Correlated long-term optical and X-ray variations in NGC 5548

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ABSTRACT

We combine the long-term optical light curve of the Seyfert 1 galaxy NGC 5548 with the X-ray light curve measured by the Rossi X-ray Timing Explorer over 6 years, to determine the relationship between the optical and X-ray continua. The X-ray light curve is strongly correlated with the optical light curve on long (∼year) time-scales. The amplitude of the long-term optical variability in NGC 5548 is larger than that of the X-ray variability (after accounting for the host galaxy contribution), implying that X-ray reprocessing is not the main source of the optical/X-ray correlation. The correlated X-ray and optical variations in NGC 5548 may be caused by instabilities in the inner part of the accretion flow, where both the X-ray and optical emission regions may be located.

Subject headings: galaxies:active — galaxies: individual (NGC 5548) — galaxies: Seyfert — X-rays: galaxies

1. Introduction

It is commonly supposed that the X-ray and optical emission in Seyfert 1 galaxies is produced by different, but possibly related physical processes. The X-rays are thought to be produced by Comptonization of lower energy ‘seed photons’ by a hot optically thin corona, while optical photons arise as thermal emission from the cooler, optically thick accretion disk. The relationship between flux variations in the optical and X-ray band can be used to probe...
the relationship between the X-ray and optical emitting regions. Optical/X-ray correlations might be produced if the emitting regions are somehow connected, e.g. if variable optical emission is caused by X-rays heating the disk, or if the optical photons are the seed photons in the X-ray Comptonization process. On the other hand, if the emitting regions are physically separated, we might expect to see no correlation between optical and X-ray variations.

The current picture regarding correlated optical/X-ray variability in AGN is ambiguous. In early work on the optical/X-ray correlation in NGC 4051, Done et al. (1990) showed there was very little optical variability (< 1%) on time-scales of days, and no apparent correlation with the much larger amplitude X-ray variability, although a possible short-term UV/X-ray correlation in this source has been recently reported by Mason et al. (2002). Also, using long-term optical and X-ray monitoring observations of NGC 4051, Peterson et al. (2000) suggested that the optical and X-ray light curves were correlated on time-scales of months-years. Early, sparsely-sampled monitoring suggested a correlation between ultraviolet and X-ray variations in NGC 5548 (Clavel et al. 1992) and NGC 4151 (Edelson et al. 1996). A possible 100 day X-ray-to-optical lag in NGC 3516, based on ~ 1.5 yr duration optical and X-ray monitoring lightcurves (Maoz et al. 2000), was not confirmed with further monitoring over an additional 3.5 yr (Maoz et al. 2002). An intensive 3 day observation of NGC 3516 found no correlation between optical (HST) and X-ray variations (Edelson et al. 2000). Intensive X-ray and IUE monitoring of NGC 7469 showed no correlation between X-ray and UV flux (Nandra et al. 1998), but there does appear to be a correlation between UV flux and X-ray energy spectral index (Nandra et al. 2000). In Ark 564, a possible weak optical/X-ray correlation (based on a single flaring event) was observed (Shemmer et al. 2001). In general, the amplitude of optical variations in AGN appears to be less than that of X-ray variations, especially on short time-scales (Peterson et al. 2000; Shemmer et al. 2001; Maoz et al. 2002).

In this Letter, we re-examine the optical-X-ray correlation in NGC 5548, combining 6 years of Rossi X-ray Timing Explorer (RXTE) monitoring observations with the corresponding optical light curve from the International AGN Watch monitoring campaign.

2. Observations and data reduction

For 13 years, from late 1988 until the end of 2001, NGC 5548 was monitored in the optical band by the International AGN Watch in order to reverberation map its broad line region (Korista et al. 1995; Peterson et al. 2002). Since 1996 May, NGC 5548 has been monitored in X-rays by the Rossi X-ray Timing Explorer (RXTE), using sampling intervals ranging from 8 times daily to every two weeks, primarily to measure its X-ray variability power spectrum (Uttley, McHardy & Papadakis 2002; Markowitz et al. 2002).
We obtained the latest optical 5100 Å continuum flux light curve from the International AGN Watch public archive\(^4\). Note that all light curves from the International AGN Watch are corrected for aperture effects which might otherwise lead to spurious variability, e.g. due to varying host galaxy starlight contamination (see Peterson et al. 2002 for calibration details). We used data from the PCA instrument on board RXTE, reduced in the standard manner and with model background data generated using the latest background models and the FTOOLS v5.0 software (see Lamer, Uttley & McHardy 2000, for details). Changes in the instrument gain throughout the lifetime of the RXTE mission mean that it is not straightforward to simply compare instrument photon count rates in a given band. Therefore, for each RXTE monitoring observation (which are snapshots of length \(\sim 300 - 1000\) s), we extracted a spectrum and fitted a simple power-law plus 6.4 keV Gaussian model to determine the flux in the 2–10 keV band. Note that for the purposes of measuring the correlation between the light curves, neither the optical or X-ray light curves are corrected for the contaminating contributions due to host-galaxy starlight (\(3.4 \times 10^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) at 5100 Å accounting for \(\sim 34\%\) of the mean total 5100 Å flux, Romanishin et al. 1995) or the presence of a BL Lac object in the RXTE PCA field of view (\(\sim 10\%\) of observed flux or \(6 \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\), extrapolated from data in Chiang et al. 2000). Clearly the constant contribution from starlight will not affect any correlation, while the additional X-ray variability due to the BL Lac will act to reduce any correlation that we see, rather than produce a spurious correlation.

