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

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Abstract

In one of the fastest multi-wavelength timing studies of black hole X-ray binaries (BHBs) with large telescopes to date, we have discovered correlated optical and X-ray variability in the low/hard state of the source GX 339–4. Only two other BHBs are currently known to show rapid (sub-second) aperiodic optical flickering: XTE J1118+480 and Swift J1753.5–0127. Our simultaneous VLT/Ultracam and RXTE/PCA data reveal intriguing patterns with characteristic peaks, dips and lags down to very short timescales ($\lesssim$150 ms). Reprocessing can be ruled out as the origin of the aperiodic optical power. Instead, the variability may be driven by synchrotron emission from the inner accretion flow regions, with interactions between the disk, jet and corona resulting in the complex correlation patterns. We also show that both the optical and X-ray lightcurves are intrinsically non-linear, in the sense that the absolute variability r.m.s. amplitude linearly increases with flux. 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 disk with the inner hot flow and jet.

KEY WORDS: accretion: stars – individual: GX339–4 – stars: X-rays: binaries – stars: optical: variable – black holes

1. Introduction

Rapid flux variability is a hallmark of accretion activity around black holes, especially X-ray binaries (XRBs). A variety of missions over the past few decades have extensively probed this variability in X-rays, showing the presence of aperiodic variations on timescales down to milli-seconds. The fast timescales mean that these are arising from the inner regions within just tens to hundreds of gravitational radii around the central compact source, while their aperiodic nature is a manifestation of the chaotic accretion environment from which they arise (van der Klis 1989) with contributions from a wide range of scales.

The optical flux of XRBs, when not dominated by the donor star, is thought to arise from the outer accretion disc at many thousands of gravitational radii, where temperatures cool to well below $\sim 10^5$ K. Significant changes in accretion rate would occur on the viscous timescale, which is long at these radii, hence limiting the rapidity of any brightness changes associated with variable accretion. Any fast optical variations (on times of a few seconds) are believed to be the result of higher energy photons that impinge upon the disc or heat the surface of the secondary star, following which they are reprocessed to lower energies. Such 'echoes' have provided key constraints on the physical parameters of accreting sources over many years (Horne 1985, Marsh & Horne 1988).

Yet, this is not the whole story, as several sources are now known to show rapid optical variations not associated with reprocessing. The variations in these cases are correlated with, but not born of, the X-ray variations, and hence provide completely independent constraints on accretion activity. Not only do these optical variations show all the characteristics usually associated with X-ray fluctuations, they also possess connections across a wide range of timescales, a fact that can place important constraints on their physical origin.

Here, I review our discovery of intriguing, correlated sub-second optical and X-ray variability in the Galactic black hole candidate GX 339–4 (Hynes et al. 2003). This source has been the subject of intense study from radio to X-rays because it shows striking transient behaviour on timescales of months to years, displaying a variety of X-ray states (e.g. Makishima et al. 1986, Zdziarski et al. 2004, Dunn et al. 2008). It is classified as a microquasar based upon its strong radio outbursts (Gallo et al. 2003). Rapid optical variations were found in the source almost three decades ago (Motch et al. 1982). Cyclotron radiation from hot plasma clouds was proposed as the origin of this variability, but these observations were never followed up in greater detail (Fabian et al. 1982).

2. Observations

We used the rapid triple-beam camera ULTRACAM (Dhillon et al. 2007) to observe GX 339–4, simultaneously with *RXTE*, for about 1 hour on each of three nights in mid-June 2007 when ULTRACAM was mounted on the Very Large Telescope (VLT) in Chile. The source was in a low/hard X-ray state, having finished an outburst a few weeks before. The time resolutions ranged between $\approx 50 - 130$ ms. The results reported herein refer to photometry in the Sloan r' filter. Optical spectro-photometry around 5000 Å implies a magnitude $V_{\rm Vega} \approx 17 \;\; => \lambda L_\lambda^{0.5\ \mu{\rm m}} \approx 2.3 \times 10^{34} (d/8\ {\rm kpc})^2$ erg s^{-1}, with a high line-of-sight Galactic extinction implying an intrinsic luminosity which is at least $\sim 20 - 25$ times larger. The X-ray flux $F_{2-10} = 1.6{\times}10^{-10}$ erg s^{-1} cm^{-2}, $=> L_{2-10} = 1.2{\times}10^{36}$ erg s^{-1}, resulting in an optical:X-ray (V:2–10 keV) luminosity ratio ∼40%. X-ray lightcurves were extracted over the full PCA energy range from standard GoodXenon mode observations.

