MCG–6-30-15: long time-scale X-ray variability, black hole mass and active galactic nuclei high states

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ABSTRACT

We present a detailed study of the long time-scale X-ray variability of the Seyfert 1 Galaxy MCG–6-30-15, based on eight years of frequent monitoring observations with the Rossi X-ray Timing Explorer. When combined with the published short-time-scale XMM–Newton observations, we derive the power-spectral density (PSD) covering six decades of frequency from $\sim 10^{-8}$ to $\sim 10^{-2}$ Hz. As with NGC 4051, another narrow-line Seyfert 1 galaxy (NLS1), we find that the PSD of MCG–6-30-15 is a close analogue of the PSD of a galactic black hole X-ray binary system (GBH) in a ‘high’ rather than a ‘low’ state. As with NGC 4051 and the GBH Cygnus X-1 in its high state, a smoothly bending model is a better fit to the PSD of MCG–6-30-15, giving a derived break frequency of $7.6^{+10}_{-3} \times 10^{-5}$ Hz. Assuming linear scaling of the break frequency with black hole mass, we estimate the black hole mass in MCG–6-30-15 to be $2.9^{+1}_{-1.8} \times 10^6 M_\odot$.

Although, in the X-ray band, it is one of the best observed Seyfert galaxies, there has as yet been no accurate determination of the mass of the black hole in MCG–6-30-15. Here we present a mass determination using the velocity dispersion ($M_{BH}–\sigma^*$) technique and compare it with estimates based on the width of the Hα line. Depending on the calibration relationship assumed for the $M_{BH}–\sigma^*$ relationship, we derive a mass of between $3.6$ and $6 \times 10^6 M_\odot$, consistent with the mass derived from the PSD.

Using the newly derived mass and break time-scale, and revised reverberation masses for other active galactic nuclei (AGN) from Peterson et al., we update the black hole mass–break-time-scale diagram. The observations are still generally consistent with narrow-line Seyfert 1 galaxies having shorter break time-scales, for a given mass, than broad-line AGN, probably reflecting a higher accretion rate. However, the revised, generally higher, masses (but unchanged break time-scales) are also consistent with perhaps all of the X-ray bright AGN studied so far being high-state objects. This result may simply be a selection effect, based on their selection from high-flux X-ray all-sky catalogues, and their consequent typically high X-ray/radio ratios, which indicate high-state systems.

Key words: black hole physics – galaxies: active – galaxies: individual: MCG–6-30-15 – X-rays: binaries – X-rays: galaxies.

1 INTRODUCTION

It is now reasonably well established that the X-ray power-spectral densities (PSDs) of active galactic nuclei (AGN) are broadly similar to those of galactic black hole X-ray binary systems (GBHs; McHardy 1988; Edelson & Nandra 1999; Uttley, McHardy & Papadakis 2002; Markowitz et al. 2003; McHardy et al. 2004). The PSDs are described by power laws of the form $P(\nu) \propto \nu^\alpha$, where $P(\nu)$ is the power at frequency $\nu$, but $\alpha$ varies with frequency (see Section 3.2.1 for details). At high frequencies the PSDs of both AGN and GBHs are steep (slope, $\alpha \sim -2$) but below a break frequency, $\nu_B$, typically at a few Hz for GBHs, they flatten to a slope of $\alpha \sim -1$. To first order, the break time-scale scales linearly with the black hole mass but there is still considerable uncertainty in the mass–break-time-scale relationship and hence in our understanding of the physical similarities between AGN and GBHs.

The uncertainty arises largely because GBHs occur in several distinct states (e.g. see McClintock & Remillard 2003). Most commonly they are found in the so-called ‘low’ state where their X-ray fluxes are low and their medium-energy (2–10 keV) X-ray spectra
are hard. The second most common state is the ‘high’ state where their fluxes are high and their 2–10 keV spectra are soft. The PSDs of GBHs in these two states are quite different. In the low state, there is a second break, approximately a decade below the high-frequency break (Nowak et al. 1999). Below the lower-frequency break the PSD flattens further to a slope of zero. In the high state there is no second break and the PSD continues with slope $\sim -1$ to very low frequencies (Cui et al. 1997). In addition the break from slope $\sim -2$ to slope $\sim -1$ occurs at a higher frequency in the high state than in the low state ($\sim 15$ Hz cf. $\sim 3$ Hz in the best-studied GBH Cyg X-1). Before comparing AGN with GBHs it is therefore important to know whether the AGN is a high- or low-state system.

Based on their 2–10 keV X-ray spectra, it has generally been assumed that AGN are the equivalent of low-state GBHs. However, although the high-frequency ($\nu > 10^6$ Hz) parts of many AGN PSDs are now reasonably well determined, the lower frequencies are, in general, not well determined and so it is not usually possible to be sure whether AGN are the analogues of low- or high-state GBHs. In general, it is not possible to determine whether there is a second, lower-frequency break or not. The difficulty in determining the low-frequency shape of AGN PSDs has been in obtaining well-sampled light curves stretching over sufficiently long time-scales. For an assumed linear scaling of break time-scale with mass, we require well-sampled light curves of a few years duration to detect the second, lower break in a black hole of mass $\sim 10^6 M_\odot$.

Prior to the launch of RXTE in 1995 November it was not possible to obtain long time-scale light curves of sufficient quality but, since early 1996 we (McHardy, Papadakis & Utley 1998; Utley et al. 2002; McHardy et al. 2004) and others (Edelson & Nandra 1999; Markowitz et al. 2003), have been monitoring a small sample of AGN, typically observing each AGN once every 2 d, and so are able to determine the shape of the low-frequency PSD to high precision. Using these observations we (McHardy et al. 2004) recently showed that the PSD of the narrow-line Seyfert 1 (NLS1) galaxy NGC 4051 was, in fact, identical to that of a high-, rather than low-state GBH and so provided the first definite confirmation of a high-state AGN. Markowitz et al. (2003) plotted the black hole mass against the time-scales associated with well measured PSD breaks, some from slope $\sim -2$ to $\sim -1$ and some from slope $\sim -1$ to $\sim 0$. They claimed that there was a linear relationship between the two parameters. With a somewhat larger sample we (McHardy et al. 2004) plotted the black hole mass against the time-scale associated with the specific PSD break from slope $\sim -2$ to $\sim -1$ for a sample of AGN. We found that the best fit to all of the AGN together had a slope flatter than unity and did not extrapolate to either the high- or low-state break time-scales of Cyg X-1. However, we noted that the break time-scales associated with broad-line Seyfert 1 galaxies were, for a given black hole mass, generally longer than those for those objects usually classed as NLS1s. NLS1s are probably not a distinct class of object but, more likely, just lie at one end of a spectrum of AGN properties, characterized perhaps by a higher accretion rate. However, taking the crude broad-/narrow-line distinction which is commonly used in the literature, we note that a linear BH-mass–break-time-scale relationship fits broad-line AGN and Cyg X-1 in the low state, and a displaced linear relationship fits the NLS1s and Cyg X-1 in the high state. We therefore suggested that there is no fixed break time-scale–mass relationship which fits all AGN but that the break time-scale–mass relationship may actually vary in response to one or more other factors, which might be accretion rate or black hole spin.

