The high frequency power spectrum of Markarian 766

S. Vaughan* and A. C. Fabian

Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA

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ABSTRACT

An analysis is presented of the power spectrum of X-ray variability of the bright Seyfert 1 galaxy Mrk 766 as observed by XMM–Newton. Over the 0.2–10 keV energy range the power spectral density (PSD) is well-represented by a power-law with a slope of $\alpha_{\text{low}} \approx 1$ at low frequencies, breaking to a slope of $\alpha_{\text{br}} = 2.8 \pm 0.2$ at a frequency $f_{\text{br}} \approx 5 \times 10^{-5}$ Hz. As has been noted before, this broken power-law PSD shape is similar to that observed in the Galactic black hole candidate Cygnus X-1. If it is assumed that Mrk 766 shows a power spectrum similar in form to that of Cyg X-1, and that the break time-scale scales linearly with black hole mass, then the mass of the black hole in Mrk 766 is inferred to be $\lesssim 5 \times 10^5 \, M_\odot$. This rather low mass would mean Mrk 766 radiates above the Eddington limit. The coherence between different energy bands is significantly below unity implying that variations in the different energy bands are rather poorly correlated. The low coherence can be explained in the framework of standard Comptonization models if the properties of the Comptonizing medium are rapidly variable or if there are several distinct emission sites.

Key words: galaxies: active – galaxies: individual: Mrk 766 – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

X-ray variability appears to be ubiquitous in active galactic nuclei (AGN). The rapid and seemingly random fluctuations in the X-ray luminosity of Seyfert galaxies provided early support for the standard black hole/accretion disc model (e.g. Rees 1984) by implying compact emission regions and high luminosity densities (Fabian 1979; McHardy 1989).

The long (~3 d), uninterrupted observations possible with EXOSAT allowed the power spectral density (PSD) of Seyfert 1 galaxies to be measured for the first time (Lawrence & Papadakis 1993; Green, McHardy & Lehto 1993). The PSD represents the average of the (squared) amplitude of variations as a function of temporal frequency (see van der Klis 1989). The EXOSAT observations showed that the PSDs of Seyfert 1s above $\sim 10^{-3}$ Hz could be approximated by a power-law [$P(f) \propto f^{-\alpha}$ where $P(f)$ is the power at frequency $f$ and $\alpha$ is the PSD slope] rising steeply at low frequencies with a slope $\alpha \gtrsim 1$ (so-called ‘red noise’ spectra; Press 1978). It was noted early on (e.g. Lawrence et al. 1987; McHardy 1989) that this red noise variability of Seyferts is similar to that observed in Galactic black hole candidates (GBHCs; van der Klis 1995), perhaps suggesting that the same physical processes operate in these sources that differ in black hole mass by factors of $\gtrsim 10^5$.

The steep slopes of the EXOSAT PSDs mean that at lower frequencies the PSD must flatten in order for the integrated power to converge. Indeed, breaks in the PSDs of Seyfert galaxies have recently been detected (Edelson & Nandra 1999; Uttley, McHardy & Papadakis 2002; Vaughan, Fabian & Nandra 2003; Markowitz et al. 2003). The position of these breaks represent ‘characteristic time-scales’ in the aperiodic variability of Seyfert 1s, and interestingly they appear to scale linearly with the mass of the central black hole (Markowitz et al. 2003). The PSDs of GBHCs usually show at least two breaks (Nowak et al. 1999; Lin et al. 2000), and it is becoming increasingly apparent that the PSDs of Seyfert galaxies (and their timing properties in general) are very similar to those of GBHCs except shifted to longer time-scales according to the black hole mass (Vaughan et al. 2003; Markowitz et al. 2003).

