Explaining the Moderate UV/X-Ray Correlation in AGN

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Received 2022 September 6; revised 2022 November 10; accepted 2022 November 11; published 2022 December 13

Abstract

The UV/optical and X-ray variability of active galactic nuclei (AGN) have long been expected to be well correlated as a result of the X-ray illumination of the accretion disk. Recent monitoring campaigns of nearby AGN, however, found that their X-ray and UV/optical emission are only moderately correlated, challenging the aforementioned paradigm. In this work, we aim to demonstrate that due to the definition of the cross-correlation function, a low UV/X-ray correlation is well expected in the case of an X-ray illuminated accretion disk, when the dynamic variability of the X-ray source is taken into account. In particular, we examine how the variability of the geometric or physical configuration of the X-ray source affects the expected correlation. Variations of the geometric configuration are found to produce a range of UV/X-ray cross correlations, which match well the observed values, while they result in a high correlation between the UV and optical variability, reconciling the observed results with theoretical predictions. We conclude that the detection of a low UV/X-ray correlation does not contradict the assumption of the UV/optical variability being driven by the X-ray illumination of the disk, and we discuss the implications of our results for correlation studies.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Seyfert galaxies (1447)

1. Introduction

The small spatial size of active galactic nuclei (AGN) makes it unfeasible to image their inner region directly with current instruments. As a result, several methods have been developed to indirectly probe these regions. A popular and very successful technique, termed the “reverberation mapping”, lies in studying the relation between the flux variability of two emissions that are physically connected (Blandford & McKee 1982). This method has been used to probe a range of structures in AGN, from the dusty torus to the innermost X-ray source (see Cackett et al. 2021, for a recent review).

Recently, a number of long monitoring campaigns were performed to apply the above method in mapping the accretion disk by probing the relation between the X-ray and UV/optical variability. Multiwavelength observations with subdaily cadence made it possible for the first time to study the disk variability on short timescales. For instance, Edelson et al. (2015) explored the UV/optical variability of the typical Seyfert galaxy NGC 5548 and were able to accurately constrain the interband time lags between the various wavebands.

Following the analysis of NGC 5548, several more AGN were monitored by disk reverberation mapping campaigns (e.g., McHardy et al. 2018; Edelson et al. 2019; Cackett et al. 2020; Hernández Santisteban et al. 2020). In general, all the conducted studies reached the same conclusions about the connection between the UV/optical and X-ray variability. Namely, (i) the observed time lags increase with wavelength following roughly the relation $\tau \propto \lambda^{4/3}$, (ii) the absolute value of the time lags is larger than expected by a factor of around 3, and (iii) the X-rays are not that well correlated with the UV/optical variability (see Table 1 for a compilation of observed cross-correlation functions, CCFs).

Taken at face value, the latter finding seems to contradict the long-standing assumption that the X-ray source illuminates the accretion disk, which drives the observed UV/optical variability. This led several authors to explore alternative mechanisms that could explain the observed variability (e.g., Sun et al. 2020).

Moreover, it was suggested that the observed UV/optical light curves cannot be the result of disk X-ray illumination, given the observed X-ray light curve (e.g., Starkey et al. 2017; Gardner & Done 2017). However, it should be noted that previous studies assumed a static configuration of the system, while contrary, recent advanced investigations of high-quality data found evidence of a dynamic X-ray source (Caballero-Garcia et al. 2020; Alston et al. 2020; Panagiotou et al. 2022).

Here, we examine how the dynamic variability of the X-ray source affects the resulted UV/optical light curves and explore whether this dynamic variability can account for the moderate correlation between the X-ray and UV/optical variability of AGN. In particular, we will demonstrate that the limiting assumptions and the definition of CCF lead naturally to low correlation values when the configuration of the X-ray source is not static. We present the motivation of our work in Section 2. Section 3 presents the results of our analysis, which are further discussed in Section 4.