In order to test and clarify the above hypothesis, it is necessary to place AGN on the break time-scale–mass plane with high precision and to determine whether they are high- or low-state analogues. There are very few AGN for which the X-ray observations are extensive enough to make the latter determination possible and a particularly important object is therefore the Seyfert galaxy MCG–6-30-15. Although MCG–6-30-15 is not always described as an NLS1, it has many of the properties commonly associated with NLS1s, i.e. rapid X-ray variability and relatively narrow permitted emission lines [FWHM 1700 km s$^{-1}$ (Pineda et al. 1980), cf. the 2000 km s$^{-1}$ limit which is usually quoted for NLS1s]. In this paper we therefore class MCG–6-30-15 as an NLS1, such as NGC 4051.

MCG–6-30-15 is one of the best-studied X-ray bright Seyfert galaxies. It was the galaxy in which the first detection of a relativistically broadened X-ray iron line was made, providing direct evidence for the existence of a massive black hole (Tanaka et al. 1995). We have monitored it extensively with the Rossi X-ray Timing Explorer (RXTE) and have presented its long time-scale PSD (Utley et al. 2002), based on 3 years of observations (1996–1999). From that early, limited, data set Utley et al. (2002) were able to show that a simple unbroken power law was not a good fit to the PSD (at greater than 99 per cent rejection confidence) but that a broken power law did provide a good fit (rejection confidence 33 per cent). However, it was not possible to determine, with any accuracy, the low-frequency PSD slope. If they assumed a power law of slope $-1$, Utley et al. were able to derive a break frequency in the PSD at a few $\times 10^{-5}$ Hz and to estimate the high-frequency power-law slope ($\sim -2$). Thus Utley et al. were unable to distinguish a high- from a low-state system, or measure the break time-scale with high precision, although they preferred the high-state interpretation, as a low-state interpretation implied a luminosity close to the Eddington limit. Vaughan, Fabian & Nandra (2003) have subsequently published a detailed study of the short-time-scale X-ray variability of MCG–6-30-15 using observations from XMM–Newton. These observations are insufficient, on their own, to determine the low-frequency PSD slope but, by also assuming a low-frequency PSD slope of $-1$, they have determined the break frequency to be $\sim 1 \times 10^{-4}$ Hz.

In this paper (Section 2) we present our full RXTE observations, of 8 yr duration, and consisting of over 800 separate observations, compared with 100 in Utley et al. (2002). In Section 3 we combine these RXTE observations with the published XMM–Newton observations and derive a PSD of excellent quality covering over six decades of frequency from $< 10^{10}$ to $> 10^{2}$ Hz. We determine accurately the shape of the PSD below the $\sim 10^{-4}$ Hz break and we thereby show that MCG–6–30–15 is, such as NGC 4051 (McHardy et al. 2004), the analogue of a high-state GBH. Using our improved determination of the low-frequency PSD shape, we slightly refine the break time-scale.

The most widely accepted method of determining black hole masses in Seyfert galaxies is that of reverberation mapping (e.g. Peterson 2001) but this technique has not yet been applied to MCG–6-30-15. The best current estimate of the BH mass in MCG–6–30–15 is $\sim 1 \times 10^6 M_\odot$ (Utley et al. 2002).

That mass is based on an estimated bulge mass of $3 \times 10^6 M_\odot$ (Reynolds 2000) and on the correlation between black hole mass and galactic bulge mass presented by Wandel (1999), where he claims that Seyfert galaxies have a lower black hole mass, for a given bulge mass, than was claimed in the original relationship of Magorrian et al. (1998). In a later paper Wandel (2002) revises the black hole mass/bulge ratio to 0.0015 and shows that Seyfert galaxies fit the same relationship as normal galaxies. Using the revised ratio, and the estimated bulge mass from Reynolds (2000), the revised black hole mass would be $4.5 \times 10^6 M_\odot$. 

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An upper limit to the black hole mass of $10^7 \ M_\odot$ has been derived by Morales & Fabian (2002), using a method based on balancing the radiative and gravitational forces acting on outflowing warm absorber clouds. However, it has recently become clear that the successful technique of determining black hole masses from the central velocity dispersion of the galaxy bulge can be applied to active, and quiescent, galaxies by observing the width of the Ca II triplet in the far red, where the AGN continuum is not dominant (Ferrarese et al. 2001). In Section 4 we report the determination of the black hole mass in MCG–6-30-15 from central velocity dispersion measurements. For comparison (Section 5) we also estimate the BH mass using the ‘photoionization’ method (Wandel, Peterson & Malkan 1999).

In Section 7 we discuss the implications of our results for the comparison of AGN and GBHs.

2 X-RAY OBSERVATIONS AND DATA REDUCTION

2.1 RXTE

The RXTE observations discussed here consist of our own monitoring observations, which have continued since 1996, and two ‘long looks’ in 1997 August and 1999 July that we have obtained from the RXTE archive. The monitoring observations cover time-scales from less than a day to approximately a few years and the long looks cover time-scales from approximately days to approximately minutes.

2.1.1 Monitoring observations

The RXTE monitoring observations, of typically $\sim$1 ks duration, were made and analysed in exactly the same way as for NGC 4051 (McHardy et al. 2004). Prior to 2000, we used a quasi-logarithmic sampling pattern, covering all time-scales, but in order to improve the signal-to-noise (S/N) ratio on our resulting PSDs, we then increased our coverage. From 2000 onwards, our typical observation frequency has been once every 2 d. In addition, to sample the higher frequencies properly, we observed once every 6 h for 2 months in 2000. Each observation, of $\sim$1 ks duration, contributes one flux point to the monitoring light curve. We do not attempt to split the monitoring data into higher time resolution bins.

