THE FLUX-DEPENDENT RMS VARIABILITY OF X-RAY BINARIES IN THE OPTICAL

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ABSTRACT

A linear relation between absolute rms variability and flux in X-ray observations of compact accreting sources has recently been identified. Such a relation suggests that X-ray light curves are nonlinear and composed of a lognormal distribution of fluxes. Here, a first investigation of the optical rms versus flux behavior in X-ray binaries is presented. Fast timing data on three binaries in the X-ray low/hard state are examined. These are XTE J1118+480, GX 339–4, and SWIFT J1753.5–0129—all show aperiodic (nonreprocessed) optical fluctuation components. Optical rms amplitudes is found to increase with flux in all sources. A linear fit results in a positive offset along the flux axis, for most frequency ranges investigated. The X-ray and optical relation slopes track the source fractional variability amplitudes. This is especially clear in the case of GX 339–4, which has the largest optical variance of the three targets. Nonlinearity is supported in all cases by the fact that flux distributions of the optical light curves are better described with a lognormal function than a simple Gaussian. Significant scatter around linearity is found in the relation for the two sources with lower optical variability amplitude, though observational biases may well contribute to this. Implications for accretion models are discussed, and the need for long well sampled optical light curves is emphasized.

Key words: accretion, accretion disks – black hole physics – stars: individual (XTE J1118+480, GX339-4, Swift J1753.5–0127) – X-rays: binaries

1. INTRODUCTION

Several recent works have shown that the X-ray timing characteristics of accreting sources including Galactic black hole candidates, neutron stars, and as active galactic nuclei follow a linear relationship between their rms variation and average flux over a wide range of timescales (e.g., Uttley & McHardy 2001, hereafter U01; Uttley 2004; Gleissner et al. 2004, hereafter G04). Such a relation suggests nonstationarity of the light curves; specifically, the level of instantaneous variance in a light curve is not constant, but is rather linked to longer-term flux averages. Uttley et al. (2005) (hereafter U05) point out that these properties imply a lognormal distribution of instantaneous flare strength. This, in turn, can be explained if the variations are composed not by a superposition of independent shots, but instead are the result of accretion rate fluctuations operating at every location in the accreting flow of matter. These fluctuations propagate inward through the flow, effectively coupling perturbations at all inner radii. Interestingly, a similar “rms–flux relation” has been shown to apply in other sources as well, for instance in a narrow-line Seyfert galaxy (Gaskell 2004) and in solar coronal X-ray and radio flares (Zhang 2007; Wang et al. 2008). The relation thus seems to provide strong constraints on the fluctuating conditions of hot plasmas universally.

In this Letter, a first investigation of the rms versus flux behavior of X-ray binaries (XRBs) in the optical is presented. The presence of fast, aperiodic optical activity in some accreting sources has been known since very early days (e.g., Motch et al. 1982). Recent work has found intriguing correlations between the X-ray and optical variations in at least three XRBs: XTE J1118+480 (Kanbach et al. 2001), GX 339–4 (Gandhi et al. 2008), and SWIFT J1753.5–0129 (Durant et al. 2008). The main driver of the rapid optical variability remains unclear, but several pieces of evidence disfavor an origin as reprocessing of, or irradiation by, primary higher-energy photons. Instead, it is likely that both the optical and X-ray rapidly variable components share some common underlying cause, with exchange of energy between the components creating the complex interplay of timing patterns observed (cf., Malzac et al. 2004). Studying the optical behavior in the rms–flux plane should provide new clues on the underlying source of variability, independent of commonly used correlation function analyses. The only other investigation of such optical behavior (as far as the author is aware) is for the active galaxy NGC 4151 for which Lyutyi & Oknyanskii (1987) discovered a linear rms–flux relationship in the $U$ band.

2. OBJECTS AND DATA

The sources chosen for this study include all three XRBs known to show direct, accretion-driven rapid variability in the optical. The optical data come from the Skinakas/OPTIMA photometer (Straubmeier et al. 2001) for XTE J1118+480, and from the VLT/ULTRACAM camera (Dhillon et al. 2007) for GX 339–4 and SWIFT J1753.5–0129. They were observed at optical flux levels several magnitudes brighter than in quiescence, so the companion stars contribute negligibly in all cases. The most relevant details including used filter, time resolution, and observation period are listed in Table 1.

The corresponding X-ray data are from the RXTE/PCA detector, observed simultaneously with the optical (but see below). The RXTE ObsID prefixes are 50407 for XTE J1118+480 and 93119 for both the remaining sources, respectively. The counts and background were extracted over 2–44 keV for XTE J1118+480 and over the full PCA energy range for the remaining targets, but the results herein are relatively insensitive to the exact range. Fuller details regarding the X-ray data can be found in the relevant papers cited in the previous section.