2. Motivation

The X-ray light curve of AGN is undoubtedly variable on all timescales, from minutes to months and years (e.g., Lawrence et al. 1987; Markowitz et al. 2003; McHardy et al. 2004). On short timescales, the X-ray emission is typically found to be considerably more variable than the UV/optical emission (e.g., Uttley et al. 2003; Edelson et al. 2019), which implies that the short-term X-ray variability is not caused by variations in the flux of the disk seed photons. It is, thus, reasonable to attribute this short-term variability to fast variations of the physical state...


Table 1

| Source   | Reference | UVW2/X-ray $\beta_{\text{max}}$ | UVW2/B $\beta_{\text{max}}$ |
|----------|-----------|---------------------------------|-----------------------------|
| Mrk 509  | E19       | 0.63                            | 0.98                        |
| NGC 5548 | E19       | 0.39                            | 0.97                        |
| NGC 4515 | E19       | 0.68                            | 0.90                        |
| NGC 4593 | E19       | 0.69                            | 0.85                        |
| Mrk 142  | C20       | 0.54                            | 0.80                        |
| Fairall 9| HS20      | 0.59                            | 0.79                        |

Note. The values were retrieved from E19 (Edelson et al. 2019), C20 (Cackett et al. 2020), and HS20 (Hernández Santisteban et al. 2020).

(e.g., electron density or energy) or the geometry of the X-ray source.

This simple consideration reveals that the inner region of AGN does not correspond to a static configuration, which as we shall illustrate below, significantly affects the variability studies of these sources. In particular, it is customary to investigate the connection between the UV/optical variability of AGN and their X-ray variability by estimating the corresponding CCF, defined as:

$$ CCF(\tau) = \frac{E \{ [F_X(t) - \mu_X][F_X(t + \tau) - \mu_X] \}}{\sigma_X \sigma_X} $$ (1)

where $E$ denotes the expectation operator, $\tau$ is the so-called time lag, $F_X$ denotes the X-ray flux, $\mu_X$, $\sigma_X$ denote the mean and standard deviation of the corresponding light curves, respectively.

The cross correlation quantifies the degree of similarity between the variability of the two light curves, that is, the extent to which the two time series deviate from their average values in a similar fashion for a given $\tau$. It has, therefore, been reasonably expected that the X-ray/UV CCF of AGN should be large if their UV/optical variability is driven by the X-ray illumination of the disk. However, defined in the above way, the detection of a large CCF depends on the assumption that the time delay $\tau$ between the two variable fluxes remains the same for the whole duration of the considered light curves. If this is not the case, namely, if the variability of the X-ray emission leads that of the disk emission by different time values in different parts of the light curves, then the time lag $\tau_{\text{max}}$ that maximizes the CCF would most likely be representative of the average time delay, but it is unclear whether the maximum value of CCF would still be large in this case.

Kammoun et al. (2021a) performed a systematic investigation of the accretion disk reprocessed emission when illuminated by X-rays. Specifically, they computed the expected time lags for different physical properties of the AGN and they showed that different configurations of the X-ray source, as parameterized by its position and its X-ray spectrum, result in significantly distinct values for the predicted lag. Combining this result with the discussion of the previous paragraph, it is tempting to argue that the low UV/X-ray cross correlation detected in the recent literature may simply be due to the variability of the X-ray source’s physical properties. In other words, the detection of a low correlation may be explained by the use of the CCF notion and the lack of a single time lag value between the UV/optical and X-ray variability over the full observation period, which is expected in the case of a dynamic X-ray source. In this work, we proceed to test this idea.