The observations were made with the proportional counter array (PCA) which consists of five xenon-filled proportional counter units (PCUs). We extracted the xenon 1 (top) layer data from all PCUs that were switched on during the observation as layer 1 provides the highest S/N ratio for photons in the energy range 2–20 keV where the flux from AGN is strongest. We used rtools version 4.2 for the reduction of the PCA data. We used standard ‘good-time’ data selection criteria, i.e. target elevation $>10^\circ$, pointing offset $<0.01^\circ$, time since passage through the South Atlantic Anomaly of $>30$ min and a standard threshold for electron contamination. We calculated the model background in the PCA with the tool PCABACKEST version 2.1 using the L7 model for faint sources. PCA response matrices were calculated individually for each observation using PCARSP version 2.37, taking into account temporal variations of the detector gain and the changing number of detectors used. Fluxes in the 2–10 keV band were then determined using XSPEC, fitting a simple power law with variable slope but with absorption fixed at the Galactic level of $4.06 \times 10^{20}$ cm$^{-2}$ (Elvis, Wilkes & Lockman 1989). The errors in the flux are scaled directly from the observed errors in the measured count rate.

As with NGC 4051, we produce a light curve in flux units, rather than raw observed count s$^{-1}$, so that we may use together data from periods when the number, and gain, of the PCUs changes. The resulting light curve, from 1996 to 2004, is presented in Fig. 1.

From the monitoring observations we make three light curves. The 6-h sampled light curve consists of the 2 months of observations four times per day (Fig. 2). The 2-d sampled light curve consists of the period from 2000 onwards where sampling is once every 2 d. The total light curve consists of all of the observations since 1996, but when used in the PSD analysis it is always heavily binned to 28- or 56-d resolution.

2.1.2 Long looks

There have been two long looks with RXTE, one in 1997 August and the other in 1999 July. The total duration of each observation was

![Figure 1. Long-term RXTE 2–10 keV light curve of MCG–6-30-15. Each data point represents an observation of $\sim$1 ks.](https://academic.oup.com/mnras/article-abstract/359/4/1469/1008323/1469-1480)
Figure 2. The 2–10 keV RXTE light curve of MCG–6-30-15 covering the 2-month period of four observations per day. Each data point again represents an observation of ∼1 ks.

~ 9 d, consisting of continuous segments of ∼3 ks, separated by gaps of approximately equal length caused by Earth occultation. The 1997 August observations have been published by Lee et al. (2000) who have carried out a preliminary analysis of their variability properties. Lee et al. (2000) claim a break in the power spectrum at ~4–5 × 10^{-6} Hz. Nowak & Chiang (2000) have analysed the same data set, together with ASCA observations, and claim that the resultant PSD resembles that of a GBH in a low state. The claim that the PSD is flat below 10^{-5} Hz, has a slope of approximately −1 from 10^{-5} to ~10^{-4} Hz and, above ~10^{-4} Hz it steepens to a slope of −2. Neither Lee et al. or Nowak and Chiang carry out simulations to determine the validity of their PSDs. Uttley et al. (2002) do carry out simulations and conclude that although there is a break in the PSD of MCG–6-30-15, the model of Nowak and Chiang can be rejected at 99 per cent confidence and that there is significant power in the PSD below 10^{-5} Hz. A time-series analysis of the 1999 July observations has not yet been published.

The two long looks were analysed in exactly the same way as the monitoring observations, except that we retained 16-s time resolution. As the 1999 July light curve has not previously been published, we include it here (Fig. 3) and, for the convenience of the reader, we also include the 1997 August light curve, which has previously been published by Lee et al.

2.2 XMM–Newton

The XMM–Newton timing observations of MCG–6-30-15 have been discussed extensively by Vaughan et al. (2003) to which we refer readers for a detailed discussion. For the convenience of readers, we reproduce their light curve here (Fig. 4).

3 PSD DETERMINATION

The method used to determine the PSD is the same Monte Carlo simulation-based modelling technique (Uttley et al. 2002), PSRESP, which we employed in the analysis of the combined XMM–Newton and RXTE observations of NGC 4051 (McHardy et al. 2004). This method is able to take account of non-uniform sampling and gaps in the data.

3.1 Long time-scale PSD

A variety of data sets are available for determination of the overall PSD but the RXTE monitoring observations provide the only information on time-scales longer than approximately days. We therefore begin by fitting a simple power law to the PSD from the combined...
6-h, 2-d and total RXTE light curves. We retain the intrinsic 6-h and 2-d resolution for the first two light curves but bin the total light curve up to 28-d resolution.

The resulting PSD is well fitted (fit probability = 68 per cent) by a slope of 0.9 ± 0.15 (90 per cent confidence intervals are used throughout this paper). In Uttley et al. (2002) we describe how we determine the goodness of fit from the simulations. A fit probability of 68 per cent means that the model is rejected at 32 per cent confidence. The fit is shown in Fig. 5. For a GBH in the low-hard state, we do not expect the region of slope ∼ −1 to extend for more than one or 1.5 decades, before flattening to a slope near zero. Although this fit would not be very sensitive to breaks near to the end of the frequency spectral range covered, none the less the fit to a simple power law, of slope close to −1 over approximately three decades, from ∼10⁻⁸ to ∼10⁻² Hz, suggests that MCG–6–30–15 is the analogue of an XRB in a high-soft state rather than in a low-hard state.

3.2 Combined long- and short-time-scale PSD

3.2.1 RXTE monitoring observations and XMM–Newton 4–10 keV observations

In order to determine properly the overall long- and short-time-scale PSD, and hence measure any break frequency and high-frequency PSD slope, and refine measurements of the low-frequency PSD slope, we must combine the RXTE monitoring observations with observations that sample shorter time-scales.

Both the RXTE long looks and the XMM–Newton long observations provide information on shorter time-scales. The RXTE long looks provide a good determination of the PSD on time-scales shorter than the length of the individual segments (∼3000 s). However, on time-scales between ∼3000 s and few days, the PSD is distorted by the many gaps in the data sets. Our PSRESP analysis software is able to cope with those gaps, but they do give the software considerable work to do as the dirty PSD differs a good deal from any likely underlying true PSD. Thus the errors are larger than if there were fewer gaps. The XMM–Newton data are continuous and so the XMM–Newton PSD suffers negligibly from distortion.

However, the sensitivity of XMM–Newton is less than that of RXTE in the 2–10 keV range, which is the only energy band in which the long time-scale PSD is determined. None the less, the long XMM–Newton observations of MCG–6–30–15, which total approximately three times as long as those of NGC 4051, do allow a reasonable determination of the high-frequency PSD.

