The relation between optical and X-ray variability in Seyfert galaxies

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Abstract. Studying simultaneous optical and X-ray light curves of radio-quiet AGN can help to probe the relationship between very different physical components - the cool, optically thick disk and hot, optically thin corona. Here, we review the relationship between optical and X-ray variability in Seyfert galaxies, which due to observing constraints was difficult to study for many years, but was given a huge boost with the launch of the RXTE satellite in 1995. We summarise the diverse results of several monitoring campaigns, which pose a challenge for standard theories relating optical and X-ray variability, with sources showing either correlated optical and X-ray flux variations, correlated optical flux and X-ray spectral variations, or no correlation at all. We discuss possible explanations for these results, some of which may be explained using a more standard AGN picture, while others may require additional components, such as the 2-phase accretion flows suggested to explain black hole X-ray binary behaviour.

1. Introduction

Temporal variability of emission across the electromagnetic spectrum is a key characteristic of all AGN. In Seyfert galaxies and radio-quiet quasars, different components - optically thin corona and optically thick disk - are thought to produce the continuum emission in X-ray and optical/UV wavebands respectively\(^1\). Studying the relation between variability in these different bands can provide important clues about how the disk and coronal emission are connected, and help answer the key question of what causes the variability in the first place.

It has been known for many years that variability is strongest and most rapid at the highest energies, in the X-ray band and above (e.g. see McHardy, these proceedings), and light-travel-time arguments then imply that the X-rays originate close to the central black hole, where most of the accretion energy is liberated. Therefore, if the central engine also drives variability in other wavebands, we might expect a correlation of some sort between X-ray and optical emission. For example, the X-rays might be reprocessed into optical photons by heating the disk \((\text{Krolik et al. 1991})\). Alternatively, if optical photons provide the source of ‘seed’ photons for the X-ray Comptonisation process, the X-ray variability may track the optical variability. In either case, a correlation between X-ray and optical variations would be expected, perhaps with measurable time-

\(^1\)Since the optical and UV emission are thought to originate from the same optically thick blackbody component, we will refer to them interchangably when discussing variability.
lags which indicate which is the driving continuum band. Even if the optical and X-ray emitting regions are physically separate, a common variability mechanism might lead to correlated optical/X-ray variability, for example if underlying accretion rate variations drive the variability in both bands.

Perhaps surprisingly, it was not until the last decade of the last century, some twenty years after the dawn of X-ray astronomy, that observations of simultaneous optical/X-ray variability started to be made. The difficulty in obtaining these observations lay primarily with the inflexible scheduling of X-ray satellites, which are generally not designed to carry out multiple, well-sampled monitoring observations required to study simultaneous optical/X-ray variability. Furthermore, until recently, the difficulty of scheduling large ground-based monitoring campaigns has made organising multiwavelength monitoring campaigns an almost heroic task - as a glance at the lengths of author lists of early papers in the subject will testify! However, the situation improved in December 1995 with the launch of the Rossi X-ray Timing Explorer (RXTE), which has a rapid pointing capability and a scheduling ethos that allows well-sampled X-ray monitoring campaigns to run parallel with long-term optical monitoring for weeks or even years. In this review I will consider the results of the last decade or so of simultaneous X-ray/optical monitoring campaigns of Seyfert galaxies, obtained prior to RXTE and in the RXTE era, which reveal a surprisingly complex picture of the relation between optical and X-ray variability in Seyfert galaxies.

2. Before RXTE

A seminal paper studying the relation between optical and X-ray variability was published by [Done et al. (1990)] who, over the course of two nights, used simultaneous optical photometric observations and X-ray observations with the Japanese Ginga satellite to monitor the simultaneous optical/X-ray variability of the Narrow Line Seyfert 1 galaxy NGC 4051. The campaign revealed the physically interesting, if disappointing, result that the X-rays varied significantly (by more than a factor 2) while the optical emission did not appear to vary at all (to within photometric 1% accuracy). This result primarily showed that the optical and X-ray continua didn’t originate from the same component, e.g. the same population of synchrotron-emitting electrons. But the fact that the optical emission was much less variable than the X-ray emission could still be reconciled with reprocessing models if the reprocessor in NGC 4051 was very large (e.g. light-days), so that light travel time effects dilute the variability, or if only a small fraction of the optical emission is due to reprocessed X-rays (as might be expected if internal heating in the disk dominates over the external heating by X-rays).

