Rapid X-ray Variability of Seyfert 1 Galaxies

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Abstract. The rapid and seemingly random fluctuations in X-ray luminosity of Seyfert galaxies provided early support for the standard model in which Seyferts are powered by a supermassive black hole fed from an accretion disc. However, since EXOSAT there has been little opportunity to advance our understanding of the most rapid X-ray variability. Observations with XMM-Newton have changed this.

We discuss some recent results obtained from XMM-Newton observations of Seyfert 1 galaxies. Particular attention will be given to the remarkable similarity found between the timing properties of Seyferts and black hole X-ray binaries, including the power spectrum and the cross spectrum (time delays and coherence), and their implications for the physical processes at work in Seyferts.

1. In the beginning...

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 (Rees, 1984) by implying compact emission regions and high luminosity densities (Barr & Mushotzky, 1986).

2. The EXOSAT era

EXOSAT (1983–1986) was the first mission to provide long (∼ 3 day), uninterrupted X-ray observations of Seyfert galaxies. From these observations the X-ray power spectra (see van der Klis, 1989) of Seyfert galaxies were measured for the first time (Lawrence et al., 1987; Green et al., 1993; Lawrence & Papadakis, 1993). The EXOSAT observations showed that the power spectra of Seyferts above ∼ 10^{-5} Hz could be approximated by a power-law: \( \mathcal{P}(f) \propto f^{-\alpha} \) where \( \mathcal{P}(f) \) is the power at frequency \( f \) and \( \alpha \) is the power spectrum slope. The measured slopes from the EXOSAT observations were typically \( \alpha \approx 1.5 \). Processes such as these, which have broad-band power spectra with more power at...
lower frequencies, are called “red noise” (see Press, 1978). It was noted early on (Lawrence et al., 1987) that this red noise variability of Seyferts is similar to that observed in Galactic Black Hole Candidates (GBHCs; Belloni & Hasinger, 1990; Nowak et al., 1999; M'Clintock & Remillard, 2004), perhaps suggesting that the same physical processes operate in these sources that differ in black hole mass by factors of \( \sim 10^5 \).

3. Low frequency power spectra from RXTE

The steep slopes found in the EXOSAT power spectra required there to be a flattening at even lower frequencies (so that the integrated power remains finite). In recent years long RXTE monitoring observations have detected these breaks (e.g. Uttley et al., 2002; Markowitz et al., 2003; see also the article by Ian M'Hardy in these proceedings). Below the break the slope is typically \( \alpha_{lo} \approx 1 \) and at frequencies above the break the slope is \( \alpha_{hi} \approx 2 \). (The EXOSAT power spectra spanned intermediate frequencies and often measured an intermediate slope over the break.) The breaks represent “characteristic timescales” in the aperiodic variability of Seyferts and, significantly, appear to scale linearly with the mass of the central black hole: \( f_{\text{break}} \propto 1/M_{\text{BH}} \).

4. XMM-Newton results: high frequency power spectra

Until the launch of XMM-Newton (Jansen et al., 2001) high frequency timing studies of Seyferts were not able to substantially improve on the EXOSAT results. XMM-Newton’s success is due to a combination of high throughput, broad energy bandpass and long (\( \sim 2 \) day) orbit. Figure 1 shows an example of a broad-band (0.2 – 10 keV) light curve from a single orbit observation.

Figure 1. XMM-Newton light curve of Mrk 766 binned to 100 second resolution.
Several Seyfert 1 galaxies have been studied with long XMM-Newton observations and yielded interesting power spectra. These include: NGC 4051 (M'Hardy et al., 2004), Mrk 766 (Vaughan & Fabian, 2003), MCG—6-30-15 (Vaughan et al., 2003), NGC 4395 (Vaughan et al., 2004) (and also Ark 564; Vignali et al., 2004). Figure 2 shows the power spectra for three of these. The XMM-Newton results clearly reveal similar high frequency breaks in the power spectra (also measured by RXTE in some cases) but clearly show a substantial object-to-object differences in the normalisation of the power spectrum (which describes the overall variability amplitude).

These XMM-Newton observations have also demonstrated the energy dependence of the power spectrum. Above the break frequency the slope $\alpha_{hi}$ tends to be steeper at lower energies. This is clearly observed in MCG—6-30-15 (Vaughan et al., 2003) and NGC 4051 (M'Hardy et al., 2004) but is not constrained by the other observations. This energy dependence was also measured in NGC 7469 using an intensive RXTE monitoring campaign (Nandra & Papadakis, 2001).
5. **XMM-Newton results: high frequency cross spectrum**

In addition to the energy dependence of the power spectrum, the excellent quality *XMM-Newton* light curves have allowed the cross spectrum to be investigated in several Seyfert 1s for the first time. Prior to *XMM-Newton* only Papadakis et al. (2001) had measured the cross spectrum for a Seyfert (NGC 7469 using *RXTE*).