3. Cross-correlating the optical and X-ray lightcurves

3.1. Results

The net optical and X-ray light curves were translated to a common time frame, and cross-correlated. The resultant cross-correlation function (CCF) is shown in Fig. 1. A single, significant peak at an optical lag of ∼150 ms is clearly seen. The peak itself has a narrow core, with a shallow rise a steep decline. Weaker, but significant anti-correlation troughs are seen on either side. Or perhaps there is a single broad trough from negative to positive lags, superposed with a narrow positive component. Each of these structures is visible in all the observations (in spite of some clear inter-night variation), suggesting that they are real. The full details and observations have been published in Gandhi et al. (2008).

3.2. Implications

The complex behaviour of the optical/X-ray CCF is difficult to reproduce with simple linear reprocessing models: the timescales are too short for light-travel times to the outer accretion disk or companion star, which ought to be $\gtrsim 10$ s for the wide binary orbit of the source. Furthermore, the anti-correlated optical and X-ray fluctuations are contrary to linear transfer model predictions. Finally, it has also been found that the optical auto-correlation function (ACF) is narrower than the corresponding X-ray one (Gandhi et al. 2008), which means that the mean optical fluctuations have a shorter coherence time as compared to the X-ray ones. In a reprocessing scenario, one would expect the reprocessed component to be smeared out on longer times as compared to the source photons; hence the optical is not a result of X-ray driving, at least not the fast optical variability that concerns us here.

3.3. Comparison with XTE J1118+480

Until our 2007 observation, only one other source was known to show complex optical vs. X-ray flux correlations not due to reprocessing. This was XTE J1118+480, which also showed an asymmetric CCF with anti-correlated components, as well as an optical ACF narrower than in the X-rays (Kanbach et al. 2001, Spruit & Kanbach 2002). A plethora of models have been propounded to explain the rapid optical variations, with most invoking synchrotron emission from strong magnetic fields (e.g. Merloni et al. 2000, Esin et al. 2001, Malzac et al. 2004, Yuan et al. 2005). The complex time correlations may be explained if accretion energy is being divided between two or more physical components in the accretion flow, e.g. optical synchrotron from a jet (typically associated with the low/hard state in which the observations were carried out), and inverse Compton X-rays from the corona. The characteristic CCF timescales can then be used to constrain the dimensions of, or dominant accretion processes within, these physical components (See discussion in Gandhi et al. 2008).

4. Flux-scaling of optical variability amplitudes

Whatever the physical origin of the variability may be, it must satisfy one more observable. Several recent works have shown that the X-ray lightcurves of accreting black hole candidates, neutron stars as well as active galactic nuclei (AGN) follow a linear relationship between their average flux and root-mean-square (rms) variation over many different time-scales (e.g. Uttley & McHardy 2001, Uttley 2004, Gleissner et al. 2004). In other words, the absolute values of the instantaneous variance is not constant, but is rather linked to longer-term flux averages.