As discussed in McHardy et al. (2004), the mean photon energy of the 4–10 keV XMM–Newton band is approximately the same as that of the RXTE 2–10 keV band. In order to derive a PSD of uniform energy at all frequencies we have therefore included the 4–10 keV XMM–Newton PSD with the RXTE monitoring data sets described above in our PSD simulation process. The high, soft state PSD of Cyg X-1 is better described by a bending power-law model than a sharply broken power-law model, and the PSD of NGC 4051 is also slightly better fitted by the bending power-law model

\[ P(v) = A v^\alpha L \left[ 1 + \left( \frac{v}{v_b} \right)^{(-\alpha_L + \alpha_H)} \right]^{-1}, \]

where \( \alpha_L \) and \( \alpha_H \) are the low- and high-frequency power-law slopes, respectively, and \( v_b \) is the bend, or break, frequency. As stated in the introduction, here we use the convention that a slope decreasing towards high frequencies will be defined by \( P(v) \propto v^\alpha \), where \( \alpha \) is a negative number, e.g. \( \alpha = -2 \).

We fit this model to the combined RXTE and XMM–Newton observations and the result is shown in Figs 6 and 7. In Fig. 6 we plot the log of power versus the log of frequency, as in Fig. 5. In both of these figures the observed dirty PSDs from the various constituent light curves are given by the jagged lines. The model, distorted by the effects of sampling, red noise leak and aliasing, is given by the points with errorbars, and the underlying, undistorted, model is given by the smooth dashed line. In Fig. 7 we unfold the observed dirty PSD from the distorting effect of the sampling in order to produce the closest approximation that we can to the true underlying PSD. Thus

\footnote{This convention is used throughout the tables and text of McHardy et al. (2004). Note that when we defined the formula for a bending power law in McHardy et al. (2004, top of second column, p. 788), we forgot to make the formula consistent with the rest of the text and tables and so, only in that one formula, a slope decreasing towards high frequencies is defined by \( P(v) \propto v^\alpha \), where \( \alpha \) is a positive number, e.g. \( \alpha = +2 \).}
displacements of the observed PSD from the model distorted PSD are translated into displacements from the best-fitting underlying model PSD. The technique is identical to that used to deconvolve energy spectra from count rate (i.e. instrumental) spectra in standard X-ray spectral fitting. In this case the error is translated on to the observed data points and the underlying best-fitting model is shown as a continuous line. As in standard X-ray spectral fitting, the position of the data points does depend on the shape of the assumed, best-fitting, model. Note that in Fig. 7 we plot frequency×power so that a horizontal line would represent power(ν) ∝ ν−1 and equal power in each decade. Similar plots for NGC 4051, 3516 and Cyg X-1 are shown in fig. 18 of McHardy et al. (2004).

The combined PSD is well fitted (P = 45 per cent) by this model with low-frequency slope αL = −0.8 ± 0.16, high-frequency slope αH = −1.98 ± 0.32 and break frequency νB = 6.0 ± 10 −5 Hz. A sharply broken power law, although tolerable, is not such a good fit (P = 14 per cent) but the best-fitting parameters are similar to those of the smoothly bending model (αL = −0.8, αH = −1.74 and νB = 3.2 × 10−3 Hz). As is often the case, the break frequency is slightly lower for the sharply bending model than for the smoothly bending model but, in this case, the errors are not well determined. (Note that our software performs a simple grid search so the values given here are those of the minimum point on the grid and so may differ very slightly from the optimum values which may lie slightly off any particular grid point.) The confidence contours for these parameters are shown in Figs 8–10.

The break frequency for Cyg X-1, assuming a high state, bending power-law model, is 22.9 ± 1.5 Hz (McHardy et al. 2004, or 13.9 ± 0.8 Hz for a sharply breaking high-state model). Assuming linear scaling of black hole mass with frequency, and a black hole mass of 10 M⊙ for Cyg X-1 (Herrero et al. 1995), we derive a black hole mass for MCG–6-30-15 of 3.6 ± 18 × 106 M⊙.

We note that, although consistent within the errors with the break frequency derived by Vaughan et al. (2003) using purely XMM–Newton observations, our break frequency is slightly lower. The reason for the difference is that Vaughan et al. were unable to measure the PSD slope below the break and so assumed a value of −1. However, our data show that the slope is actually slightly flatter, which leads to a lower break frequency.

Figure 7. Unfolded combined 2–10 keV RXTE and 4–10 keV XMM–Newton PSD of MCG–6-30-15. Here the errors have been translated on to the data points and the continuous line represents the best-fitting underlying PSD. Note that here we plot frequency×power. See the text for details.

Figure 8. 68, 90 and 99 per cent confidence contours for high-frequency slope, αH, and break frequency, νB, for a bending power-law fit to the combined RXTE and XMM–Newton 4–10 keV PSD shown in Fig. 6. Note we plot −αH.

Figure 9. 68, 90 and 99 per cent confidence contours for low-frequency slope, αL, and break frequency, νB, for a bending power-law fit to the combined RXTE and XMM–Newton 4–10 keV PSD shown in Fig. 6. Note we plot −αL.

Figure 10. 68, 90 and 99 per cent confidence contours for low- and high-frequency slopes, αL and αH, respectively, for a bending power-law fit to the combined RXTE and XMM–Newton 4–10 keV PSD shown in Fig. 6. Note we again plot −αL and −αH.
3.2.2 RXTE monitoring observations and low-energy XMM–Newton observations

In M' Hardy et al. (2004) we refined our determination of the break frequency in NGC 4051 by combining RXTE monitoring observations with continuous XMM–Newton observations in the 0.1–2 keV band, where the break is better defined. We assumed that the break frequency was independent of energy. We have carried out the same procedure here (again taking proper account of the different PSD normalizations between the 0.1–2 and 2–10 keV bands) and find that $\alpha_L = -0.8_{-0.4}^{+0.2}$, $\alpha_H = -2.5_{-0.8}^{+0.3}$ and $v_B = 7.6_{-3}^{+10} \times 10^{-5}$ Hz. The fit probability is 67 per cent. Apart from the steeper high-energy slope, which is well known at low energies (Vaughan et al. 2003; M' Hardy et al. 2004), the other fitting parameters are very similar to those obtained when using the RXTE and XMM–Newton 4–10 keV observations. Thus within the errors, we find no evidence for a change of break frequency with photon energy. The implied black hole mass is more tightly constrained by the smaller errors on the break frequency and is $2.9_{-1.5}^{+1.5} \times 10^6 M_\odot$.

