on the u band than the V band, so the change in u flux is too large while the corresponding change in V is not large enough. The best overall fit, to the shape and the average flux levels is obtained by varying h_X , though the quality of the fits does not allow us to strictly rule out any of the scenarios.

We also fitted the multicolour light curves obtained with the Faulkes Telescope with the reprocessing model, to confirm that this process can produce the short-term fluctuations in the different optical bands. We fixed the model parameters to the values obtained from fitting the third segment of the u and V light curves with either variable h_X or variable \dot{m} , as explained above, i.e. $R_{in} = 6R_g$, $\dot{m} = 1$ per cent and $h_X = 6R_g$. As high-resolution images exist only for the V band, we cannot estimate the galaxy contribution to the flux in the other optical bands, so we left the galaxy flux as a free parameter. The resulting galaxy fluxes are $u = 0.27$, $B = 0.67$, $V = 2.54$, $R = 4.08$ and $i = 5.83$ mJy. The reprocessed light curves for each band are shown by the solid lines in Fig. 10.

5 CONCLUSIONS

We have presented the long-term optical (u and V band) and X-ray light curves of Mrk 79, obtained by combining data from several monitoring programs of this source. The u -band light curve is the result of 2.5 yr of monitoring with the LT and the V -band light curve was constructed from the combined data from six ground based telescopes, including the LT. The X-ray observations, which were made every ~ 2 d, are from our continuing monitoring program with the *RXTE* satellite. We further included the results from a three month multiwavelength program on the Faulkes Telescope in u , B , V , R and i .

We summarize our findings as follows.

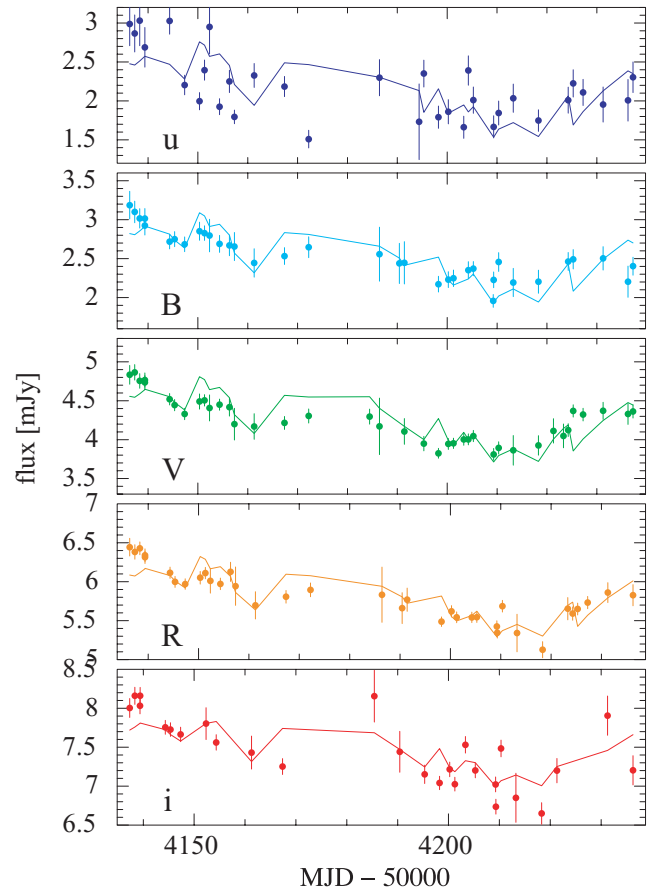


Figure 10. Reprocessed light curves for the multicolour intensive sampling data. The model parameters were fixed to the best-fitting parameters to the V band and the galaxy contribution in the other bands was allowed to vary as a free parameter.

(i) The light curves are variable on time-scales as short as days (X-rays) and as long as thousands of days (optical), with highly correlated variability on time-scales of tens of days or months.

(ii) Long time-scale (\sim years) variations are clearly seen in the optical light curve, but are not present in the X-ray light curve.

(iii) Although there is more variability in the X-rays than in the optical bands on short (\sim day) time-scales, the fractional variability of the V -band light curve on long time-scales is greater when corrected for host galaxy flux, due to the large amplitude of these long-term optical variations.

(iv) The lags measured between the X-rays and long-term optical bands, are consistent with 0 d for the data set as a whole. Formally, we find that the V band lags behind the X-rays by $0.00^{+1.91}_{-4.00}$ d and the u band lags by $-1.95^{+1.95}_{-3.89}$ d.

