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Rapid timing studies of black hole binaries in Optical and X-rays: correlated and non-linear variability

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Abstract. In a fast multi-wavelength timing study of black hole X-ray binaries (BHBs), we have discovered correlated optical and X-ray variability in the low/hard state of two sources: GX 339-4 and SWIFT J1753.5-0127. After XTE J1118+480, these are the only BHBs currently known to show rapid (sub-second) aperiodic optical flickering. Our simultaneous VLT/Ultracam and *RXTE* data reveal intriguing patterns with characteristic peaks, dips and lags down to very short timescales. Simple linear reprocessing models can be ruled out as the origin of the rapid, aperiodic optical power in both sources. A magnetic energy release model with fast interactions between the disk, jet and corona can explain the complex correlation patterns. We also show that in both the optical and X-ray light curves, the absolute source variability r.m.s. amplitude linearly increases with flux, and that the flares have a log-normal distribution. The implication is that variability at both wavelengths is not due to local fluctuations alone, but rather arises as a result of coupling of perturbations over a wide range of radii and timescales. These 'optical and X-ray rms-flux relations' thus provide new constraints to connect the outer and inner parts of the accretion flow, and the jet.

Keywords: X-ray binaries, black holes, rapid time variations, optical and x-ray telescopes
PACS: 97.80.Jp, 97.60.-s, 97.60.Lf, 95.55.Cs, 95.55.Ka

INTRODUCTION

X-ray emission is widely accepted as the main driver of the optical fluxes in accreting X-ray binary stellar systems (hereafter, XRBs). Irradiation by a central X-ray source is thought to heat outer portions of the disk (and companion star), resulting in copious optical emission correlated with long-term X-ray variations for a wide variety of systems (e.g. [1]).

But from new multi-wavelength studies, it is becoming increasingly clear that reprocessing does not always dominate the optical flux and its variations. As early as 1981, the Galactic BH candidate GX 339–4 was found to show dramatic optical variability down to tens of milli-seconds [2]. Later results trickled in on several other sources, including V4641 Sgr [3] and GRS 1915+105 (in the infrared; [4]). The first extensively-studied system, though, was XTE J1118+480 [5, 6]. Thereafter, we observed GX 339–4 [7] and

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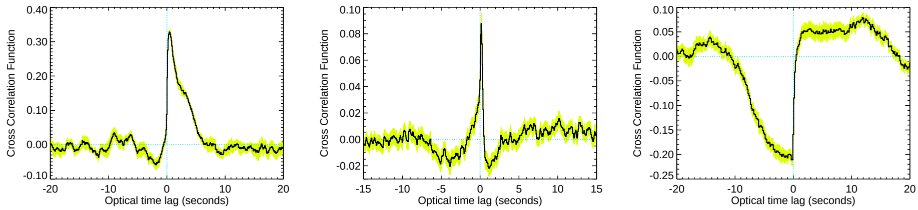

FIGURE 1. Optical vs. X-ray cross-correlations of rapid light curves for XTE J1118+480 (*Left*), GX 339–4 (*Middle*) and Swift J1753.5–0127 (*Right*). These have been recomputed from portions of the original datasets [5, 7, 8], using time bins ∼50–140 ms for inter-comparison, to illustrate the complexity and diversity of behaviour. Shaded region is the mean standard deviation from many light curve segments.

another BH candidate Swift J1753.5–0127 [8] with the rapid imaging camera ULTRACAM [9] mounted on the Very Large Telescope, simultaneously with *RXTE*. All these sources show optical variability on a range of timescales. Several lines of reasoning argue against canonical linear reprocessing (on the disk or donor star) as the origin of the rapidly varying ($\lesssim$1s) component.

EVIDENCE AGAINST REPROCESSING

Rapidity of variations and delays : In all cases, significant variability power is found on sub-second times. The fastest optical flares, though rare, may increase the local flux by factors of a few, within just tens of milli-seconds. For XTE J1118+480 and GX 339–4, a peak optical delay of only ∼30 ms – 1 s is found in the cross-correlation function (CCF) with respect to X-rays, computed with the fastest light curves available [10, 11]. Figure 1 shows some typical CCFs. This delay is stable over several observations, and is too short for typical light travel times to the outer disk or companion star.