Let us assume the illumination of the accretion disk by a central X-ray source. In the case of a steady-state system, the disk emission at wavelength $\lambda$ is given by

$$ F_X(t) = F_{NTX}(\lambda) + \int_{0}^{\infty} \psi_{\lambda}(t') \cdot F_X(t - t')dt', $$ (2)

where $F_{NTX}(\lambda)$ denotes the (constant) disk emission in the absence of X-ray illumination (Novikov & Thorne 1973) and $\psi_{\lambda}$ is the so-called response function, which remains constant in time under the assumption of a steady system. In the case of a dynamic system, though, $\psi_{\lambda}$ is no more constant and Equation (2) is not valid. Then, the disk emission may be estimated by the generalization of the above equation:

$$ F_X(t) = F_{NTX}(\lambda) + \sum_{i=0}^{N-1} \int_{t_i}^{t_{i+1}} \psi_{\lambda,i}(t') \cdot F_X(t - t')dt', $$ (3)

where $t_0 = 0$ and $t_N = \infty$. In this equation, it is assumed that the source configuration, and hence the response function, remains constant within the time interval $(t_i, t_{i+1})$, while $N$ can be arbitrarily large.

Equation (3) shows that the connection between the disk and X-ray emission becomes nontrivial in a dynamic system. In fact, the observed disk emission will depend strongly on variations of the physical or geometric state of the X-ray source, even if these do not modify significantly the X-ray flux.

We explored whether the variations of the physical state or the geometry of the X-ray source can account for a low CCF as follows.

3. Simulations Setup and Results

We used the newest version of the KYNXILREV code (Dovčiak et al. 2022) to compute the disk response function following the same approach presented in detail by Kammoun et al. (2021a). In brief, a lamp post geometry is assumed for the X-ray source, the emission of which follows a power-law distribution with a high-energy cutoff, fixed at $E_C = 300$ keV. We also assumed a black hole mass of $M_{BH} = 5 \cdot 10^7 M_\odot$, an accretion rate of $\dot{m} = 0.05 \dot{m}_{\text{Edd}}$, an X-ray corona power $L_X = 0.35L_{\text{acc}}$, where $L_{\text{acc}}$ stands for the total accretion power, a dimensionless black hole spin $a = 0.5$, a color correction factor of 1, and a source inclination of $\theta = 45^\circ$. It should be stressed that the results of our analysis do not depend on the aforementioned assumed values.

We computed two sets of responses, one for different values of the X-ray source height above the black hole, $h_X$, with the height ranging from 5 to 30 $R_g$ with a step of 1 $R_g$, and one set for different values of the photon index, $\Gamma_X$, which ranged from $5^\circ$ for simplicity, it is assumed that the X-ray corona power remains constant in time since variations of $L_X$ do not modify remarkably the resulted disk light curve (see the discussion in Appendix A of Kammoun et al. 2021a).

6 The gravitational radius, $R_g$, is defined as $R_g = \frac{GM}{c^2}$. 

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5 In practice, CCF is computed using the notion of the interpolated CCF (Gaskell & Sparke 1986; Peterson et al. 2004) or of the discrete CCF (Edelson & Krolik 1988) to account for unevenly sampled light curves.

4 It should be noted that the definition of CCF in Equation (1) assumes that both the X-ray and UV/optical light curves are stationary, which leads to the assumption of a constant $\tau$ outlined in the text. Recent studies of high-quality light curves, though, found evidence against the assumption of stationarity (Caballero-Garcia et al. 2020; Panagiotou et al. 2020; Alston et al. 2020), which may further affect the results of cross-correlation studies.
We chose to follow a rather conservative approach and divide the light curve into only 10 intervals of 15 days each, although the properties of the X-ray source may well vary on even shorter timescales as well. In any case, our choice is sufficient to probe the idea outlined in Section 2 and we expect our qualitative results to remain rather unchanged for different choices of bins.

Having estimated the three light curves, we then compute the CCF between the X-rays and the UVW2 flux and the CCF between the UVW2 and the B flux and we record their maximum values, $R_{XW2}$ and $R_{W2B}$, respectively. The CCFs are calculated using the PyCCF code (Peterson et al. 1998; Sun et al. 2018a). The first 5.7 days of the X-ray light curve are excluded in the CCF computation, as the UV/optical light curves cannot be estimated accurately in this early period due to the temporal width of the response.