Although Seyferts show very weak optical variability on time-scales of days or less, on longer time-scales the amplitude of variability increases, as had been demonstrated since the first AGN optical monitoring campaigns began several decades ago\(^2\). Therefore, it was realised that longer-term monitoring in both optical and X-ray wavebands would provide a better probe of the relation be-

\(^2\)Many of them at the Crimean Astrophysical Observatory where this meeting was held
tween the two bands than observations over just a few days. However, the
difficulty with scheduling X-ray monitoring observations limited the number of
such campaigns, which were primarily accomplished using ROSAT to monitor
the variability in the soft X-ray band. The results of these campaigns were sug-
gestive of an optical/X-ray correlation on time-scales of weeks to months in the
Seyfert 1 galaxies NGC 5548 (Clavel et al. 1992) and NGC 4151 (Edelson et al.
1996). However, since both correlations were dependent on only one ‘event’ (a
rise or fall) in the light curve, it couldn’t be proven conclusively that the light
curves were really correlated, or if the observed correlations were an artefact
of the ‘red-noise’ nature of the variability. Clearly, longer simultaneous light
curves were needed, covering time-scales of years.

3. The RXTE era

With the launch of RXTE, it became possible to obtain well-sampled X-ray
light curves of AGN covering a very broad range of time-scales. Many such
light curves have been obtained by campaigns to measure the broadband X-ray
power spectra of Seyfert galaxies, e.g. Uttley, McHardy & Papadakis (2002);
Markowitz et al. (2003) and see McHardy, these proceedings. Fortunately a
number of Seyfert galaxies with X-ray monitoring have also been observed by
various optical monitoring campaigns, revealing clearly the relations between
long-term optical and X-ray variability for the first time. The picture revealed
by these campaigns is diverse, and we concentrate here on several case studies
of specific AGN, which reveal the range of behaviour observed in the multiwave-
length campaigns carried out so far.

3.1. NGC 7469

The first extensive multiwavelength monitoring campaign in the RXTE era was
carried out in 1996, with a month-long RXTE campaign to monitor the Seyfert 1
galaxy NGC 7469, simultaneous with UV observations by the International Ul-
traviolet Explorer (IUE) (Nandra et al. 1998). The surprising result of this
campaign was that the X-ray flux was not correlated with the variable UV flux
in any obvious way (Nandra et al. 1998). However, a subsequent X-ray spec-
tral analysis of the X-ray data suggested that the X-ray continuum slope and
the UV flux were correlated (Nandra et al. 2000, and see Fig. 1). The reality of
this correlation between X-ray spectral properties and UV flux was subsequently
confirmed using Monte Carlo simulations by Petrucci et al. (2004).

At first glance, the correlation between X-ray spectral slope and UV flux
might be explained if the UV luminosity dominates that of the corona, and
UV variability drives the X-ray variations through Comptonisation, with the
increases in UV flux acting to cool the X-ray emitting corona, steepening the

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3Red-noise light curves show temporally-correlated variability, i.e. one data point is correlated
with the next in the time series, and so normal cross-correlation statistics, which assume
temporally-uncorrelated data, cannot be used to estimate the significance of a correlation
between light curves in two energy bands. Either an extensive data set must be obtained,
much longer than time-scales present in the light curve (usually impossible with AGN), or
Monte-Carlo simulations should be performed.
resulting X-ray spectrum. However, in that case, if the UV flux simply increases, one should expect correlated increases in X-ray flux (as well as spectral steepening), which are not observed. Instead, Petrucci et al. (2004) explained the data in terms of a model where the coronal power is dominant and X-rays drive UV variations through reprocessing, requiring almost all of the UV flux to be produced by X-ray heating (i.e. internal heating is negligible). However, their model also suggested that the X-ray (and resulting UV) variations are primarily driven by changes in the geometry of the X-ray source, thus changing the fraction of UV photons that are Comptonised and hence cool the corona.