We fitted a sharply breaking power-law model to the combined RXTE and XMM–Newton 0.1–2 keV data. As with the combined RXTE and 4–10 keV XMM–Newton data, the fitting parameters are almost exactly the same as for the bending power-law model, but the fit probability is worse (19 per cent). The fact that a bending power law is a better fit than a sharply bending power law to the PSD of MCG–6-30-15, as it is the PSD of Cyg X-1 in its high state, strengthens our conclusion that MCG–6–30–15 is the analogue of a GBH in the high, rather than the low, state.

3.2.3 RXTE monitoring observations and RXTE long looks

We have also determined the overall PSD shape by including the RXTE long looks binned up to 128-s time resolution with the RXTE monitoring observations, and also including a very high-frequency PSD ($>10^{-3}$ Hz) made from the individual segments of the RXTE long looks. The fitting parameters are approximately the same as in the combined RXTE and XMM–Newton fit ($\alpha_L = -0.8_{-0.4}^{+0.2}$, $\alpha_H = -2.1_{-0.6}^{+0.4}$ and $v_B = 5.0_{-3}^{+10} \times 10^{-5}$ Hz). The fit is formally good ($P = 74$ per cent), but the errors are rather large because of the difficulty of coping with the many gaps in the RXTE long look light curves.

3.3 Search for a second, lower-frequency break

We searched for a second, lower-frequency break, using the RXTE and XMM–Newton 4–10 keV data. We assumed a low-state PSD model, fixing the slope below the lower break at 0, and the slope between the lower and upper breaks at $-0.8$, i.e. the value we measure in the same frequency range assuming a high-state model. We allowed the two break frequencies and the slope above the upper break to vary. The best-fitting frequency for the higher break and for the slope above the higher break was the same as in our high-state fit and the best fit for the lower break frequency ($6 \times 10^{-9}$ Hz) was almost at the end of the fitting range. The fit probability was 43 per cent. In Fig. 11 we show the 68, 90 and 99 per cent confidence ranges for the two break frequencies. As the typical ratio of the two break frequencies for a low-state GBH is between 10 and 30, we plot, as dashed straight lines, the limits corresponding to ratios of 10 and of 100. The best-fitting ratio is over 1000, but a ratio of 100 is just within the edge of the 90 per cent confidence region.

We repeated the above analysis after fixing the intermediate slope at $-1.0$ and obtained almost identical frequency ratios, although the high break frequency was then approximately half a decade higher in frequency.

On the basis of its PSD, the above analysis strongly suggest that MCG–6–30–15 is the analogue of a high-state GBH, although a low state cannot be entirely ruled out.

4 MASS DETERMINATION: ABSORPTION LINE VELOCITY DISPERSION

As discussed in the introduction, the mass of the black hole in MCG–6-30-15 is not well determined. In particular, there have been no reverberation mapping observations, and no measurement of the stellar velocity dispersion, the two techniques widely regarded as giving the most reliable measurement of black hole masses. However, a reliable measurement of the mass in MCG–6-30-15 is important for any discussion of mass/time-scale scalings in AGN and for any discussions of whether AGN are in low or high states. In this section we therefore present stellar velocity dispersion measurements from which we estimate the black hole mass. In subsequent sections (Sections 5 and 6) we present secondary determinations of the black hole mass, based on the width of the H$\beta$ emission line and on photoionization calculations. We find that all of these optically based mass determination methods give consistent answers.

4.1 Observations

The observations of MCG–6-30-15 described here were taken by the service programme of the 3.6-m Anglo-Australian Telescope on 2002 June 5. The RGO Spectrograph was used, with the 25-cm camera plus the 1200R grating (blazed at 7500 Å). The detector is an EEV2 CCD, windowed to $600 \times 4096$ pixel$^2$ for the science observations and $150 \times 4096$ pixel$^2$ for the standard stars. A slit width of 1 arcsec (0.15 mm) was chosen, resulting in a spectrum of resolution $R \sim 9500$ covering a wavelength range of 1000 Å. The slit was placed along the major axis of the galaxy, at a position angle of 116$^\circ$.

The measured widths of the Ca II triplet lines are used to estimate the black hole mass. At the redshift of MCG–6-30-15, $z = 0.00775$,
the Ca II lines are shifted to 8566, 8610 and 8731 Å, and therefore the central wavelength was chosen to be 8620 Å. The total wavelength coverage of 1000 Å, spanning the wavelength range 8120–9120 Å, allows accurate determination of the continuum on either side of the lines, and therefore correct measurement of the linewidths.

Observations of late-type giant stars, which have very narrow lines, and which dominate the stellar light of nearby galaxy bulges, were performed in order to measure the instrumental broadening and provide templates for the cross-correlation analysis. The K0III standard stars HD 117927 and 118131 were observed, with the same set-up and wavelength coverage as MCG–6–30–15, since the rest wavelength of the Ca II triplet ($\lambda\lambda 8498, 8542, 8662$) lies within the wavelength range covered.

Dedicated flat-field exposures were taken before and after the science and standard star observations, for accurate defringing, and argon and neon arc spectra were taken for the wavelength range covered.

4.2 Data reduction

The raw data were reduced with IRAF using standard bias subtraction, flat-fielding and cosmic ray removal techniques. At the red wavelengths observed here, the EEV2 CCD suffers from fringing at a level of ~5 per cent. A comparison of the extracted science spectra with equivalent spectra taken from the flat-field frames showed that the fringes were efficiently removed from the science frames, and did not contribute any spurious features. Curvature in the spatial direction was rectified using bright night sky lines in the object frames. The narrow window used for the standard star observations meant that in this case, rectification was unnecessary. The continua of MCG–6–30–15 and the standard stars were sufficiently bright that curvature of the spectra in the dispersion direction could be traced and rectified. The total exposure time for MCG–6–30–15 was 1 h, broken into two 30-min integrations. Wavelength calibration was performed using the arc exposures bracketing each science frame. This calibration was checked by measuring the resulting wavelength of night sky emission lines, and no further correction was required.

