A brief review of long-term X-ray and optical variability in radio-quiet AGN

Philip Uttley\textsuperscript{1,2,*} and Ian M. McHardy\textsuperscript{1}

\textsuperscript{1}School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
\textsuperscript{2}Laboratory for High Energy Astrophysics, Code 662, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Long-time-scale X-ray and optical variability is a key characteristic of AGN. Here, we summarise our current understanding of the X-ray and optical continuum variability of radio-quiet AGN and the relation between the two bands. We demonstrate the strong connection between the X-ray variability properties of AGN and the variability of stellar-mass black hole candidates on much shorter time-scales, and discuss the implications of this result for the origins of the variability. The relationship between optical and X-ray variability is complex, with some AGN showing strong X-ray/optical correlations while others show no obvious correlation. We suggest a possible explanation for this variety of behaviour.

\textbf{§1. Introduction}

Time-variable emission over the entire observable spectrum is one of the defining characteristics of AGN. Variability on time-scales of months to years provided the first key evidence that the emitting regions were extremely compact, leading to the suggestion that AGN are powered by massive black holes. However, although the black hole paradigm has grown stronger due to a variety of subsequent observations, the origin of the variability largely remains a mystery. In radio-loud AGN, some progress has been made in understanding the broadband variability in terms of jet models of emission,\textsuperscript{1} but the situation is less clear in radio quiet AGN, which form the bulk of the AGN population. Because, in the optical waveband, the variability is fairly slow, it can only be studied in detail with long, well-sampled monitoring campaigns which are difficult to organise. In the X-ray band, where the variability is much more rapid, short-term variability was originally studied using ‘long-looks’ of a day or more duration, by X-ray satellites such as \textit{EXOSAT} and \textit{ASCA}, but longer time-scales were inaccessible due to the constraints of scheduling and pointing these satellites. In 1995, the launch of the Rossi X-ray Timing Explorer (\textit{RXTE}) revolutionised the study of AGN variability, because the rapid slewing capability and flexible scheduling of \textit{RXTE} allowed well-sampled long-term monitoring of AGN X-ray variability for the very first time.

With \textit{RXTE}, it has been possible to study X-ray variability of radio-quiet AGN over a very broad range of time-scales for comparison with the (as it turns out) remarkably similar variability properties of stellar mass black holes in X-ray binary systems (BHXRBs). Also, it has been possible to compare the long-term X-ray variability

\textsuperscript{*} E-mail: pu@milkyway.gsfc.nasa.gov

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with the optical variability sampled by a few optical monitoring programs, to examine the relationship between the two bands, which we might expect to be dominated by different emission mechanisms (optically thin versus optically thick). In this paper we will review our current understanding of the long-term X-ray variability of radio-quiet AGN, and how it relates to the X-ray variability on shorter time-scales. We will also consider the relationship between the X-ray and optical bands, and discuss models which might explain the variability in both bands.

§2. X-ray variability and the AGN-BHXRB connection

2.1. Before RXTE

In the 1980s, studies with EXOSAT showed that on short time-scales, AGN variability appeared to be red-noise.\(^2,3\) In other words the variability showed no obvious periodic or quasi-periodic behaviour (and hence is called noise), but showed variability over the entire range of sampled time-scales (and hence is ‘red’ with the variability power density increasing towards lower temporal frequencies).\(^\ast\) The corresponding power spectral density functions (PSDs) were described by power-laws (of index -1 to -2), which were unbroken down to the lowest sampled frequencies of \(\sim 10^{-5}\) Hz. However, it was noted\(^6\) that this power-law shaped PSD is reminiscent of the high frequency PSDs (above \(\sim 1\)Hz) of black hole X-ray binary systems, and that if the similarity holds to lower frequencies we should expect to see a break to a flatter PSD slope, below frequencies corresponding to time-scales of days-weeks (provided we make the physically plausible assumption that the break time-scale scales linearly with black hole mass). Attempts to detect this break frequency, using sparsely sampled archival data from different missions to cover long time-scales, were hampered by the distorting effects of sampling and the limited data, but they were at least suggestive that there was a flattening of the PSD at the expected frequencies.\(^6,7\)