3.2. NGC 4051

NGC 4051 which, as Done et al. (1990) showed, does not vary significantly in the optical on time-scales of hours, has been monitored extensively with RXTE since it was launched (see M. Hardy, these proceedings, and M. Hardy et al. 2004). Long-term optical monitoring by the International AGN Watch during the first three years of the RXTE campaign showed significant but weak (< 10% fractional rms) variability on long time-scales, which none-the-less appeared to be correlated with the much greater amplitude (> 60% fractional rms) long-term X-ray variability (Peterson et al. 2000).

On shorter time-scales, a 1.5 day observation using the Optical Monitor (OM) on board XMM-Newton revealed correlated UV/X-ray variability, with a fractional rms of a few per cent and the smooth near-UV flux variations appearing to lag the rapid, large-amplitude X-ray variations by about 0.2 days.
The data could be simply explained if the UV variations were caused by reprocessing of X-rays in a ring ∼ 0.14 light-days from the X-ray source - similar to the radius where near-UV emission is expected to peak in a standard accretion disk around a ∼ 10^6 M☉ black hole (which is close to the black hole mass estimated from reverberation mapping, [Peterson et al. 2000]). The small amplitude of variability would suggest that rather constant internal heating dominates the near-UV emission in this case.

However, the story for NGC 4051 may not be so simple, as daily optical monitoring, together with intensive RXTE monitoring suggested correlated variability, but with optical variations leading X-rays by an average of about 2 days ([Shemmer et al. 2003]). This result does not conflict with the XMM-Newton result however, which probes shorter time-scales. Therefore, it is possible that there are multiple time delays in the response of optical/UV to X-ray variability and vice versa, with a simple reprocessed component of optical/UV variability on short time-scales, but some other component which leads X-ray variability on longer time-scales (e.g. due to propagation of accretion flow variations from the cooler, outer disk to the inner X-ray emitting regions).

### 3.3. NGC 3516

The Seyfert 1 NGC 3516 was monitored for 5 years by RXTE and in the optical at the Wise Observatory. Although an initial analysis of the first two years worth of data showed tantalising evidence of a ∼ 100 day lag of X-rays to optical ([Maoz et al. 2000]), the subsequent 3 years of observations showed no evidence for any correlation at any lag ([Maoz et al. 2002, and see Fig. 2]), suggesting that the claimed correlation was due to low event statistics. [Maoz et al. 2002] also showed that, unlike NGC 7469, NGC 3516 showed no evidence for any correlation of X-ray spectral slope with optical flux, leaving the puzzling situation of no apparent connection at all between optical and X-ray variability. Furthermore, no obvious relationship between the optical/UV and X-ray bands was seen in variations on time-scales of a day or less (using simultaneous HST, ASCA and RXTE data, [Edelson et al. 2000]). We note that there do appear to be monotonic trends in the same direction in both optical and X-ray long term light curves, which could be suggestive of a correlation on very long time-scales, but this could easily be due to chance.

### 3.4. NGC 5548

Arguably the best long-term simultaneous optical and X-ray light curves have been obtained for the Seyfert 1 NGC 5548, with 6 years of overlapping data from the RXTE and AGN Watch monitoring campaigns. These data showed the

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4 Presumably [Done et al. 1990] did not see these short-term variations because their observations only lasted a few hours at a time, and occured at longer wavelengths where variability amplitudes may be weaker.

5 It is worth noting here that the combination of detections of correlated optical/X-ray variability in different data sets for NGC 4051 makes the correlation extremely strong in this source, with the result that lags measured are quite robust, since only a single, well-sampled event is needed in two light curves to measure an accurate lag, assuming the correlation is real.
strongest correlation yet observed between optical and X-ray variations (confirming the earlier suggestion of a correlation by Clavel et al. 1992), with no measurable lag down to time-scales of a few weeks (see Uttley et al. 2003, and Fig. 3). On short time-scales (up to a few weeks), the X-rays are significantly more variable than the optical band - this appears to be a general trend in all Seyfert galaxies monitored so far - although it isn’t possible to say if the X-rays are still correlated with the optical on these short time-scales in NGC 5548 (so we can’t be sure we are dealing with the same component).