Anti-correlated components : A feature common to most CCFs is the presence of broad anti-correlation troughs on times of several seconds at least (again, see Fig. 1), inconsistent with simple reprocessing scenarios.

Short optical average coherence times : In some cases (XTE J1118+480 and GX 339–4), the *auto-correlation* functions (ACFs) of the optical light curves are narrower than the corresponding X-ray ones [5, 7]. As discussed by Kanbach et al. [5], a reprocessed light curve would instead have slower characteristic variations, and so show an ACF broader than that of the driving light curve.

OPTICAL VARIABILITY AMPLITUDE SCALES WITH FLUX

So, what then is the origin of the rapid optical flux variations? The literature is replete with models attempting to explain the properties of XTE J1118+480, usually as cyclosynchrotron emission in a strong magnetic field (e.g. [12, 13, 14, 15, 16]). All agree

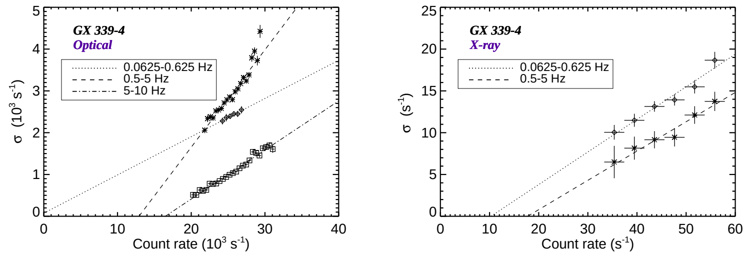

FIGURE 2. Optical (*Left*) and X-ray (*Right*) rms variability amplitudes as a function of flux for GX 339–4, as measured from the individual power spectra over various labelled frequency ranges [20].

that the full spectral+timing characteristics are complicated. Here, we discuss an additional constraint for these models to satisfy.

Uttley and collaborators have shown that the instantaneous X-ray variance (or root-mean-square [rms] amplitude) of XRBs is dependent on the flux measured on longer (averaged) times [17, 18]. Such behaviour is not expected in models of localized, stochastic shot noise energy dissipation, where the magnitude of any given flare is uncorrelated with the overall source flux. Instead, this points to inter-connections all across the accretion flow, and flux variations are a result of 'coupling' of large-scale fluctuations that propagate inwards and perturb inner flares (e.g. [19]). Such a coupling also changes the flux distributions of the light-curves to log-normal, i.e. the light curves show 'non-linear' flaring. Shot noise models would instead prefer a normal distribution,

Gandhi [20] has shown that the *optical* light curves of several XRBs obtained on fast times are also consistent with such an 'rms–flux' relation. By examining the three XRBs of Fig. 1 (all of which show aperiodic optical fluctuations), it was found that in each case, the rms amplitude scales linearly with flux over broad frequency ranges, with a slope depending on the fractional variability power in that range. This is shown in Fig. 2 for the case of GX 339–4. Furthermore, both the optical and X-ray flux distributions are well described by lognormal functions.

The implication is that both the optical and X-ray rapid flaring originate in some process which can link a broad range of radii and timescales in the accreting environment. Low/hard state studies of XRBs point to the co-existence of a jet, a corona and an outer disk. If perturbations do indeed propagate from the outwards in, then the broad frequency range encompassed by the rms–flux relation (e.g. a factor of 100 between the extreme frequencies in Fig. 2) provides excellent evidence of coupling between these various accretion components. Large-scale magnetic field energy dissipation [21] may be one way to accomplish this.

FUTURE PROSPECTS

The few sources in which complex optical/X-ray flux correlations have so far been found were low-mass BH binaries in the low/hard state. A common aspect is a bright optical counterpart in each case, and a low Eddington fraction X-ray luminosity, but these are not particularly unusual. So complex optical/X-ray correlations on rapid times may be quite common in other XRBs. The lack of fast optical instrumentation until recently, and the *expectation* that the optical ought not to be rapidly variable, may have biased prior detection of such components in general. A systematic search in known XRBs will be required to test this.