3. Light Curves and Cross-correlation Function

The optical 5100 Å and X-ray 2-10 keV light curves are shown in Figure 1. On short time-scales (days), the X-rays show more rapid variations than the optical light curve. But despite this difference, and the relatively sparse X-ray sampling throughout the first half of the RXTE campaign, an apparent correlation of the long-time-scale X-ray and optical variations can be discerned. To show this correlation more clearly, we smooth out the short time-scale variations by binning both light curves into 30 d bins, and plot the resulting light curves, renormalized by their respective means, in Figure 2. The correlation extends not just to the general rising then falling trend of the light curve, but also to variations on shorter time-scales.

We confirm the apparent strong correlation between the X-ray and optical light curves by measuring the cross-correlation function (CCF) of the 30-d binned light curves (see Fig-

\(^4\)available at URL http://www.astronomy.ohio-state.edu/~agnwatch/.
ure 3), using the Discrete Correlation Function (DCF) method of Edelson & Krolik (1998). The peak value, $r_{\text{max}}$ of the 30-d binned lightcurve’s CCF, at zero lag, is $r_{\text{max}} = 0.95$, compared to $r_{\text{max}} = 0.85$ observed in the CCF of the unbinned lightcurves. Using the Flux Randomization/Random Subset Selection (FR/RSS) method of Peterson et al. (1998), with both binned and unbinned light curves, we find the lag of the CCF peak is consistent with 0 ± 15 d (1-σ error).

Unfortunately, we cannot assess the significance of this correlation directly from $r_{\text{max}}$, since that assumes that individual data points in each light curve are uncorrelated with adjacent points, when in fact they are correlated, ‘red-noise’ data. Thus, the effective number of data points in the correlation, and hence its significance, is reduced by an amount which depends on the sampling pattern and power-spectral shape of both light curves, and cannot be determined analytically. We therefore test the significance of the correlation using Monte-Carlo simulations of uncorrelated red-noise light curves. We used the method of Timmer & König (1995) to simulate $10^4$ pairs of continuous red-noise light curves (one for each band) of time resolution 0.1 d, assuming appropriate power spectral shapes and normalization for each band. Each simulated light curve was resampled to the sampling pattern of the corresponding observed light curve and observational noise added, in the form of a Gaussian deviate with mean zero and standard deviation equal to the average error of the observed light curve. We then rebinned the simulated, resampled light curves to the same 30 d bins as used in our real analysis, measured the CCF using the DCF method, and counted the number of simulated CCFs containing peak values $r_{\text{max}} > 0.95$. When searching for peaks in the plausible lag range of ±200 d, peak CCF values with $r_{\text{max}} > 0.95$ were observed in zero out of $10^4$ simulations. We conclude that the observed long-term correlation between the optical continuum and X-ray bands in NGC 5548 is significant at better than 99.99% confidence.

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5We assumed a broken power-law shape power spectrum, with high-frequency slopes of -1.6 and -2.5 in X-ray and optical bands respectively and identical slopes of -1 in both bands below a break frequency of $\nu < 0.01$ d$^{-1}$, as implied by scaling to the power spectra of black hole X-ray binaries (Uttley, McHardy & Papadakis 2002) and assuming a $\sim 10^8$ M$_{\odot}$ black-hole mass estimated from reverberation mapping (Wandel, Peterson & Malkan 1999). The high-frequency power-spectral slopes and assumed normalization are the best-fits to the data assuming this break frequency and low-frequency shape (see Uttley, McHardy & Papadakis (2002) for details of the power-spectral fitting procedure).
4. Amplitudes of variability