Interestingly however, the amplitude of optical variability in NGC 5548 is similar to the amplitude of X-ray variability on longer time-scales of years, and when the contamination due to host galaxy starlight is subtracted, the amplitude of optical 5100 Å variability is even larger than in X-rays (43% versus 31% respectively). This result seems to rule out the possibility that X-ray reprocessing drives the bulk of the optical variability, because in that case the amplitude of optical variability should be at least equal to or less than the amplitude of X-ray variability, as the optical variations due to reprocessing might be diluted by emission due to internal heating. Since the UV band varies even more than the optical (Gilbert & Peterson 2003), the problem is even worse for reprocessing, although a possible (if ad hoc) explanation could be that we do not see the same X-ray variations that the reprocessor sees, e.g. due to anisotropic X-ray emission.

Figure 2. NGC 3516 normalised R-band optical and 2-10 keV X-ray light curves (data taken from Maoz et al. 2002).
Figure 3. Comparison of optical and X-ray light curves of NGC 5548 and NGC 4051. The light curves have been binned up in 30 day bins, in order to smooth out the rapid X-ray variability. In NGC 5548 the amplitude of optical variability is quite large compared to X-rays, whereas in NGC 4051 the optical variability amplitude is much smaller than in X-rays, even when accounting for the galaxy-bulge starlight contamination, which contributes less than half of the optical flux (e.g. [Done et al. 1990]).

4. Putting the puzzle together

The relations between optical and X-ray variability observed in Seyfert galaxies present us with a puzzling picture. Even though the sample observed so far is rather limited, it is already clear that there are a variety of different behaviours. The four case studies presented here are also representative of the types of behaviour seen in a few other Seyfert galaxies with simultaneous optical/X-ray observations, which we have not detailed here. Broadly speaking, we can discern three types of behaviour:

1. **Correlated optical and X-ray flux variability.** NGC 5548 and NGC 4051 fall into this category, as does the NLS1 Ark 564 [Shemmer et al. 2001]. In all cases X-rays vary strongly, but we find both weak optical variability (in NGC 4051 and Ark 564) and strong optical variability (in NGC 5548).

2. **Correlated optical/UV flux and X-ray spectral variability.** NGC 7469 does not show an obvious correlation between UV and 2-10 keV X-ray flux variations, but does show a correlation between UV flux variations and changes in X-ray spectral slope. This type of correlation is probably not so common in Seyfert galaxies, as it implies no strong correlation...
between X-ray spectral slope and 2-10 keV flux (otherwise the X-ray flux would be well-correlated with UV). Most Seyferts seem to show a strong correlation between spectral slope and 2-10 keV flux however (e.g. Markowitz, Edelson & Vaughan [2003]).

3. Uncorrelated optical and X-ray variability: NGC 3516 shows no obvious correlation between optical and X-ray flux variations, on either short or long time-scales, or between optical flux variations and X-ray spectral variations. This behaviour stands in sharp contrast to that of NGC 5548.

The first class of behaviour, correlated flux variability, is what was originally anticipated, and fits into a picture where the optical and X-ray variations are closely related, either through heating of the disk by X-rays, or Comptonisation of the optical seed photons so that X-rays track the optical variations. What is perhaps surprising is that the optical variability of NLS1, such as NGC 4051 and Ark 564, is so weak compared to their X-ray variations, whereas the amplitude of optical variability of NGC 5548 is large, and is even greater than the X-ray variability amplitude, at least on long time-scales. A similar picture, of rather weak optical variability in NLS1 is also presented by Klimek, Gaskell & Hedrick (2004) (and see Gaskell, these proceedings).

However, this discrepancy might also be understood in terms of the ‘standard’ picture of AGN. Fig. 4 demonstrates some of the possible ways that optical variations and X-ray variations might be interconnected. The kinds of interaction we expect are likely to be strongly governed by the disk temperature: in
hotter disks, the optical emitting region is likely to come from many gravitational radii (e.g. \( > 1000 \, R_G \) in NGC 4051) from the central region where most of the accretion energy is liberated (and where the X-ray emission likely originates). Thus the main connection between X-ray and optical variations is likely to be reprocessing, by X-ray heating of the optical-emitting disk at large radii (although we also expect a correlation which has longer lags in the opposite direction, due to the propagation of variations in the accretion flow as suggested by Shemmer et al. 2003). For the expected geometry, the optical emitting region will subtend only a small fraction of the sky as seen from the X-ray source, so it is likely that constant (at least at large radii) internal heating will dominate the optical band, diluting the variability amplitude. In cooler disks, the optical/UV emission will originate much closer to the X-ray emitting region (and may be embedded within it), opening the way for other interactions, such as optical/UV variations (e.g. due to accretion instabilities in the inner disk) driving X-ray variations via Comptonisation.