The above is repeated 300 times. In each repetition, a new X-ray light curve is simulated (using the same PSD shape) and new heights for the different time intervals are randomly selected. The whole process is then repeated 300 times more with the different time intervals corresponding now to different values for the photon index. In the end, we have obtained a sample of maximum CCF values expected in the case of a variable X-ray source height and a sample of maximum CCF values expected in the case of a variable X-ray spectrum.

Figures 2 and 3 plot the histogram of $R_{XW2}$ for a variable $h_X$ and $\Gamma_X$, respectively. Clearly, the variations of height have a significant impact on the obtained value of $R_{XW2}$, which ranges from 0.2 to 1 with a preference for values between 0.45 and 0.8. In fact, a variable $h_X$ leads to $R_{XW2}$ values that seem to agree well with the observed cross correlation stated in Table 1.

On the contrary, the values of $R_{XW2}$ resulted from a variable $\Gamma_X$ are consistently larger, with most of them lying at $R_{XW2} > 0.75$. This suggests that variations in the X-ray spectrum have a lesser effect on the expected cross correlation in comparison to variations of the X-ray source’s geometric configuration. This was intuitively expected because the time lag between the X-ray and disk emission depends more strongly on the height than the photon index (see, for example, Figures 18 and 19 of Kammoun et al. 2021a and therefore, following the reasoning of Section 2, height variations will modify more profoundly $R_{XW2}$. In any case, our analysis suggests that spectral variations of the X-ray emission alone cannot account for the low cross-correlation values obtained in observational studies.

Figure 4 shows the histogram of the UVW2/B cross correlation when the height varies. The two light curves are very well correlated with $R_{W2B}$ being always larger than 0.9. Hence, the assumption of a variable height seems to reproduce

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7 The gravitational time, $t_g$, is defined as $t_g = \frac{r_g}{c}$.

8 We chose to follow a rather conservative approach and divide the light curve into only 10 intervals of 15 days each, although the properties of the X-ray source may well vary on even shorter timescales as well. In any case, our choice is sufficient to probe the idea outlined in Section 2 and we expect our qualitative results to remain rather unchanged for different choices of bins.
The observed results of a low X-ray/UV cross correlation and a large UV/optical correlation. It should be pointed out though that the simulation-based $R_{W2B}$ are slightly larger than the observed values, which might be due to the simple nature of our simulations as will be further discussed in the following section.

Furthermore, we explored how our results are modified when we divide the X-ray light curve in different numbers of bins of static configuration, from 5 up to 15, and we found that they remain qualitatively the same. For example, in the case of a variable height, $R_{XW2}$ obtains a range of values, from 0.2 to around 1, regardless of the used bin number. As may be expected intuitively, the average value of the $R_{XW2}$ distribution is larger when using a smaller number of bins, but its scatter is always large and consistent with the observed values. Therefore, we deduce that our results do not depend strongly on the used number of bins. This also highlights that the value of CCF cannot be used to accurately retrieve the dynamic variability of the source.

4. Discussion

The main goal of the present study was to examine whether a low cross correlation between the X-ray and UV/optical emission of AGN is consistent with the assumption that the X-ray illumination of the disk drives the observed UV/optical variability. Our study was motivated by the limiting assumptions of the definition of CCF, which are very likely not met in the case of AGN light curves. To that end, we decided to probe the expected CCF in the case of a dynamic X-ray source, as it is physically unlikely for the X-ray source to have a steady-state configuration (see, for example, Panagiotou et al. 2022, for recent observational evidence of a variable $h_X$). In particular, we simulated the cases of a variable source height and of a variable photon index. It is worth highlighting at this point that the height variations correspond mostly to variations of the solid angle subtended by the disk, which is the main change we expect when the geometric configuration of the source varies. On the other hand, variations of the photon index serve as a proxy for variations in the physical state, such as the particle density and energy, of the X-ray source. Therefore, we expect our main conclusions to be applicable regardless of the exact geometry and production mechanism of the X-ray source.