The nuclear spectrum of MCG–6–30–15 was extracted from the central 5.6 pixels of the trace, which corresponds to a $2.4 \times 1$ arcsec$^2$ aperture. To be compatible with the $M_{BH}$–$\sigma$ relation defined by Ferrarese & Merritt (2000), the length of this aperture was chosen to correspond to $r_e/8$, where $r_e$ is the effective radius of the galaxy, measured from the profile of the spectral data, compressed along the dispersion direction. We note, however, that the choice of extraction aperture has only a very small effect on the results obtained (Ho, private communication). Sky subtraction was performed using regions either side of the galaxy, 50 pixels (21.5 arcsec) wide, at a distance of 50 pixels (21.5 arcsec) from the centre of the galaxy. The resulting spectrum is shown in Fig. 12, normalized by a spline fit to the continuum to emphasize the emission and absorption features.

In a similar analysis, Filippenko & Ho (2003) detect Paschen emission lines in the spectrum of NGC 4395, adjacent to each of the calcium absorption features. For MCG–6–30–15, there is perhaps a suggestion of a broad Paschen 15 line at ~8615 Å, but it is not conclusive. Even if present, the strength of such a line is very small compared with those detected in NGC 4395, and as such, would not significantly affect our results.

4.3 Data analysis

The calcium absorption features in a galaxy spectrum are broadened compared with those of an individual star due to the bulk motion of the stars in the galaxy. The extent of this Doppler broadening is related to the mass of the central black hole, giving rise to the observed tight relationship between the two quantities. The region of the galaxy spectrum of MCG–6–30–15 containing the calcium triplet is therefore cross-correlated with the equivalent region of the K0III stellar templates using the IRAF task FXCOR. The task fits a spline function to the continuum of each input spectrum, and cross-correlates the resulting features, giving as output a velocity measurement, due to the redshift of MCG–6–30–15, and a velocity width, due to the Doppler effect of the motion of stars in the galaxy caused by the gravitational influence of the black hole.

The width of the cross-correlation peak function calculated by FXCOR measures the combined Doppler and instrumental broadening, therefore in order to ascertain the Doppler broadening alone, the stellar templates themselves were broadened using a Gaussian of various widths, and cross-correlated with the unbroadened templates. The width of the Gaussian which gave rise to a cross-correlation peak width equal to that of MCG–6–30–15 provides our measurement of the true velocity dispersion of the galaxy. We found that broadening the stellar templates by 11 pixels gave the best match to the cross-correlation peak width of MCG–6–30–15. The velocity dispersion of the spectra is 8.5 km s$^{-1}$ pixel$^{-1}$, giving a velocity dispersion for MCG–6–30–15 of $\sigma = 93.5$ km s$^{-1}$.

The statistical errors on this measurement are very small, and therefore do not provide a realistic estimate of the true errors involved. Ferrarese et al. (2001) estimate that the systematic uncertainties involved in making such measurements are of the order of 15 per cent. We therefore undertook a number of tests in order to ascertain the likely error in our result. First, since we have three standard star observations (two of HD 117927 and one of HD 118131), each spectrum was broadened in turn and cross-correlated with the two unbroadened stellar templates to estimate the variation due to the use of differing standards. The results usually varied by less than 1 per cent, and never by more than 2 per cent. Secondly, to assess the possible impact of the proximity of the O1 line to the first feature in the calcium triplet, we restrict the region of the spectra used in the cross-correlation analysis to containing only two of the three calcium absorption lines. By changing the wavelength range over which the cross-correlation analysis is performed, a maximum variation of ±4 per cent in the peak width was measured. Thirdly,
we vary the amount of smoothing of the stellar templates required to match the result from MCG–6-30-15, and find that all the results of the above tests are easily bracketed by taking a Gaussian width of 11 ± 1 pixel, which is equivalent to $\sigma = 93.5 \pm 8.5$ km s$^{-1}$ (±9.1 per cent). We therefore take this as our conservative estimate of the error in our measurement, and note that this is small compared with the uncertainty in the relationship between this quantity and the inferred black hole mass, as described in the following section.

4.4 Black hole mass estimate

The largest source of error in estimating the mass of the black hole from the width of the absorption lines is not uncertainty in the measurement of the width but uncertainty in the M$_{BH}$–$\sigma$ relation itself. The two main groups concerned with deriving the relationship use slightly different observational methods and fit slightly different relationships to the resultant data (see Merritt & Ferrarese 2001; Tremaine et al. 2002 for full discussions). Recently, Greene, Ho & Barth (2004) have shown that AGN with very low black hole masses (down to $\sim 10^5$ M$_\odot$) fit reasonably well on to the relationship given by Tremaine et al. (2002), i.e.

$$M_{BH} = 1.35^{+0.20}_{-0.18} \times 10^8 M_\odot \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^{4.02(\pm0.32)}.$$

Our observations then imply $M_{BH} = 6.3^{+3.0}_{-2.0} \times 10^6$ M$_\odot$. As can be seen from fig. 4 of Greene et al. (2004), the spread in the data points implies an uncertainty in the derived mass of at least 50 per cent.

An alternative version of this relationship has been given by Merritt & Ferrarese (2001). Using the most recent version of this alternative relationship (Ferrarese 2002), i.e.

$$M_{BH} = 1.66(\pm0.32) \times 10^8 M_\odot \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^{4.58(\pm0.52)},$$

we derive $M_{BH} = 5.1^{+1.8}_{-2.4} \times 10^6$ M$_\odot$, which is entirely consistent with the mass derived using the relationship of Tremaine et al. (2002).

5 MASS DETERMINATION: EMISSION-LINE WIDTH

An alternative estimate for $M_{BH}$ can be obtained using the empirical relationships found by Kaspi et al. (2000) in reverberation studies of nearby Seyfert 1 galaxies and quasars between $M_{BH}$, the velocity dispersion of the broad emission-line gas, $V_{\text{FWHM}}$, and the effective size, $R_{\text{BLR}}$, of the broad-line emitting region, i.e.

$$M_{BH} = 1.464 \times 10^9 \left( \frac{R_{\text{BLR}}}{\text{lt-d}} \right) \left( \frac{V_{\text{FWHM}}}{10^5 \text{ km s}^{-1}} \right)^2 M_\odot.$$

$R_{\text{BLR}}$ is determined from the measured delay between the continuum and emission-line variations and is related to the galaxy subtracted continuum luminosity at 5100 Å by

$$R_{\text{BLR}} = 32.9 \pm 1.9 \left( \frac{\lambda L_\lambda(5100 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.7} \text{lt-d}.$$

$^2$While one might expect $V_{\text{FWHM}}$ of the root mean square profile to better represent the velocity dispersion of the variable part of the BLR, and thus show a better correspondence with $R_{\text{BLR}}$, in practice there is little difference in the derived masses (Kaspi et al. 2000).