The optical and X-ray data used for XTE J1118+480 are strictly simultaneous. For GX 339–4, RXTE monitoring extends a few minutes longer on either side of the optical monitoring; this full 62 minutes long data set is used for better statistics. For SWIFT J1753.5–0129, changeable weather resulted in the...
Table 1

| Source          | UT Date | Telescope/Instrument | \(\Delta \lambda\) (filter) | \(\Delta T\) | \(T\) | \((\chi^2/dof)_{LN}\) | \((\chi^2/dof)_{N}\) |
|-----------------|---------|----------------------|-----------------------------|-------------|------|------------------------|------------------------|
|                 | (1)     | (2)                  | (3)                         | (4)         | (5)  | (6)                    | (7)                    | (8)                    |
| XTE J1118+480   | 2000 Jul 5 | Skinakas 1.3 m/OPTIMA | 4500–9500 (–)               | 3           | 40   | 79.8/63                | 2587.5/64              |
| GX 339–4        | 2007 Jun 18 | VLT/ULTRACAM         | 5500–7000 (r′)              | 50          | 47   | 76.8/38                | 2712.9/39              |
| SWIFT J1753.5–0129 | 2007 Jun 18 | VLT/ULTRACAM         | 5500–7000 (r′)              | 39          | 31   | 28.7/20                | 101.5/21               |

Notes. Column 4 lists the approximate wavelength coverage (and filter name in brackets); in Column 5, \(\Delta T\) refers to the best time resolution available in the optical, in milliseconds; Column 6 lists the approximate full length of the light curves used in the analysis, in minutes. Columns 7 and 8 report the chi-square/degrees of freedom for the lognormal ("LN") and simple normal ("N") histogram fits to the distribution of light-curve fluxes (see Section 5 and Figure 3).

Figure 1. Optical (red) and X-ray (blue) PSDs of each source. The PSDs are normalized so that their integral gives the fractional variance of the light curves over any frequency interval, and are plotted in units of frequency \(\times\) power/Hz so that a horizontal line denotes equal power per unit frequency-decade. The narrow spikes above \(\sim 7\) Hz in the optical PSD of XTE J1118+480 may be a result of telescope vibrations in high wind (Spruit & Kanbach 2002). The optical peaks below 0.1 Hz for the remaining two sources are real (cf. P. Gandhi et al. 2009, in preparation; Durant et al. 2009).

Power spectral densities (PSDs) for the sources in the listed order in Table 1 can be found in Spruit & Kanbach (2002), P. Gandhi et al. (2009, in preparation), and Durant et al. (2009), respectively. These have been recomputed here from averages of long light-curve segments (256 s) of the same data sets used for the rms–flux relation below, and are displayed in Figure 1. The standard \(\text{rms}^2\)-normalization has been used, so that integration over positive frequencies results in the fractional light-curve variance (Belloni & Hasinger 1990).

3. Computing RMS versus Flux

To compute the absolute rms (\(\sigma\)) as a function of flux, I followed the procedure described by G04 (which is largely similar to that described by U01). In short, the light curve for each source was split into many segments of equal length ranging over 1–16 s, depending on the frequency range of interest (see below). The mean source flux in each segment was computed and this distribution was divided into a number of equal-size flux bins \((\bar{F})\). The binning was optimally chosen so that the fraction of bins containing more than an adopted threshold of 20 segments was maximized; only bins above this threshold were retained in the end. The PSD of each segment (\(\text{rms}^2\)-normalized) was computed, as was the expected white
noise level. These two quantities were separately averaged, giving an average PSD in each flux bin as well as an average noise level. Finally, the mean level of the PSD over any particular range of frequencies (Δν) was computed, and white noise subtracted from this. This is the excess (above Poisson) mean fractional variance (√var) in each flux bin, per unit frequency. σ is then simply √varΔν × 〈F〉. Uncertainties on the mean σ value in each bin are computed with usual periodogram statistics (van der Klis 1989) and error propagation.