Our analysis shows that moderate variability of $h_X$ at a rather slow pace produces a range of X-ray/UV cross-correlation values, which match well the observations, while at the same time the UV/optical cross correlation remains large, similarly to the results of recent monitoring campaigns. This is a direct consequence of Equation (3), which illustrates that the disk emission at any wavelength responds to both the variability of the X-ray emission and the variability of the X-ray source’s physical properties. Thus, when the latter is important, the X-ray and disk emission may not be strongly correlated, while
the disk emission at different wavelengths will always be so. This is due to the nature of the CCF statistic.

Undoubtedly, our simulations do not capture the full complexity expected in AGN. For instance, we naturally expect more than a single property of the X-ray source to vary at a time, with these variations being perplexed and not well structured, as we assumed. It also stands to reason that these variations should to some extent be connected to the X-ray light curve. Moreover, our analysis did not consider any variations should to some extent be connected to the X-ray structured, as we assumed. It also stands to reason that these at a time, with these variations being perplexed and not well expected more than a single property of the X-ray source to vary complexity expected in AGN. For instance, we naturally This is due to the nature of the CCF statistic.

The Astrophysical Journal, explored how our results change when dynamic variability of the X-ray source can be explained in the case of a dynamically variable X-ray scope of the present work, it is worth noticing that such a trend Although a detailed reproduction of this result is outside the assumption of a dynamic X-ray source, Equation (3) dictates that an accurate reproduction of the disk emission requires the knowledge of the source’s state at any given time, which is of course not known a priori. Instead, we suggest that the X-ray/ disk connection should be studied by performing a time-resolved broadband spectroscopy. Such an approach would also constrain the variability of the X-ray source physical properties at different timescales. Further insight into the dynamic variability of the X-ray source may also be obtained by Fourier-resolved studies; for instance, by examining the coherence or the time lag between the X-ray and UV variability at different temporal frequencies.

Moreover, Sun et al. (2018b) noted that the UV/X-ray CCF in the case of NGC 5548 seems to vary between two consecutive periods, with the cross-correlation coefficient decreasing from $\rho_{\text{max}} = 0.62$ in one period to $\rho_{\text{max}} = 0.36$. Although a detailed reproduction of this result is outside the scope of the present work, it is worth noticing that such a trend can be explained in the case of a dynamically variable X-ray source, if, for example, the properties of the X-ray source vary differently in the two periods.

Finally, it is interesting to note that the variability of the X-ray source configuration offers an appealing way to reconcile seemingly contradictory results of the source physical properties in the literature. For instance, values that range from as low as $5 R_g$ to larger than $100 R_g$ have been reported for the height of the X-ray source in the case of NGC 5548 (Brenneman et al. 2012; Emmanoulopoulos et al. 2014; Kammoun et al. 2021b). While this discrepancy may be due to the different approaches followed by the various studies, it can also be well explained if we assume an intrinsically variable height since the aforementioned studies have used observations of different duration, taken at different time epochs.

C.P. acknowledges financial support from the Swiss National Science Foundation (SNF), project number P2GE2P_200053. E.K. acknowledges support from NASA grant No. 80NSSC22K1120, and is supported by the Sagol Weizmann-MIT Bridge Program. M.D. acknowledges the Czech MEYS grant No. LTAUSA17095 that supports international collaboration in relativistic astrophysics, the Czech Science Foundation grant No. 21-06825X and the institutional support from RVO:67985815.

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9 It is worth mentioning that in addition to the analysis of Section 3, we also explored how our results change when $b_\text{w}$ varies according to the bin-averaged X-ray flux instead of randomly. Preliminary investigations suggest that a positive correlation between the height and the X-ray flux would result to higher than typically observed values for $R_{\text{w}}$, while an anticorrelation leads to similarly low values as in the case of random height variations.