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Reynolds et al. (1997) discuss in detail the optical spectrum of MCG–6-30-15 and, in their fig. 4, derive an estimate of the intrinsic non-stellar optical flux (i.e. $vF_\nu$ or $\lambda F_\lambda$) at 5100 Å of $\sim 6 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Assuming the standard flat cosmology of $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $\Lambda_{\text{matter}} = 0.3$, with $z = 0.007749$, this flux equates to a rest-frame luminosity of $\lambda L_\lambda = 7.2 \times 10^{42}$ erg s$^{-1}$ and yields $R_{\text{BLR}} = 5.2$ lt-d.

We note that there is considerable scatter in the relationship between $R_{\text{BLR}}$ and $\lambda F_\lambda$ at 5100 Å. Vestergaard (2002) repeated the empirical study of Kaspi et al. (2000) using the linear regression techniques of Akritas & Bershady (1996) and obtained a slightly different relationship. However, the derived value of $R_{\text{BLR}}$, i.e. 5.36 lt-d, is, within the errors, identical to the value derived using the relationship of Kaspi et al. (2000). Vestergaard (2002) derives the relationship using only broad-line Seyfert 1 galaxies. The narrow-line Seyfert galaxy, NGC 4051, is an outlier and is not used in deriving the relationship, although it is used by Kaspi et al. (2000).

Using archival Hubble Space Telescope Space Telescope Imaging Spectrograph (HST/STIS) data for MCG–6-30-15 (Fig. 13) we have measured (rest frame) $V_{\text{FWHM}} = 32.9 \pm 1.9$ Å (± 200 ± 120 km s$^{-1}$) which, together with $R_{\text{BLR}}$, gives a virial mass for the black hole in MCG–6-30-15 of $3 \times 10^6$ M$_\odot$.

6 MASS DETERMINATION: PHOTOIONIZATION

The size of the BLR may also be found from photoionization calculations, but with a relatively large uncertainty. The calculated BLR size, combined with the velocity at FWHM of the H$\beta$ line profile can then be used to provide an estimate for the virial mass of the central black hole. From a sample of 17 Seyfert 1 galaxies and two quasars, Wandel et al. (1999) found an approximately linear relationship between photoionization mass estimates and reverberation mass estimates, suggesting that photoionization calculations might providing a route for mass determinations in systems with only single epoch mass observations. The empirical relationship derived by Wandel et al. (1999) is

$$M_{BH} = 2.8 \times 10^6 f \left( \frac{L_{\text{H}\alpha}}{U_{\text{H}\alpha}} \right)^{1/2} \left( \frac{V_{\text{FWHM}}}{10^5 \text{ km s}^{-1}} \right)^2 M_\odot,$$

Figure 13. HST/STIS spectrum of MCG–6-30-15, showing broad and narrow H$\beta$ components, and [OIII] $\lambda\lambda4959, 5007$ emission lines.
where $U$ is the ionization parameter (the dimensionless ratio of photon to gas density), $n_{10}$ is the electron density in units of $10^{10}$ cm$^{-3}$ and $f$ is the product
\[ f_{\text{DE}} \left( \frac{E}{\text{erg}} \right)^{-1/2}, \]
where $f_{\text{DE}}$ is a factor relating the effective velocity dispersion to the projected velocity dispersion, $f_L$ relates the observed luminosity $L$ to the ionizing luminosity, and $E = E_{1,4}$ 1/16. If we assume a BLR ionization parameter and gas density typical for nearby Seyfert 1 galaxies ($U = 0.1$, $n_{10} = 10$), and a weighted $f$ value $\sim 1.45$ (Wandel et al. 1999) we derive a black hole mass of $4.5 \times 10^6$ M$_\odot$.

7 DISCUSSION

7.1 Summary of mass determinations for MCG–6-30-15

Although considerable systematic uncertainties and large assumptions (e.g., in $n_{10}$ and $U$) are involved in their derivations, the various optical measurements of the black hole mass in MCG–6-30-15, including the revised estimate based on the bulge mass, are in reasonable agreement. All values lie between $\sim 3$ and $\sim 6 \times 10^6$ M$_\odot$. We cannot tell which measurement is correct and so, as a working value, we take the middle of the range, i.e., $\sim 4.5 \times 10^6$ M$_\odot$ and adopt an error equal to the spread in the measurements (i.e., $3 \times 10^6$ M$_\odot$). We note that although there are again large uncertainties in the mass derived from the PSD, the most tightly constrained mass, i.e., that derived from a combination of RXTE and low-energy XMM–Newton observations and assuming linear scaling of break time-scale with mass from Cyg X-1 in the high state, i.e., $\sim 2.9 \times 10^6$ M$_\odot$, is in agreement with the mass as determined by optical methods.

The average 2–10 keV X-ray flux of MCG–6-30-15 from our RXTE monitoring is $5.9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which corresponds to a luminosity of $\sim 7 \times 10^{37}$ erg s$^{-1}$. For an assumed X-ray/bolometric correction of 27 (Padovani & Raffanelli 1988; Elvis et al. 1994), the bolometric luminosity is $1.9 \times 10^{44}$ erg s$^{-1}$, implying that, for a mass of $\sim 4.5 \times 10^6$ M$_\odot$, MCG–6-30-15 is radiating at $\sim 40$ per cent of its Eddington luminosity. For narrow-line Seyfert galaxies, the bolometric correction should probably be less than 27 but probably still greater than 10, so MCG–6-30-15 is almost certainly radiating at $>10$ per cent of its Eddington luminosity. A low-state interpretation of the PSD which, although very unlikely, cannot be ruled out entirely, implies a black hole mass of $\sim 5 \times 10^5$ M$_\odot$, thus requiring a super-Eddington luminosity.

7.2 X-ray-selected AGN and high-state PSDs

Using our newly derived black hole mass, and slightly refined break time-scale, we plot (Fig. 14) MCG–6-30-15 on a revised version of the break time-scale/black hole mass diagram which we presented in M'Hardy et al. (2004). Although bending, rather than sharply breaking, power laws fit the PSDs best, we still use time-scales derived from sharp breaks in this diagram as we do not yet have time-scales derived from bending power-law fits to all of the AGN. Like NGC 4051, MCG–6-30-15 also sits above the high-state line. The break time-scales are taken from the compilation in M'Hardy et al. (2004) with the addition of NGC 4395 from Vaughan et al. (2005), with mass estimate from Filippenko & Ho (2003). Kraemer et al. (1999) present ultraviolet (UV) and optical spectral of NGC 4395 and show broad, although rather weak, wings to H$\beta$. They estimate $FWHM \sim 1500$ km s$^{-1}$, but do not give an error. We are therefore unsure whether to class it as a broad- or narrow-line Seyfert galaxy and so mark it by an open triangle in Fig. 14. We also include NGC 3227 from Uttley & M'Hardy (in preparation). Uttley & M'Hardy also discuss NGC 5506 in considerable detail but we do not include it here as its mass is highly uncertain.