As is apparent in Figure 2, the amplitude of variations in both bands is comparable on long-time-scales (>months). In fact, when one subtracts the estimated contaminating contributions in the X-ray and optical bands from BL Lac object and host-galaxy starlight respectively, one finds that the optical 30 d binned light curve is more variable than the 30 d binned X-ray light curve (fractional rms variability $F_{\text{var}} = 43 \pm 0.2\%$ versus $31 \pm 0.1\%$ respectively, where errors are statistical errors due to observational noise only). This result is particularly robust, since even assuming the 68% confidence lower limit on optical contamination from the host galaxy ($2.83 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, Romanishin et al. 1995 and references therein), any constant, contaminating component in the X-ray lightcurve would have to contribute $\sim 29\%$ of the observed X-ray flux, simply for the underlying X-ray variability amplitude to match that in the optical band. Note that the BL Lac contribution to the X-ray lightcurve is likely to be only 10% of the total flux, and is not constant (Chiang et al. 2000), so it may in fact contribute to the observed X-ray variability, rather than simply reducing its fractional amplitude. The unbinned lightcurves (Figure 1) show that, on short time-scales (<30 d) the amplitude of X-ray variations is larger than the amplitude of optical variations, contributing $\sim 10\%$ of the total rms variability in the X-ray band, as opposed to $\sim 2\%$ contributed by short-time-scale variations in the optical band. This result is also implied by the X-ray power spectrum being flatter than the optical power spectrum at high frequencies (e.g. Uttley et al. 2002, Collier & Peterson 2001).

5. Discussion

We have shown that the long-term X-ray and optical continuum light curves of NGC 5548 are both highly variable and highly correlated. This result contrasts with the situation so far observed in other AGN, where X-ray and optical/UV lightcurves are either not very well correlated (e.g. Nandra et al. 1998, Shemmer et al. 2001, Maoz et al. 2002), or a long-term optical/X-ray correlation is seen but the optical lightcurves are only weakly variable compared to the X-ray lightcurves (NGC 4051, Peterson et al. 2000). Note also that although the absolute time-scales (months-years) for correlated optical/X-ray variability in NGC 5548 are similar to those observed in NGC 4051, the relative time-scales (in terms of characteristic time-scales of the system) are much shorter, since NGC 5548 has a factor $\sim 100$ larger black hole mass than NGC 4051 (Wandel, Peterson & Malkan 1999).

It is possible that the X-ray/optical production mechanisms in NGC 5548 are physically different to those in other AGN. Perhaps the optical variability in NGC 5548 is driven by X-ray reprocessing, whereas other processes are dominant in other AGN. However, the large
amplitude of optical variability poses problems for the reprocessing model. One would expect that any reprocessed emission would exist \textit{in addition to} a non-reprocessed component due to intrinsic thermal emission from the disk, so that the amplitude of long-term optical variability should be less than the amplitude of X-ray variations. In contrast, we see that on long time-scales, the optical variations in NGC 5548 are larger than the X-ray variations. The problem for reprocessing models is further compounded by the spectral variability in the optical and X-ray bands. Specifically, the X-ray spectrum softens as the 2-10 keV flux increases (Chiang et al. 2000), so that the broadband X-ray luminosity probably varies less than the 2-10 keV variations we observe here. At the same time, the UV continuum is strongly correlated with and even more variable than the optical (with $F_{\text{UV}} \propto F_{\text{opt}}^{1.8}$, Peterson et al. 2002), so that the total optical/UV luminosity is even more variable than the 5100Å continuum lightcurve we show here. In defence of reprocessing models, one could invoke a large variable component available for reprocessing in the hidden EUV band which may itself be Comptonized thermal emission (Magdziarz et al. 1998). However, the response of the H$\beta$ emission line to changes in the optical/UV continuum is consistent with photoionization calculations, which assume the ionizing (EUV) continuum simply tracks the UV continuum (Gilbert & Peterson 2002). Therefore it is unlikely that the EUV continuum is much more variable than the UV.

Assuming the standard disk-corona model for the continuum emission in AGN, it is almost certain that at least some component of the optical variability is associated with X-ray reprocessing. However, an additional component is probably required to explain the high amplitude of optical variability in NGC 5548. The simplest possibility is that both X-ray and optical variations are tracking some other, more fundamental variations in the accretion flow, for example thermal instabilities in the inner disk (Treves, Maraschi & Abramowicz 1988). Provided that the X-ray and optical emission regions are close together, such variations could lead to correlated X-ray variability, e.g. through optical seed photon variations modulating X-rays directly (as suggested by the correlated X-ray spectral and UV variability seen in NGC 7469, Nandra et al. 2000), or through simple viscous heating in the disk correlating with coronal heating by magnetic reconnection. The additional short-term X-ray variability may be caused by additional variability processes in the X-ray emitting region (e.g. magnetic reconnection) or by the X-rays being relatively more concentrated towards the centre of the accretion flow, where variability time-scales are shorter.