Amongst the observations analyzed herein, there exists a wide range of source count rates, light-curve sampling (∆T and T values in Table 1) and intrinsic source variability levels (Figure 1). So there is only a restricted selection of frequency ranges which are ideally suited for intercomparison of the rms–flux relation. A base range of 0.5–5 Hz was found to be a good compromise for all sources in both X-rays and optical, also helping us to probe the broadband optical noise continuum free from sharp features (e.g., near ∼7–10 Hz) for XTE J1118+480 and from the low-frequency peaks below 0.1 Hz for the other sources; Figure 1). The rms–flux behavior over this frequency range is plotted for all sources in Figure 2. For more complete comparison, the behavior over two more ranges is also plotted where possible: an appropriate “low” range including frequencies lower than 0.5 Hz, and a “high” range extending beyond 5 Hz. The exact limits of these ranges vary individually according to ∆T, T, and count rate. The high-frequency range for XTE J1118+480 was not computed as it may be affected by telescope vibrations due to wind (Figure 1; Spruit & Kanbach 2002). For SWIFT J1753.5–0129, on the other hand, the total light-curve duration is too short to produce a meaningful fit at low frequencies, while the PSD variance is too low to give enough signal at high frequencies, restricting the analysis to the base frequency range.

4. RESULTS

1. The first important result of Figure 2 is that XRBs do show optical rms increasing with flux over large ranges in frequency. Fitting with the linear parameterization of U01, σ = k(〈F〉−C), the intercept along the flux axis is generally consistent with a positive offset. These results are listed in Table 2.

2. Compared to the X-ray σ–F relation, the optical relation apparently exhibits more deviations around a linear fit,
Table 2

| Source          | Optical | X-ray |
|-----------------|---------|-------|
|                 | low $\bar{F}_O$ | $\sigma_{O,low}$ | high $\bar{F}_X$ | $\sigma_{X,high}$ |
| XTE J1118+480   | 0.11±0.05 | 14.29±1.18 | 0.60 | 0.09±0.01 | 11.41±2.5 | 0.67 | ... | ... | ... |
| GX 339–4        | 0.09±0.04 | ...±0.82±1.13 | 0.87 | 0.23±0.01 | 12.86±1.1 | 0.95 | 0.12±0.01 | 16.52±0.9 | 0.94 |
| SWIFT J1753.5–0127 | ... | ... | ... | ...±0.08±0.01 | 18.59±3.16 | 0.82 | ... | ... | X-ray |

Notes. The slope ($k$) and intercept ($C$) linear fit parameters are stated for three frequency ranges. The first is a “low” range including frequencies below 0.5 Hz (Columns 2 and 3) along with Kendall’s rank correlation coefficient ($\tau$) as a measure of linearity between $\bar{F}$ and $C$ (Column 4). This is followed by the corresponding values for the range of 0.5–5 Hz (Columns 5–7) and a “high” range at greater frequencies (Columns 8–10). See Figure 2 for corresponding plots and details. The fits to the optical are in the first three rows and are denoted by subscript $O$. The corresponding parameters for the X-ray fits are below these, with subscript $X$. The units of $\bar{F}$ are counts s$^{-1}$, with the optical values ($\bar{F}_O$) being normalized to 1000 counts s$^{-1}$ for better legibility. Errors quoted are for $\Delta \chi^2=1$ on each fit parameter.

5. DISCUSSION

A linear-like rms–flux relation is exhibited by XRBs in the optical. The scatter in this relation is apparently larger than in X-rays, but this may well be the result of observational biases.

For instance, the optical data for XTE J1118+480 were observed without any filters over the full optical wavelength range (Table 1). The origin of the variable optical emission from this source remains unclear, with several components including the disk, accretion flow, and jet likely to contribute (e.g., Merloni et al. 2000; Esin et al. 2001; Chaty et al. 2003; Yuan et al. 2005; Reis et al. 2009). This could allow for the emission from distinct components to overlap and introduce significant scatter in any underlying strong correlation. On the other hand, it is to be noted that the X-ray data have lower signal/noise than the optical. So the larger error bars could well be hiding more scatter in X-rays, because the $\tau$ statistic does not account for measurement uncertainties.

Furthermore, optical timing observations are sensitive to prevailing weather conditions. In the case of XTE J1118+480, at least, there is some evidence of the wind contaminating the variability power (Spruit & Kanbach 2002), though only the night least affected by this bias has been chosen here. Finally, the fact that the overall source variability rms levels are much lower in the optical is an important limitation. The impact of this is that the X-ray relations in Figure 2 cover a wider dynamic range on the $x$-axis ($\bar{F}$) and can hence be better determined than the corresponding optical ones.