This paper presents an analysis of the X-ray continuum variability of the bright Seyfert 1 galaxy Mrk 766 (also known as NGC 4253; $z = 0.012$ 929) using a long XMM–Newton observation. XMM–Newton offers the possibility to improve upon the high-frequency PSDs provided by EXOSAT, having as it does a similarly long orbit but greatly increased throughput and a wider bandpass. The rest of this paper is organised as follows. Section 2 describes the basic data reduction procedures, Section 3 details the results of the PSD analysis and Section 4 describes the cross spectral results. Finally, the implications of these are discussed in Section 5.

2 DATA REDUCTION

Mrk 766 was observed by XMM–Newton (Jansen et al. 2001) over the period 2001 May 20 – 2001 May 21 (revolution 265), during which all instruments were operating nominally. The present
analysis is restricted to the data from the European Photon Imaging Cameras (EPIC). Other aspects of this observation are discussed in Mason et al. (2003). The EPIC pn camera (Strüder et al. 2001) was operated in small-window mode, as was the MOS2 camera (Turner et al. 2001), and MOS1 was operated in timing mode. Here only data from pn are used as these have the highest signal-to-noise ratio and are free from photon pile-up.

Extraction of science products from the Observation Data Files (ODFs) followed standard procedures using the XMM–Newton SCIENCE ANALYSIS SYSTEM v5.3.3 (SAS). The EPIC data were processed using the standard SAS processing chains, source data were extracted from a circular region of radius 35 arcsec from the processed pn image. Only events corresponding to patterns 0–4 (single and double pixel events) were used for the pn analysis. Background events were extracted from regions in the small window least affected by source photons. These showed the background to be relatively low and stable throughout the first 105 ks of the observation. During the final ~15 ks the background rate increased dramatically. The much stronger (and highly variable) background level during this part of the observation contributed a significant amount of non-source variability, and so only the first 105 ks of the light curve are used for the variability analysis presented here.

Light curves were extracted from the EPIC pn data in four different energy bands: 0.2–10.0 keV (full band), 0.2–0.7 keV (soft band), 0.7–2.0 keV (medium band) and 2.0–10.0 keV (hard band). These were corrected for telemetry drop-outs (less than 1 per cent of the total time), background subtracted and binned to 100 s time resolution. The errors on the light curves were calculated by propagating the Poisson noise. The light curves were not corrected for the ~71 per cent ‘live time’ of the pn camera (Strüder et al. 2001), which is only a scaling factor. The full band light-curve is shown in Fig. 1. The average source (background subtracted) and background count rates are shown in Table 1 along with the fractional excess rms variability amplitude of the source ($F_{var}$; Edelson et al. 2002) in each energy band.

| Band    | Source ($ct \ s^{-1}$) | Background ($ct \ s^{-1}$) | $F_{var}$ (per cent) |
|---------|------------------------|-----------------------------|----------------------|
| Full    | 19.9                   | 0.3                         | 17.6 ± 0.4           |
| Soft    | 11.2                   | 0.2                         | 17.8 ± 0.4           |
| Medium  | 6.68                   | 0.07                        | 19.0 ± 0.4           |
| Hard    | 2.03                   | 0.05                        | 17.8 ± 0.4           |

3 POWER SPECTRAL ANALYSIS

The analysis presented here followed very closely that applied by Vaughan et al. (2003) to XMM–Newton light curves of the bright Seyfert 1 galaxy MCG-6-30-15. The periodogram of the contiguous (100 s binned) light curve was calculated using the standard Discrete Fourier Transform (DFT). The periodogram was then binned using the method of Papadakis & Lawrence (1993), using $N = 15$ periodogram points per bin, to produce a consistent PSD estimate with Gaussian error bars. The periodogram was normalized to (rms/mean)$^{2}$ Hz$^{-1}$ units, as defined by van der Klis (1997). The binned periodogram is shown in Fig. 2 and appears steep at low frequencies (due to the red noise variability of the source) and flattens at high frequencies due to the variability introduced by the Poisson noise (which has a flat, ‘white’ power spectrum).