The disk temperature is expected to be a function of black hole mass, \( M_{\text{BH}} \), and accretion rate (\( \dot{m} \) in Eddington units), scaling as \( T \propto (\dot{m}/M_{\text{BH}})^{\frac{1}{4}} \), according to standard disk theory. Since the emerging consensus is that NLS1 have relatively low black hole masses and are accreting at high rates (e.g. see reviews by Boller, M’Hardy, these proceedings), it is perhaps not surprising that they show rather weak optical variability. On the other hand, the broad line Seyfert 1 NGC 5548 has a rather high mass (\( \sim 10^8 \, M_\odot \), Peterson et al. 2002) and low accretion rate, so its optical and X-ray emitting regions may be co-spatial, in which case the larger amplitude of optical variability compared to X-rays may be because the optical is directly driving the X-ray variations through Comptonisation.

The other types of optical/X-ray relation, shown by NGC 7469 and NGC 3516, are more difficult to explain in the standard picture. Petrucci et al. (2004) have suggested geometrical changes in the X-ray source as an explanation of the UV/X-ray-slope correlation (and lack of UV/X-ray-flux correlation) in NGC 7469. In NGC 3516, the lack of any correlation is even more puzzling, and raises the possibility that the X-ray source and optical source are somehow not ‘aware’ of each other’s variations, for example if the X-ray emission is anisotropic (e.g. see discussion by Gaskell, these proceedings).

Since other contributions at this meeting have demonstrated the importance of the analogy with black hole X-ray binaries (BHXRBs) in understanding AGN behaviour (e.g. Uttley, M’Hardy, elsewhere in these proceedings), it might be fruitful to look to BHXRBs for clues to the origin of different optical/X-ray relations. In BHXRBs, the thermal disk emission is mainly seen in the X-rays, due to the much higher disk temperatures (\( kT \sim 1 \, \text{keV} \)) than in AGN. In the disk-dominated ‘high/soft’ state, the disk X-ray emission is remarkably stable (e.g. Churazov, Gilfanov & Revnivtsev 2001), and this result immediately suggests an intriguing difference with AGN, perhaps because the inner disks of AGN are subject to instabilities that are important at lower temperatures, e.g. due to Hydrogen ionisation (Burderi, King & Szuszkiewicz 1998). But on long time-scales, BHXRBs show evidence for state transitions, where the strength of the corona and disk emission change on different time-scales, suggesting two different accretion flows, a hot coronal flow, with short variability time-scales, and a slower
optically thick flow, i.e. the standard disk (Churazov, Gilfanov & Revnivtsev 2001). It is interesting to speculate whether the relative strengths of these components could play a role in the different types of X-ray/optical relation. For example, if optical and X-ray variations originate in two different accretion flows, with shorter variability time-scales (at a given radius) in the hot X-ray flow, then the optical and X-ray variations we see on similar time-scales in NGC 3516 may originate from two very different radii and hence be unconnected for that reason. Such a situation might occur in AGN where the energy release in optical and X-ray emitting flows is evenly balanced, so neither dominates the variability in the other band (e.g. through reprocessing or Comptonisation).

Much progress has already been made, simply by observing a few objects. However, in order to make further progress in disentangling the complex connections between optical and X-ray emission components in AGN, simultaneous optical/X-ray monitoring of a larger sample (including quasars) is required, which covers a wide range of black hole mass and accretion rate. The new generation of robotic or queue-scheduled optical telescopes will help to facilitate such campaigns, but a continued, more sensitive X-ray monitoring capability is urgently needed to pick up the reins from RXTE when it reaches the end of its remarkably productive life.

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