Around the same time as the early AGN PSD studies, an inverse correlation was noted between the amplitude of variability in \(\sim\)day-long AGN X-ray light curves and the X-ray luminosity of the AGN.\(^8-10\) Of a number of possible models to explain this result, the most promising was that the effect represented the expected correlation between the black hole mass (which is tracked by luminosity assuming a common fractional accretion rate) and the variability time-scale, with more massive (and luminous) AGN showing slower variability due to their larger size. The situation was complicated by the discovery that Narrow Line Seyfert 1s (NLS1) do not follow this correlation (they show large variability amplitudes even at high luminosities).\(^11,12\)

\(^\ast\) We note here that to date, no statistically significant examples of (quasi)-periodicities have been found in AGN X-ray light curves\(^5\) with the possible (and intriguing) exception of long EUVE observations of two Narrow Line Seyfert 1s.\(^5\) This situation is probably to be expected, because assuming such signals exist in AGN at equivalent frequencies (i.e. scaled by black hole mass) and powers to those seen in BHXRBs, only very long (weeks) and continuous observations would be likely to detect them.
2.2. The RXTE era

The prospect of a direct analogy between AGN and BHXRB X-ray variability led a number of researchers\(^6,13,14\) to show how the X-ray PSD might be used to estimate the black hole mass of the AGN, by simply scaling from the PSDs of BHXRBs (for example the well-studied Cyg X-1) and assuming a BHXRB black hole mass of \(\sim 10 \, M_\odot\). However, without actual confirmation of the PSD break time-scales in AGN, it was impossible to tell if the variability time-scales really did scale with black hole mass, or indeed if AGN variability really is similar to that of BHXRBs\(^*\)).

The situation changed with the launch of RXTE and the first high-quality AGN X-ray monitoring campaigns (see Fig. 1), which sampled a broad range of time-scales. One notable aspect of the long-time-scale data is that, although the variability amplitudes of AGN with different luminosities are very different on short time-scales, they are similar on long time-scales (e.g. compare NGC 4051 with the 100 times more luminous NGC 5548 in Fig. 1), as would be expected if there is a PSD break at a time-scale which scales with the mass.\(^16\)

Within a few years, sufficient long-term monitoring data was available to confirm the existence of PSD breaks.\(^17\)–\(^21\)

Detailed analyses, using Monte Carlo methods to robustly constrain the PSD shape (e.g. accounting for ‘aliasing’ effects), were able to show that the PSD appeared to break from an index \(-2\) to index \(-1\) and not \(0\), implying that the breaks are more likely to be analogous to the high-frequency breaks in the PSD of Cyg X-1 (in either the low or high state), and that the break time-scales were consistent with a linear scaling of characteristic time-scales with black hole mass.\(^19\),\(^20\)

Several AGN show PSD breaks at high enough frequencies that they are detectable in XMM-Newton long-look observations.\(^22\)–\(^24\) The time-scales of these breaks are too short for these AGN to be analogues of low-state BHXRBs, since the inferred low masses (estimated by scaling from the low-state PSD break in Cyg X-1) would imply super-Eddington accretion rates, inconsistent with the low accretion rate thought to