The periodogram was fitted using the Monte Carlo procedure described in Vaughan et al. (2003) (similar to that discussed by Uttley et al. 2002) in order to derive parameters of the PSD of Mrk 766. For each trial PSD model, 500 simulated light curves were generated (using the algorithm of Timmer & König 1995). The simulated light curves were generated from a PSD model that extended down to much lower frequencies than the measured periodogram, and each simulated light curve was a factor ~50 longer than the observed light curve. This allows for variability power on time-scales longer than the observed light curve and thereby accounts for any effect this might have on the observed periodogram (‘red noise leak’)

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Full-band (0.2–10.0 keV) EPIC pn light curve in 100 s bins.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Top panel: binned periodogram of the full band (0.2–10 keV) light curve (data points) and best-fitting single power-law model (solid line). The dotted line marks the expected Poisson noise level. Bottom panel: residuals from the power-law fit. Inset panel: variation in $\chi^2$ with power-law slope.
– see Uttley et al. 2002 and Vaughan et al. 2003). A section of each long simulated light curve was re-sampled to match the sampling of the observed light curve. Periodograms were then calculated for each of the 500 simulated data sets (and binned exactly as the real data were) and the 500 binned periodograms averaged to produce an average periodogram. This average represents the PSD model after being distorted by the light-curve sampling (‘folded’ through the response of the observation). The constant Poisson noise component is then added (at the level expected for Poisson noise) and the folded model is compared to the data by measuring the \( \chi^2 \) of the fit. Further details of the procedure are given in Vaughan et al. (2003).

Fitting the data with a power-law PSD model gave a poor fit to the data (\( \chi^2 = 80.4 \) for 33 degrees for freedom, dof, rejected at \( \sim 99.9 \) per cent confidence) with a best-fitting power-law slope of \( \alpha = 1.95 \). The steep slope seen from these XMM–Newton data requires that the PSD flatten at lower frequencies (as observed in other Seyfert galaxies; Uttley et al. 2002; Vaughan et al. 2003; Markowitz et al. 2003) for the total integrated power to be finite. The poor fit of the single power-law model further suggests that the power spectral break may occur within (or close to) the frequency range probed by this XMM–Newton observation.

In order to test this hypothesis, a broken power-law PSD model was fitted to the data. The PSD was assumed to break from a slope of \( \alpha_{\text{low}} = 1 \) at low frequencies to a steeper slope. The free parameters of the model were the PSD normalization, the break frequency \( (f_{\text{br}}) \) and the high-frequency slope \( (\alpha_{\text{hi}}) \). As shown in Fig. 3, this model provided a reasonable fit to the data (\( \chi^2 = 43.2/32 \) dof with a rejection probability of 91.5 per cent), much better than the unbroken power law (\( \Delta \chi^2 = 37.6 \) improvement for one additional parameter). The slightly high rejection probability may be indicating that a broken power law is only an approximation to the true underlying PSD. The best-fitting parameters are as follows: \( \alpha_{\text{hi}} = 2.8^{+0.2}_{-0.4} \) and break frequency of \( f_{\text{br}} = 5.3^{+1.1}_{-1.3} \times 10^{-4} \) Hz. (The errors represent 90 per cent confidence limits calculated using a \( \Delta \chi^2 = 2.7 \) criterion.)

The PSD slope below the break is not well-constrained with these XMM–Newton data. An alternative model, in which the power-law breaks from \( \alpha_{\text{low}} = 0 \) to a steeper slope was also compared to the data. The best-fitting high-frequency slope was \( \alpha_{\text{hi}} = 2.4^{+0.3}_{-0.2} \) and the break frequency was \( 1.6 \pm 0.8 \times 10^{-4} \) Hz, giving \( \chi^2 = 48.1/32 \) dof (rejected at 96.6 per cent), slightly worse than the model assuming a break from \( \alpha_{\text{low}} = 1 \). Thus it is not possible to constrain in detail the shape of break in Mrk 766, but the broken power-law models did provide a significant improvement over the single power-law model. As a low-frequency slope of \( f_{\text{br}} \) fitted the data slightly better, and seems more likely in other Seyfert galaxies (Uttley et al. 2002; Markowitz et al. 2003), this model is used throughout the rest of this paper to describe the PSD of Mrk 766.