It is apparent that, in this picture, the relation between optical and X-ray variability in an AGN should depend on the location of the optical emitting region relative to the X-ray emitting region. Comparisons of the X-ray variability power spectra of AGN and black hole X-ray binaries are consistent with the interpretation that, in units of Schwarzschild radii ($R_s$), the size of the X-ray emitting region is independent of black hole mass (Uttley, M’Hardy & Papadakis 2002; Markowitz et al. 2002). However, since the disk temperature
is dependent on the black hole mass and accretion rate, with AGN with lower mass black
holes or higher accretion rates having higher disk temperatures, the region of peak optical
emission should occur at larger radii (in $R_S$ units) in these AGN. It follows that in AGN
with lower black hole mass and/or higher accretion rate, the optical emitting region exists
further from the X-ray emitting region, where variability time-scales are longer than the
inner regions and/or the disk may be more stable, so that the optical emission varies less
than the X-ray emission and may also respond to variations which the X-ray emitting region
does not even see (and vice versa).

We illustrate this simple physical picture by considering the emission from a standard
thin disk. At each small increment of disk radius, we assume local black body emission
with a temperature determined assuming the radial temperature dependence of a thin disk
(Frank, King & Raine 1992):

$$ T = 3.53 \times 10^7 \left( \frac{\dot{m}}{\eta M_{BH} R^3} \right)^{\frac{1}{4}} \text{ K} \quad (1) $$

where $\dot{m}$ is the specific accretion rate, i.e. mass accretion rate expressed as a fraction of
the Eddington rate, $\eta$ is the efficiency of accretion (here we assume the canonical value of
$\eta = 6\%$ for accretion on to a non-rotating black hole, e.g. Frank et al. 1992), $M_{BH}$ is the
black hole mass in solar mass units, and $R$ is the radius in terms of Schwarzschild radii. By
integrating the derived flux at 5100Å over a range of radii, we determine where most of the
5100Å emission originates. Assuming a black hole mass in NGC 5548 of $\sim 10^8 M_\odot$ (from
reverberation mapping, Wandel et al. 1999), and accretion rate $\dot{m} \sim 0.01$ (Wandel, Peterson
& Malkan 1999), we find that 50% of the 5100Å emission is contained within 42 $R_S$ of the
central black hole. Given the relatively rapid X-ray variability, it is likely that most of the
X-ray emission originates within this radius. Assuming a viscosity parameter $\alpha = 0.1$, the
corresponding thermal time-scale at this radius is $\sim 280$ d (Treves, Maraschi & Abramowicz
1988), consistent with the timescales of variability we observe here. By contrast, in NGC 4051
if we assume $M_{BH} \sim 10^6 M_\odot$ and $\dot{m} \sim 0.1$ (Wandel, Peterson & Malkan 1999), we find that
only 4% of the 5100Å continuum flux is emitted within $R = 42 R_S$. Similarly, in NGC 3516
($M_{BH} \sim 2 \times 10^7 M_\odot$, Onken et al. 2002, and $\dot{m} \sim 0.1$), only 14% of the 5100Å emission
originates within $R = 42 R_S$. The precise numbers we quote here should be taken very lightly,
since the optical continuum of NGC 5548 likely consists of a Comptonized component, in
addition to the black body emission we assume here (Magdziarz et al. 1998). Furthermore,
the thin disk model we use is almost certainly too naive, as it does not account for, e.g.
dissipation of accretion power in a corona (Svensson & Zdziarski 1994), or the possibility
that the inner disks of the higher $\dot{m}$ AGN may in fact be geometrically thick. However,
regardless of the details of the model, it is reasonable to assume that high mass, low $\dot{m}$
AGN such as NGC 5548 should have lower temperature disks and hence more centrally-
concentrated optical emitting regions (i.e. closer to the X-ray emitting region) than low mass, high ˙m AGN. This difference may help to explain the confusing range of optical/X-ray correlations seen in Seyfert galaxies so far.

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REFERENCES


AAS LaTeX macros v5.0.
Fig. 1.— Long-term optical 5100Å (top) and X-ray 2-10 keV (bottom) light curves of NGC 5548, in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and erg s$^{-1}$ cm$^{-2}$ respectively. The constant level of contamination due to host-galaxy starlight (see Section 2) has not been subtracted from the optical lightcurve, but is shown for information purposes as a dashed line.
Fig. 2.— Binned-up long-term optical 5100Å (open squares) and X-ray 2-10 keV (filled squares) light curves of NGC 5548. Bin time is 30 d and the light curves have been renormalized by their respective means. The constant level of contamination due to host-galaxy starlight (see Section 2) has not been subtracted from the optical lightcurve.
Fig. 3.— Cross-correlation function of optical and X-ray light curves. Note: the error bars on the correlation are shown for convention purposes only. For red-noise light curves, standard errors in CCFs are correlated and do not have the usual, formal meaning.