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REFERENCES

1. J. van Paradijs, and J. E. McClintock, *A&A* **290**, 133–136 (1994).
2. C. Motch, S. A. Ilovaisky, and C. Chevalier, *A&A* **109**, L1–L4 (1982).
3. M. Uemura, T. Kato, R. Ishioka, K. Tanabe, S. Kiyota, B. Monard, R. Stubbings, P. Nelson, T. Richards, C. Bailyn, and R. Santallo, *PASJ* **54**, L79–L82 (2002), `arXiv:astro-ph/0208146`.
4. S. S. Eikenberry, K. Matthews, E. H. Morgan, R. A. Remillard, and R. W. Nelson, *ApJL* **494**, L61+ (1998), `arXiv:astro-ph/9710374`.
5. G. Kanbach, C. Straubmeier, H. C. Spruit, and T. Belloni, *Nature* **414**, 180–182 (2001).
6. R. I. Hynes, C. A. Haswell, W. Cui, C. R. Shrader, K. O'Brien, S. Chaty, D. R. Skillman, J. Patterson, and K. Horne, *MNRAS* **345**, 292–310 (2003), `arXiv:astro-ph/0306626`.
7. P. Gandhi, K. Makishima, M. Durant, A. C. Fabian, V. S. Dhillon, T. R. Marsh, J. M. Miller, T. Shahbaz, and H. C. Spruit, *MNRAS* **390**, L29–L33 (2008), `arXiv:astro-ph/0807.1529`.
8. M. Durant, P. Gandhi, T. Shahbaz, A. P. Fabian, J. Miller, V. S. Dhillon, and T. R. Marsh, *ApJL* **682**, L45–L48 (2008), `arXiv:0806.2530`.
9. V. S. Dhillon, T. R. Marsh, M. J. Stevenson, D. C. Atkinson, P. Kerry, P. T. Peacocke, A. J. A. Vick, S. M. Beard, D. J. Ives, D. W. Lunney, S. A. McLay, C. J. Tierney, J. Kelly, S. P. Littlefair, R. Nicholson, R. Pashley, E. T. Harlaftis, and K. O'Brien, *MNRAS* **378**, 825–840 (2007), `arXiv:0704.2557`.
10. J. Malzac, T. Belloni, H. C. Spruit, and G. Kanbach, *A&A* **407**, 335–345 (2003), `arXiv:astro-ph/0306256`.
11. P. Gandhi, V. S. Dhillon, M. Durant, A. C. Fabian, A. Kubota, K. Makishima, J. Malzac, T. R. Marsh, J. M. Miller, T. Shahbaz, H. C. Spruit, and P. Casella, *MNRAS submitted* (2010).
12. A. Merloni, T. Di Matteo, and A. C. Fabian, *MNRAS* **318**, L15–L19 (2000), `arXiv:astro-ph/0006139`.
13. A. A. Esin, J. E. McClintock, J. J. Drake, M. R. Garcia, C. A. Haswell, R. I. Hynes, and M. P. Muno, *ApJ* **555**, 483–488 (2001), `arXiv:astro-ph/0103044`.
14. J. Malzac, A. Merloni, and A. C. Fabian, *MNRAS* **351**, 253–264 (2004), `arXiv:astro-ph/0402674`.
15. S. Markoff, M. A. Nowak, and J. Wilms, *ApJ* **635**, 1203–1216 (2005), `arXiv:astro-ph/0509028`.
16. F. Yuan, W. Cui, and R. Narayan, *ApJ* **620**, 905–914 (2005), `arXiv:astro-ph/0407612`.
17. P. Uttley, and I. M. McHardy, *MNRAS* **323**, L26–L30 (2001), `arXiv:astro-ph/0103367`.
18. P. Uttley, I. M. McHardy, and S. Vaughan, *MNRAS* **359**, 345–362 (2005), `arXiv:astro-ph/0502112`.
19. Y. E. Lyubarskii, *MNRAS* **292**, 679–+ (1997).
20. P. Gandhi, *ApJL* **697**, L167–L172 (2009), `arXiv:astro-ph/0904.2791`.
21. S. N. Zhang, *Highlights of Astronomy* **14**, 41–62 (2007), `arXiv:astro-ph/0702246`.