The cross spectrum compares the variations in one band with those in another as a function of frequency. The amplitude of the cross spectrum gives the coherence (Vaughan & Nowak, 1997) while the argument gives the phase lag (time delay; Nowak et al., 1999). The coherence quantifies any (linear) correlation between the variations in the two bands, irrespective of any time delays. The observations typically show high coherence at the lowest frequencies (i.e. strong correlation) with a decrease at higher frequencies which implies there are independent variations between the two bands occurring on short timescales (Vaughan et al., 2003; McHardy et al., 2004; Vaughan et al., 2004). At low frequencies, where the coherence is high, the data also exhibit small time delays, with the soft leading the hard variations (Vaughan et al., 2003; McHardy et al., 2004). The magnitude of the time delay decreases with increasing frequency (although the functional form of the relation is poorly constrained).

6. **Summary of results**

*XMM-Newton* has already made significant progress towards improving our understanding of the high frequency variability of Seyfert galaxies. The timing studies have revealed:

- Similar broken power spectra in Seyferts but object-to-object differences in normalisation (variability amplitude) and high frequency slope.
- Energy-dependent high frequency power spectrum slope (steeper at lower energies).
- High coherence at low frequencies, falling off at high frequencies.
- Small ($\Delta T \sim 0.01/f$) soft-to-hard time delays.
7. Comparison with GBHCs

The frequencies of the breaks in the power spectra are broadly consistent with the long-held notion that the characteristic frequencies should scale as $\propto 1/M_{\text{BH}}$ right down to stellar mass black holes. Figure 3 shows the available data for 11 Seyferts. Although the uncertainties are rather large, the data seem consistent with an extrapolation of the $f_{\text{br}} \propto 1/M_{\text{BH}}$ relation from the well-studied GBHC Cygnus X-1 (Belloni & Hasinger, 1990; Cui et al., 1996; Nowak et al., 1999; McClintock & Remillard, 2004). Note that the break frequency measurements come from a combination of XMM-Newton and RXTE observations. Long XMM-Newton observations are sensitive to breaks in the range $\sim 10^{-4} - 10^{-2}$ Hz while the RXTE monitoring campaigns are sensitive to breaks at lower frequencies.

The connection between Seyferts and GBHCs is reinforced by the similarity between their cross spectra. It is well known that GBHCs show highly coherent variations at low frequencies with the coherence fading away at the highest frequencies plus frequency dependent time lags similar to those measured in Seyferts (Nowak et al., 1999;
McClintock & Remillard, 2004). These all argue for a common mechanism responsible for producing the X-ray variability in Seyferts and GBHCs.

One may ask what advantage is gained by studying Seyferts in X-rays if GBHCs operate with the same physics but provide much higher quality data? One answer is that Seyferts can in fact provide data that are in some senses better than that from GBHCs for studying the highest frequencies. For example, comparing MCG−6-30-15 and Cygnus X-1 we see the timescales are longer by $\sim 10^5$ in the Seyfert, but the X-ray flux is smaller by $\sim 10^3$. This means that per characteristic timescale the Seyfert provides $\sim 10^2$ more photons! Of course, GBHC enthusiasts can argue that GBHCs reclaim much of their advantage even here because one can always observe many ($\sim 10^5$) more samples of a given timescale in a fixed amount of observing time, even if many less photons are recorded per timescale. Even so the power spectrum of MCG−6-30-15 could be measured up to $\sim 5 \times 10^{-3}$ Hz using the XMM-Newton data. This is equivalent to probing $\sim 500$ Hz in Cygnus X-1, a challenge for even the best RXTE observations (Revnivtsev et al., 2000).

8. Implications for the emission processes

The X-ray emission mechanism operating in Seyfert galaxies (and GBHCs) is usually thought to be inverse-Compton scattering. In the simplest models harder photons are expected to lag behind the softer photons due to the larger number of scatterings required to produce harder photons; the delay should be of order the light-crossing time of the corona. The direction and magnitude of the observed time lags in Seyfert 1s are consistent with an origin in a Comptonising corona. However, if the lags are frequency dependent (as expected by analogy with Cygnus X-1) the lags at lower temporal frequencies would become much longer than expected for a compact corona (see discussion in Nowak et al., 1999). In addition, some models of Compton scattering coronae predict the high frequency PSD should be steeper for higher energy photons, due to the high-frequency fluctuations being washed out by multiple scatterings (Nowak & Vaughan, 1996), contrary to the observations. Alternatively, the time delay between soft and hard bands could be due to the spectral evolution of individual X-ray events (Poutanen & Fabian, 1999) or propagation of accretion rate variations through a extended emission region (Kotov et al., 2001).
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