Where available (i.e., Fairall9, NGC 3227, 3783, 4051, 4151, 5548) we use reverberation masses from the compilation of Peterson et al. (2004). No reverberation masses are available for the other AGN, i.e., the narrow-line Seyfert 1s, and so masses are derived from stellar velocity dispersion measurements. For some objects alternative masses are available from the emission linewidth (e.g., 6.3 $\times 10^5$ M$_\odot$ for Mkn766 from Botte et al. 2005), but to reduce the number of variables we restrict ourselves to the velocity dispersion mass (3.5 $\times 10^6$ M$_\odot$ for Mkn766, using the calibration of Tremaine et al. 2002). Current work (e.g., Ferrarese et al. 2001; Peterson et al. 2004) shows that masses derived from reverberation mapping and velocity dispersion are consistent. An exception is Akn564. As in some other NLS1s, the Ca II triplet lines in Akn564 are in emission (van Groningen 1993), rather than absorption, and so cannot be used to determine the black hole mass. In this case the width of the [O III] $\lambda 5007$ emission line is used as a substitute for the width of the stellar absorption lines in order to estimate the black hole mass (Botte et al. 2004). The width of the [O III] $\lambda 5007$ emission line does correlate, although with considerable scatter (Boroson 2003), with the width of the Ca II triple stellar absorption lines. However, it has been noted (Botte et al. 2005) that the [O III] lines tend to be wider than the Ca absorption lines. Therefore, assuming that the Ca absorption lines represent the black hole mass more accurately, the [O III] line will typically give an overestimate of the black hole mass, hence the upper limit on Akn564 in Fig. 14.

As a result of recalibration to better fit the $M_{\text{BH}} - \sigma_*$ relationship, masses in the sample of Peterson et al. (2004) have generally

![Figure 14. Black hole mass versus PSD break time-scale. Broad-line Seyfert galaxies are shown as filled circles, narrow-line Seyfert galaxies as open circles and NGC 4395 is shown as an open triangle. The dashed line to the right represents linear scaling of the break time-scale with mass from Cyg X-1 in its low state. The dot-dashed line, on the left, represents linear scaling of the break time-scale with mass from Cyg X-1 in its high state. NGC 4395 is plotted as an open triangle (see the text). The arrow labelled with $\#\$ indicates the way in which the relationship of break time-scale versus mass might move with increasing accretion rate.](https://academic.oup.com/mnras/article-abstract/359/4/1469/1008323)
increased from the earlier estimates used in M'Hardy et al. (2004). Also, the black hole mass estimate for NGC 4051 from Peterson et al. (2004) is higher than the estimate from Shemmer et al. (2003) which we used in M'Hardy et al. (2004). Here, for consistency, we use the black hole mass values from Peterson et al. (2004) wherever available. Thus all AGN from the Peterson et al. (2004) sample have moved further away from the low-state line and towards the high-state line. With the exception of NGC 4151, all AGN now lie above the low-state line. Although the ‘broad-line’ Seyfert galaxies are, in general, closer to the low-state line than the ‘narrow-line’ Seyfert 1s, it is possible that all AGN considered here might be high-state systems. Thus although it may well have an important effect on determining the break time-scale, the accretion rate in all AGN studied here may be high enough to make them ‘high-state’ systems. Indeed, Peterson et al. (2004) show that the average accretion rate for the current sample of AGN is roughly 10 per cent of the Eddington rate, which exceeds the ~2 per cent rate which typifies the transition to the high state in galactic X-ray binary systems (Maccarone 2003). For completeness we also include the break time-scale of NGC 3227 from Uttley and M'Hardy (in preparation). NGC 3227 is an interesting galaxy, having broad permitted lines, a high X-ray spectrum, and a high-state PSD. It is discussed in detail by Uttley and M'Hardy (in preparation).

An additional indicator of the ‘state’ of an accreting black hole is given by the ratio of its X-ray to radio luminosity (e.g. Fender 2001, 2003; Gallo, Fender & Pooley 2003). For Galactic black hole systems, a high X-ray/radio ratio signifies a high accretion rate and a ‘high’-state system. A low X-ray/radio ratio signifies a low accretion rate and a jet-dominated ‘low’-state system. The core radio flux of MCG–6-30-15 is very low, ~1 mJy at 5 GHz (Ulvestad & Wilson 1984), and very similar to that of NGC 4051 (M'Hardy et al., in preparation). The X-ray fluxes, and hence the X-ray/radio ratios, of both galaxies are high, again indicating ‘high-state’ systems.

7.2.1 A possible selection effect

It is interesting to note that the few AGN with sufficiently good PSDs to distinguish between high and low states (NGC 4051, MCG–6-30-15, NGC 3227), all have high-state PSDs. The AGN which we, and others (e.g. Markowitz et al. 2003), have been monitoring are mainly taken from the X-ray bright AGN which are visible in the bright-flux limit, all-sky, X-ray catalogues (e.g. M'Hardy et al. 1981). As X-ray flux rather than, for example, radio flux, is the only selection criterion in such surveys, there is a strong selection effect towards selecting high-state AGN.

AGN with low-state X-ray PSDs are likely to be found amongst those AGN which have relatively more luminous radio emission (cf. Merloni, Heinz & di Matteo 2003). As X-ray emission will not be the only parameter on which we select such AGN, we may expect them to be, in general, fainter in X-rays than those studied presently. Such AGN should be present in, for example, the sample of radio and X-ray bright objects selected from the ROSAT and VLA FIRST all-sky catalogues (Brinkmann et al. 2000). The observations from RXTE presented here, and elsewhere (e.g. Markowitz et al. 2003; M'Hardy et al. 2004), demonstrate the tremendous importance of long time-scale (years/decades) X-ray monitoring observations for our understanding of AGN. RXTE has revolutionized our understanding and opened up many new exciting areas of study, and hopefully it will continue to operate for many years to come. However, in the longer term, it is crucial that a sensitive (≤mCrab in a few hours) all-sky X-ray monitor, with a long lifetime (~decade) is launched to carry on this exciting work, otherwise this newly emerging field will die with RXTE.

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