\(^*\) It is worth noting here than BHXRBs show a wide variety of variability properties, with different PSD shapes (and energy spectra) depending on the ‘state’ of the BHXRB.\(^15\) For example, the low/hard state PSD is characterised by two breaks, a high frequency break (where PSD index changes from \(-2\) to \(-1\)) around 1-6 Hz, and a low frequency break around \(0.1\) Hz (where PSD index changes from \(-1\) to \(0\)). The high/soft state PSD on the other hand shows only a single break (from index \(-2\) to \(-1\)) at around 10 Hz. Therefore, when estimating black hole mass using PSDs it is important to know which BHXRB state (if any) we are comparing with.
be associated with the low state. One possible explanation is that these AGN show PSDs which are analogous to the PSDs of BHXRBs in the high/soft state, which show higher break frequencies than in the low/hard state. However, the best way to distinguish the low and high-state PSD shapes is to look at even lower frequencies where - in the low state - we expect to see a second break to zero slope, about a decade below the high-frequency break. The best quality AGN PSD yet obtained is that of the NLS1 NGC 4051, which is reproduced here in Fig. 2, plotted for comparison with Cyg X-1 as frequency $\times$ power so that a flat top corresponds to an index of -1. Clearly there is no low-frequency break and the PSD looks much more similar to that of Cyg X-1 in the high/soft state. By scaling the PSD break time-scale seen for NGC 4051 with the equivalent break time-scale in Cyg X-1, we estimate a low black hole mass of $3 \times 10^5$ M$_\odot$, consistent with that obtained by reverberation mapping. Fig. 2 also shows the PSD of the broad-line Seyfert NGC 3516, which shows a break at longer time-scales, as one would expect given the larger black hole mass of this AGN from reverberation mapping. Because of the lower break frequency the PSD frequency coverage does not extend far enough to rule out a low/hard state PSD in this case, however there is tantalising evidence of a low state PSD in another broad line Seyfert, NGC 3783. Interestingly, a comparison of break time-scales with black hole masses estimated by various means (Fig. 3) is suggestive that the NLS1s tend to have shorter time-scales for their mass, which are consistent with high/soft state PSDs, or more generally implies that there is a decrease in variability time-scale with increasing accretion rate. If we assume that broad line Seyferts have different accretion rates as a class to NLS1s, the difference in PSD break time-scales could help explain why NLS1s do not conform to the variability amplitude-luminosity correlation observed in broad line Seyferts.

2.3. Physical implications

The fact that the broadband PSDs of AGN measured by RXTE can be described as singly broken or more gently bending continua suggests that the long-term variability is a continuation of the same red-noise process seen on shorter time-scales. More importantly, the fact that AGN X-ray variability appears analogous to that of BHXRBs suggests that the same physical mechanism is at work in generating the variability, regardless of black hole size. Furthermore, the fact that PSD break time-scales are consistent with a linear scaling with black hole mass (assuming the same accretion state) implies a similar mass-dependent scaling in the characteristic time-scales of the underlying process.

The similarities in AGN and BHXRB variability extend beyond the shape of the PSD. Both types of source show a strong linear correlation between the rms amplitude of variability and the X-ray flux, which implies that the variability process is non-linear. Both BHXRBs and AGN also show time-scale dependent lags between hard and soft X-ray bands (with lags of similar magnitude and direction), and a similar energy-dependence of PSD shape above the break frequency, with flatter PSDs at harder energies. These analogies further suggest that clues to the origin of X-ray variability in AGN can be gained by studying the
variability of BHXRBs, for which the timing data is more diverse, of higher quality and the phenomenological understanding of the variability is more advanced. For example, the various properties of the rms-flux relation observed in BH and neutron star XRBs strongly suggest that the variability originates in the accretion flow itself and is not caused by, e.g. coronal flares (although the rate or amplitude of such flares may be modulated by the accretion flow variations).\cite{34,35} Models where the variability is due to propagating variations in the accretion flow can also help to explain the energy dependent timing properties of BHXRBs\cite{36} and AGN.\cite{22,24} Finally, it is amusing to note that the existence of the PSD breaks observed in AGN provides indirect evidence for black holes in these objects. This is because XRBs which are thought to contain neutron stars do not show such breaks (their PSD slopes remain as $\sim -1$ to high frequencies), but black hole candidates do.\cite{37} Therefore by analogy, if we believe that the BHXRBs are aptly named, we should also believe that black holes power AGN!