Energy dependence of the high-frequency PSD, with the PSD slope being flatter at higher energies, has previously been seen in the Seyfert 1 galaxies NGC 7469 (Nandra & Papadakis 2001), MCG–6–30–15 (Vaughan et al. 2003) and NGC 4051 (Papadakis & Lawrence 1995, McHardy et al., in preparation). In order to test for any such variation in the PSD as a function of energy the above analysis was repeated on the light curves extracted in the three energy sub-bands. The results are shown in Table 2. The high-frequency slopes are formally consistent with one another although the hardest band does show the flattest best-fitting slope (this is also the case when the data were fitted with the PSD model assuming \( \alpha_{\text{low}} = 0 \) below the break). This hints that Mrk 766 may show the energy dependence seen in other Seyferts, and in particular adds to the evidence provided by XMM–Newton (see Vaughan et al. 2003 and McHardy et al., in preparation) that the PSDs of Seyferts are energy-dependent even at soft X-ray energies (the energy dependence in NGC 7469 could only be examined above 2 keV, the same is true for most GBHCs).

### 4 CROSS SPECTRAL ANALYSIS

The cross spectrum is related to the PSD (sometimes known as the auto spectrum). It offers a comparison of two simultaneous light curves (e.g. from different energy bands) as a function of temporal frequency. The cross spectrum can be used to derive the coherence \( [\gamma^2(f)] \) of two light curves (a measure of how well correlated the variations in the two light curves are) and time-delays between the light curves (see Vaughan & Nowak 1997 and Nowak et al. 1999 for an explanation of these properties in terms of GBHC observations and Papadakis, Nandra & Kazanas 2001 and Vaughan et al. 2003, for an application to Seyfert galaxies).

The coherence of Mrk 766 was measured using the recipe given by Vaughan & Nowak (1997). The periodograms of the two light curves and their cross periodogram were computed and binned by \( N = 15 \) consecutive frequencies per bin. The coherence and its uncertainty were then calculated using equation (8) of Vaughan & Nowak (1997). ( Vaughan et al. 2003 have shown that uncertainty estimates calculated in this way are accurate for data very similar to those examined here.)

The resulting coherence functions (Fig. 4) show that, particularly between the soft and hard bands, the coherence is significantly below unity at all frequencies. This means that either the relation between

| Band   | Slope \( \alpha_{\text{hi}} \) | \( f_{\text{br}} \) (10^-4 Hz) | \( \chi^2/\text{dof} \) |
|--------|-----------------|-----------------|-----------------|
| Full   | 2.8^{+0.2}_{-0.4} | 5^{+1.1}_{-1.3} | 43.5/32         |
| Soft   | 2.6 ± 0.4        | 3^{+1.3}_{-2.2} | 44.9/32         |
| Medium | 2.7 ± 0.5        | 5 ± 3           | 51.1/32         |
| Hard   | 2.3 ± 0.4        | 5 ± 3           | 44.0/32         |
soft and hard bands is non-linear or that a fraction of the hard-band variance is not accounted for by variations in the soft band. The apparently poor (linear) correlation between variations in different bands is confirmed by an analysis of the cross correlation function, estimated using the Discrete Correlation Function (DCF; Edelson & Krolik 1988). The DCF for the soft- versus hard-band light curves reaches a peak (at zero time-delay) of only 0.65. It should be noted that the reduced coherence is not an artifact of Poisson noise in the data as the recipe of Vaughan & Nowak (1997) correctly accounts for this. The low coherence means it is not possible to reliably search for time-delays between the different bands.

The hardness ratios were calculated to further examine the relationship between variations in different energy sub-bands (Fig. 5). The hardness ratios are significantly variable but show little correlation with the total source flux. There is a slight trend for the 0.7–2.0/2.0–10.0 keV ratio to soften as the source brightens (as has been seen in other Seyfert 1s) but the ratios show a greater deal of scatter (much larger than expected from the size of the error bars) not obviously associated with changes in the full band flux. This complements the coherence analysis and shows that the relationships between energy sub-bands are complex.