With these caveats in mind, the detection of a linear rms–flux relation is important because it provides new constraints for any model attempting to explain the underlying mechanism of the rapid variability. Uttley and collaborators have ruled out additive shot and self-organized criticality models, as these are unable to easily reproduce a linear $\sigma \sim \bar{F}$ relation in X-rays over a wide range of timescales. From observations of the accreting neutron star SAX J1808.4–3658 and correlating the source rms with the strength of high-frequency coherent pulsations, Uttley (2004) suggests that the rms–flux relation must originate within the accretion flow itself, and not in independent corona magnetic flares. So-called “propagating perturbation” models are instead favored (Lyubarskii 1997; Misra 2000; King et al. 2004; Titterchuk et al. 2007) in which accretion rate variations at any given radius in the accretion flow propagate toward smaller radii to modulate the radiative energy release in all inner regions. This naturally couples the variability over a wide range of radii (hence, timescales) and results in a flux-dependent rms amplitude. U05 have shown that this also implies that X-ray light curves must be intrinsically nonlinear; specifically, the X-ray flux distribution ought to be a lognormal distribution.

The present work now extends these results to the variable optical flux of XRBs. We can then also test the above hypothesis of nonlinearity by plotting the distribution of optical light-curve data.
fluxes. These are shown in Figure 3 for all three XRBs. In each case, we fit a symmetric Gaussian as well as a three-parameter lognormal model (cf., Equation (3) of U05). The number of flux measurements per bin (N) was required to be at least 50 for the fit, with the bin error assigned as $\sqrt{N}$.

GX 339–4 clearly exhibits a lognormal distribution with a very significant tail and even some apparent excesses above the fit in the highest flux bins. The other sources are also better described as lognormals, though the difference with respect to a simple Gaussian fit is more modest, at least to the eye. The best-fit $\chi^2$ values for all fits are listed in Table 1. For completeness, it is noted that the lognormal count-rate offset parameter ($\tau$ in Equation (3) and Section 4.1 of U05) was found to be nonzero in each case; again, this could be best-constrained in the case of GX 339–4, where it matches the range of values for the rms–flux relation offset ($C_0$).

As mentioned by U05, lognormal fits may not be formally acceptable due to weak nonstationarity of the light curves and other effects; this may explain some of the excess in the $\chi^2$ values. But, as can be inferred from Figure 3, the $\chi^2$ residuals for GX 339–4 are largely dominated by the highest three (aforementioned) flux bins alone. So GX 339–4 is the source with the highest variability (Figure 1), and it displays the tightest rms–flux relation as well as the “most” nonlinearity. Evidence for nonlinearity is present in the other two objects, but is less striking; both exhibit lower broadband noise. This behavior is exactly as predicted by U05, but now applied to the optical light curves.

Whatever the physical mechanism of variable optical emission may be (synchrotron from the base of a jet is one possible source often discussed in the literature), it should be the result of modulations from an ensemble of coupled perturbations. As compared to auto- and cross-correlation function analyses, which are most sensitive to coherent variations with the shortest delays, the rms–flux relation reveals underlying connections over much wider timescales. The new results presented herein are based on only the handful of relatively short optical observations which happened to capture the sources at differing stages of their X-ray low/hard states. For instance, GX 339–4 was observed at the onset of this state with a relatively faint optical counterpart, while XTE J1118+480 was seen in its optically brightest state. The relative fluxes of the various accretion components are bound to change as the sources evolve through their states (e.g., Gandhi et al. 2008, and also the measurement of the X-ray rms–flux relation in several states by G04). Longer light curves at multiple optical and X-ray wavelengths, and in various source states, will greatly aid more precise comparisons.

In the low/hard state, the disk is not the sole contributor to the optical and X-ray fluxes. Hence the coupling of perturbations must span not only many radii, but also various accretion structures, in order for it to be observed in the Comptonized components and the jet (e.g., Done et al. 2007, and references therein). On the other hand, Zhang (2007) stresses the fact that solar flares follow a similar rms–flux relation which, in turn, disfavors propagating perturbation models, because there is no accretion flow in the solar corona. Zhang suggests that a large-scale interconnected magnetic field in which fluctuations are able to rapidly diffuse to all parts of the corona may work instead. More investigation is needed to understand such a model in detail; but in this context, we note that the reservoir model of Malzac et al. (2004) could prove to be consistent with all the observations.

Their study proposes that the strength of the emergent variable power scales in proportion to the total amount of energy stored in some “reservoir.” Though energy injection in their model is parameterized as additive linear shots, a quasi-linear rms–flux relation is predicted in X-rays; this is a consequence of coupling between the fluctuating energy dissipation rates within the jet and corona. A simple modification of the model to include nonlinear shot amplitudes (by taking the exponential of the light curves; cf., U05) will result in a similar relation in the
optical as well. This could be achieved with minimal changes to the resultant optical/X-ray coherence and cross-correlations functions. A good candidate for the reservoir is a large-scale magnetic field. Cumulative buildup and dissipation of energy within the coronal-jet (azimuthal+poloidal) field should result in the coupled modulations required by the rms–flux relation.

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