§3. Optical variability and the Optical/X-ray relation

3.1. A confusing picture

For many years, most of our knowledge about the variability of radio-quiet AGN was learned from the optical band. These advances came largely thanks to the dedicated efforts of teams of observers using ground-based telescopes, primarily to monitor the variability of various permitted optical emission lines and their response to
continuum variations, in an effort to ‘reverberation map’ the line emitting regions of AGN and so also determine their masses.\cite{38,39} A useful byproduct of these campaigns is a wealth of data on continuum variability stretching back many years. Not surprisingly, this variability also appears to be red-noise, but on short time-scales the amplitude of variability is much smaller than seen in the X-rays. The optical continuum emission in AGN is thought to come primarily from the thermal emission of the accretion disk,\cite{40} with longer wavelength emission mainly originating from larger radii where the disk is cooler. However, the simultaneous nature of optical and UV variations (with minimal lag) led to suggestions that the variable optical/UV emission is driven by X-ray reprocessing in the disk,\cite{41} causing the shorter-time-scale X-ray variations to be ‘washed out’ in the optical by light travel-time effects. This mechanism for optical variability can be simply tested by searching for correlated optical and X-ray variability. Before RXTE, efforts to search for optical/X-ray correlations were compromised by the difficulty of obtaining good quality X-ray monitoring to match that in the optical, although hints of an optical/X-ray correlation were observed.\cite{42,43} Interesting progress was made with short-time-scale variability, with optical and X-ray monitoring of NGC 4051 showing negligible optical variability during large-amplitude X-ray variations, ruling out an origin of X-rays and optical photons from the same electron population.\cite{44}

The launch of RXTE allowed much better data to be obtained, and accordingly the situation immediately became more confusing. First, month-long IUE and RXTE monitoring of NGC 7469 showed no correlation between continuum flux variations in UV and X-ray bands, although the X-ray spectral index does appear to correlate with the UV flux, suggestive of Compton cooling by the UV photons.\cite{45,46} However, NGC 3516 showed no such correlation, with optical and X-ray variations that appear to be unrelated on both short and long time-scales.\cite{47,48} Intensive optical and X-ray monitoring of NGC 4051, has finally revealed correlated X-ray and optical variability in this source on long and short time-scales, although the optical variability remains surprisingly weak compared to the X-rays (few % fractional rms versus > 50%).\cite{25,49,50} In contrast to these results, the best optical/X-ray correlation observed in an AGN so far is seen in NGC 5548, which shows strong and highly correlated variability in both bands on time-scales of months and longer.\cite{51} The difference in optical variability amplitudes between NGC 5548 and NGC 4051 is highlighted in Fig. 4. Despite
both AGN showing strong long-term X-ray variability, only NGC 5548 shows strong optical variability. In fact, on long time-scales, the optical variability amplitude of NGC 5548 is even larger than the amplitude of X-ray variability, which seems to rule out models where optical variability is due solely to reprocessing in the disk. This is because in these models the amplitude of optical variability should be smaller than the amplitude of X-ray variability, because reprocessed optical emission would be diluted by the emission from viscous dissipation in the reprocessing disk.

3.2. Explaining the complex optical/X-ray behaviour

This complicated picture of optical variability in AGN might be explained if we consider the different origin of the optical emission compared to the X-ray emission. The X-rays are presumably produced in optically thin material close to the central black hole, at similar relative radii (i.e. in Schwarzschild radii, $R_S$) in different AGN, i.e. irrespective of the black hole mass (as is implied by the similar X-ray timing behaviour of AGN and BHXRBs, despite the huge difference in mass). However, if the optical emission originates from optically thick material (mainly via viscous dissipation but probably also through reprocessing), we expect the relative radius of the optical emitting region to depend on the black hole mass, because disk temperature is thought to scale as $mass^{-1/4}$. In AGN with lower BH mass and higher accretion rate (in terms of the Eddington rate), such as NGC 4051, most optical emission will originate relatively far from the central black hole (>few hundred $R_S$), due to the relatively high disk temperature in these objects. In contrast, higher mass and lower accretion rate AGN, such as NGC 5548 will possess lower temperature disks and so their optical emission will originate from closer to the central black hole, and closer to the X-ray emitting region. If the inner disk is also less stable than the outer disk, it is perhaps not surprising that we see strongly variable optical emission in NGC 5548 which is well correlated with X-rays, but we see only weakly varying optical emission in NGC 4051. The situation is likely to be complicated by the effects of reprocessing and Compton cooling, so that a combination of these effects could produce the range of different optical/X-ray relations that are observed. For example, in NGC 4051 the XMM-Newton monitoring suggests that the optical band lags the X-rays by $\sim 0.14$ days,$^{50}$ whereas longer term monitoring suggests that on longer time-scales the optical leads by 2 days.$^{25}$ This intriguing result may suggest that different processes produce the optical variations on different time-scales.

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