5 DISCUSSION

The shape of the high-frequency power spectrum of Mrk 766 is consistent with a power-law that breaks from a flat slope ($\alpha_{\text{low}} \approx 1$) to a steep slope ($\alpha_{\text{hi}} \gtrsim 2$) at a frequency $\sim 5 \times 10^{-4}$ Hz. There is no evidence for discrete features such as quasi-periodic oscillations (previously claimed by Boller et al. 2001, but see also Benlloch et al. 2001). Similar broken power-law PSDs have been observed in other Seyfert 1s (Uttley et al. 2002; Vaughan et al. 2003; Markowitz et al. 2003, McHardy et al., in preparation). This shape for the high-frequency PSD is similar to that of GBHCs (Nowak et al. 1999; Lin et al. 2000). Not only is the shape the same but the amplitudes are similar. The power [in $\frac{P}{f}$ units] measured at the break frequency is $\sim 0.01$ in the 2–10 keV band, which compares with the power at the high-frequency break in Cyg X-1 of $\sim 0.02$ (Belloni & Hasinger 1990). This strongly supports the idea that the variability mechanisms, and perhaps the X-ray emission processes in general, are the same in AGN and GBHCs.

In the best studied GBHC, Cygnus X-1 in its low/hard state, the PSD breaks from $\alpha \approx 1$ to a steeper slope at $\sim 3$ Hz (Belloni & Hasinger 1990; Nowak et al. 1999). In its high/soft state the position of the high-frequency break increases to $\sim 10$ Hz (Churazov, Gilfanov & Revnivtsev 2001). It is not clear which of these states is closer to the behaviour of Seyferts. The corresponding break frequency in Mrk 766 is a factor of $\sim 6 \times 10^3$ or $\sim 2 \times 10^4$ times higher than that seen in Cyg X-1, depending on whether the low/hard or high/soft state is used for comparison. Assuming a 10 M$_{\odot}$ mass black hole in Cyg X-1 (Herrero et al. 1995), and further assuming that the characteristic break time-scales linearly with black hole mass (see Markowitz et al. 2003) yields estimates for the mass of the black hole in Mrk 766 of $\sim 6 \times 10^4$ or $\sim 2 \times 10^5$ M$_{\odot}$ (comparing with low/hard and high/soft state PSDs respectively). These estimates are unusually low compared to the masses expected for Seyfert nuclei (e.g. Wandel, Peterson & Malkan 1999). Indeed, Wandel (2002) estimated the mass of Mrk 766 to be $\sim 10^7$ M$_{\odot}$ based on its luminosity and optical broad-line properties.

The highest mass estimate consistent with a linear scaling of time-scales, obtained using the 90 per cent lower limit on the break frequency in Mrk 766 and scaling by the break seen in the high/soft state in Cyg X-1, is $\sim 5 \times 10^5$ M$_{\odot}$. The (unabsorbed 0.2–10 keV) X-ray luminosity of Mrk 766 is $\sim 3 \times 10^{45}$ erg s$^{-1}$ (assuming $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$). Taking a fairly conservative estimate of the bolometric luminosity of $10^{44}$ erg s$^{-1}$ and the highest black hole mass estimate suggests Mrk 766 is radiating at $\sim 1.5L_{\text{Edd}}$. Of course, this depends on there being a linear scaling between the break time-scales in Cyg X-1 and those of Seyfert 1s. If this is the case the implication seems to be that Mrk 766 is accreting above the Eddington limit.