(v) While some strong events on a time-scale of a few days are consistent with the 0 d lag, there are also time periods where the optical and the X-rays match up poorly and events are only seen in one passband.

(vi) The variations between the short multicolour light curves are also well correlated. The measured centroid lags, τ , are consistent with the $\tau \propto \lambda^{4/3}$ prediction of X-ray reprocessing by an optically thick accretion disc. However, as the multicolour light curves are quite short, with few prominent peaks and troughs to constrain the lags, the error bars on the lag measurements are large and it is not possible to constrain the reprocessing model particularly tightly.

We also cannot exclude the possibility that the measured delays across the optical bands are affected by a contribution from light reprocessed in the dusty torus further out.

(vii) Optical variations on time-scales of \sim months are well reproduced by a reprocessing model, but longer term variations (\sim years) cannot be accounted for in this way.

In order to reproduce the long time-scale optical trends mentioned above, we are forced to include a second mechanism for the production of optical variations. This mechanism could be a variation in the geometry of either the purported accretion disc or the irradiating X-ray source. Changing the height of the X-ray source changes the fraction of the disc illuminated and hence the amount of optical emission produced by reprocessing. The intrinsic disc flux produced by viscous dissipation is governed by \dot{m} and changes in the inner truncation radius R_{in} affects the amount of optical emission produced. We have considered the effect of changing h_X , \dot{m} and R_{in} individually, in steps between the three sections of the optical light curves (Fig. 9). We find that when we vary h_X , we are able to reproduce the large and small fluctuations of the observed light curves slightly better than when we vary the disc parameters. It is not possible, however, at this level of modelling, to rule out the other two possibilities. A crude model like this cannot reproduce the observed light curves exactly. In reality, the parameters will probably all vary together, rather than one at a time as we have done here, and also gradually, rather than in a step-wise fashion. The description of the X-ray source as a point source above the centre of the disc, although providing a reasonable approximation to an extended hemispherical corona, may also not be correct. However, the requirement for an additional source of optical variation, in addition to X-ray reprocessing, is robust.

Despite the good correlation on short time-scales, there are some short time-scale variations which appear to occur only in one passband. This mismatch needs to be addressed by future studies and may be a consequence of anisotropic X-rays emission (see, e.g. Gaskell 2006).

Within the standard accretion disc model (Shakura & Sunyaev 1973), the high black hole mass and low accretion rate of Mrk 79 implies that it has a cool disc. In such a disc, the X-ray and optical emitting regions are closer together, in terms of gravitational radii, than in a system of low black hole mass and/or high accretion rate. Hence, both reprocessing and intrinsic variations are expected to contribute to the observed optical variability. Reprocessing benefits from the large solid angle subtended by the disc in the inner regions and intrinsic variations propagate on observable time-scales because of the shorter viscous time-scale at smaller disc radii. We have previously reported this behaviour in the quasar MR2251-178 (Arévalo et al. 2008). This system has a very massive central black hole ($M \sim 10^9 M_{\odot}$) and hence a cool disc, with the X-ray and optical emitting regions even closer together than in Mrk 79, in terms of gravitational radii. When accretion rate fluctuations propagate through the disc, the X-ray and optical emitting regions are modulated together, leading to a good correlation on long time-scales. Reprocessing of X-rays imprints small rapid fluctuations on to the optical light curve, resulting in a well-correlated behaviour on short time-scales as well. The strong X-ray–optical correlation we have reported here is in agreement with this picture.

For Mrk 79, we expect that 50 per cent of the V-band emission should originate within $70R_g$ of the black hole. Taking a typical value for the viscosity parameter, $\alpha \sim 0.1$, in an optically thick, standard accretion disc (Shakura & Sunyaev 1973), with thickness $(h/R)^2 \sim 0.01$, we find that the viscous time-scale at $70R_g$ is

$t_{\text{visc}} \sim 5$ y. In a geometrically thin disc, this time-scale is even longer. This (approximate) time-scale, on which we would expect accretion rate perturbations to propagate inwards to the X-ray emitting region, is longer than the time over which we have observed the steep decrease in optical flux and hence consistent with the fact that we have not yet seen a decrease in long-term average X-ray luminosity. However, the connection between the disc and the corona is not well understood and it is not clear how accretion rate variations, which may affect the optical disc emission, will be translated to the X-ray emission. If this interpretation is correct, the X-ray light curve should decline significantly over the next five or more years.

In subsequent papers, we will compare the optical and X-ray variations in a number of other AGN of differing black hole mass and accretion rate, and hence of differing disc structure, in order to determine how disc structure affects both the long and short-term optical variability of AGN.

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