A further point is that if the slope of the low-frequency PSD is significantly different from the assumed $\alpha_{\text{low}} = 1$, then the break frequency could be lower (fitting a model assuming $\alpha_{\text{low}} = 0$ gave $f_{\text{break}} = 1.6 \pm 0.8 \times 10^{-4}$ Hz). Comparing this to the low-frequency break in Cyg X-1 (the break from $\alpha \approx 0$ to $\alpha \approx 1$ in the low/hard state) gives an even lower black hole mass estimate (see the discussion in Uttley et al. 2002). However, the fact that the high-frequency PSD is steep ($\approx 2.3$ in the hardest band) suggests a slope of $\approx 1$ below the break is more likely, by comparison with the PSD of Cyg X-1.

It is perhaps worth noting that Mrk 766 has previously been classified a narrow-line Seyfert 1 (NLS1), a class of AGN often suggested...
to be accreting close to the Eddington limit (Boller, Brandt & Fink 1996). The PSDs of other NLS1s also seem to show break frequencies somewhat higher than found in ‘normal’ Seyfert 1s (Ark 564: Pounds et al. 2001; Papadakis et al. 2002; NGC 4051: M‘Hardy et al., in preparation). This is consistent with the idea that NLS1s harbour lower mass black holes accreting at a higher rate (relative to Eddington) compared to the normal Seyfert population.

It remains plausible that the mass–time-scale relation is not perfectly linear. The most important physical time-scales associated with accretion flows (e.g. Section 5.8 of Frank, King & Raine 1985) derive from a distance and a speed over which some physical process operates (such as viscosity). If the salient distance (such as the radius of the innermost edge of the accretion disc) is approximately the same in units of the gravitational radius \( r_g = GM/c^2 \) between Cyg X-1 and AGN, then the time-scales should (to the first order) scale linearly with black hole mass. However, if the relevant distance is not constant then this linear scaling can break down. For example, the innermost stable circular orbit around a black hole depends on its dimensionless spin parameter \( a/M \), with a spinning black hole allowing a steady accretion disc to extend to smaller radii (in gravitational units). If Mrk 766 has a higher spin parameter than Cyg X-1, one would perhaps expect the accretion disc to extend to smaller \( r_g \) and the physical time-scales to be somewhat smaller than the linear expectation. Such a situation would allow the black hole mass of Mrk 766 to be higher by a factor of a few (compared to the linear assumption) and thereby allow for a sub-Eddington accretion rate. An independent estimate of the mass of Mrk 766 (from e.g. reverberation mapping or gas kinematic studies) would help clarify this issue.

The variations in different energy bands show a coherence well below unity at all frequencies examined. A loss of coherence at high frequencies has also been observed in MCG–6–30–15 (Vaughan et al. 2003), but at the lowest frequencies probed the coherence was much higher than observed in Mrk 766. On longer time-scales the variations in NGC 7469 were consistent with unity coherence (Papadakis et al. 2001). In Cyg X-1 the coherence is known to be high (near unity) over a wide range in frequency but falls significantly below unity at high frequencies (Nowak et al. 1999). The reduced coherence means the relationship between variations in different energy bands cannot be described by a single (linear) transfer function.

If the X-rays are produced by inverse-Compton scattering in a hot corona, as is often thought (e.g. Haardt & Maraschi 1991), then the low coherence implies rapid changes in the coronal properties and/or multiple independent emission sites. As discussed by Nowak & Vaughan (1996), a static Comptonizing corona should produce unity coherence. Rapid changes in the properties (e.g. size, temperature, optical depth) of the X-ray emitting region could cause changes in the transfer function (relating soft to hard flux) on the time-scales probed and so reduce the coherence. Alternatively the low coherence may mean there is more than one transfer function operating simultaneously, which could be physically realised if the X-ray emission is produced at several independent sites.

**XMM–Newton** has opened the door on high-frequency timing studies of AGN, a door that has remained largely closed since the end of the EXOSAT mission. Future work must establish whether the high-frequency power and cross spectral properties observed in the handful of Seyfert 1s with XMM–Newton long-looks (see also Vaughan et al. 2003 and M‘Hardy et al., in preparation) are universal or whether different objects show different characteristics (perhaps as GBHCs show distinct states).

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