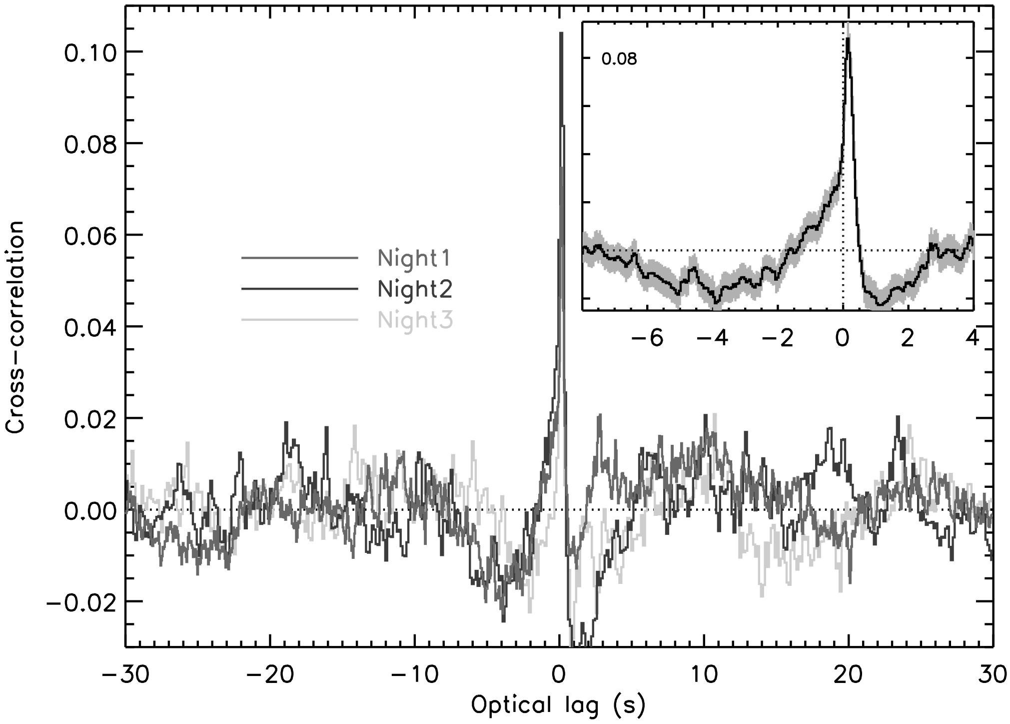

Fig. 1. Optical vs. X-ray cross-correlation function computed from many 60 s–long light curve sections on the three nights of observation (Gandhi et al. 2008). A positive delay (in this case peaked at ≈ 150 ms) implies that optical lags X-rays on this plot. The CCF (especially the peak) generally agrees well between the nights. The inset shows the zoom-in average CCF of Nights 1 and 2, and the shaded region is the average scatter computed from an ensemble of light curve sections.

Uttley et al. (2005) 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 a result of coupling of large-scale fluctuations that propagate inwards and perturb inner flares. Interestingly, a similar ‘rms–flux’ relation has been shown to apply in solar coronal flares as well (Zhang 2007); it thus seems to provide new constraints on hot astrophysical plasmas in general.

4.1. Observations

In recent work, Gandhi (2009) found that the optical lightcurves of sources which show aperiodic, non-reprocessed fluctuation components also possess an rms–flux relation with properties similar to X-rays. By computing the absolute rms variability level from the lightcurve power spectra over various Fourier frequency ranges, and binning these as a function of average source flux, a linear relation with positive slope was found in most cases. The slope is related to the fractional variability amplitude over the Fourier frequency range in question. The targets investigated were XTE J1118+480, GX 339–4 and Swift J1753.5–0127. Furthermore, the source with the highest fractional variability also showed the tightest rms–flux relation, with strongly non-linear (i.e. lognormal) flaring, i.e. GX 339–4, and its results are shown in Fig. 2.

4.2. Implications

What this means is that the optical variations cannot arise as a result of independent shot impulses, just as for X-rays. A variety of models have been invoked to explain the ‘coupling’ of fluctuations that feed the X-ray emission, including perturbations which propagate inward through the accretion flow seeding the variations over all inner regions, and large-scale magnetic fields in which variability can diffuse quickly throughout the flow (e.g. Lyubarskii 1997, Zhang 2007). If the optical variations are seeded in a similar fashion, then the fluctuations must be propagating to the optical emission region. This is variously thought to be either the corona, or the inner regions of the jet where the magnetic field and electron temperatures are commensurate with optical synchrotron. This, in turn, means that the fluctuations are free to traverse the various physical accretion components, from the outer disc to the inner flow, corona and/or jet.

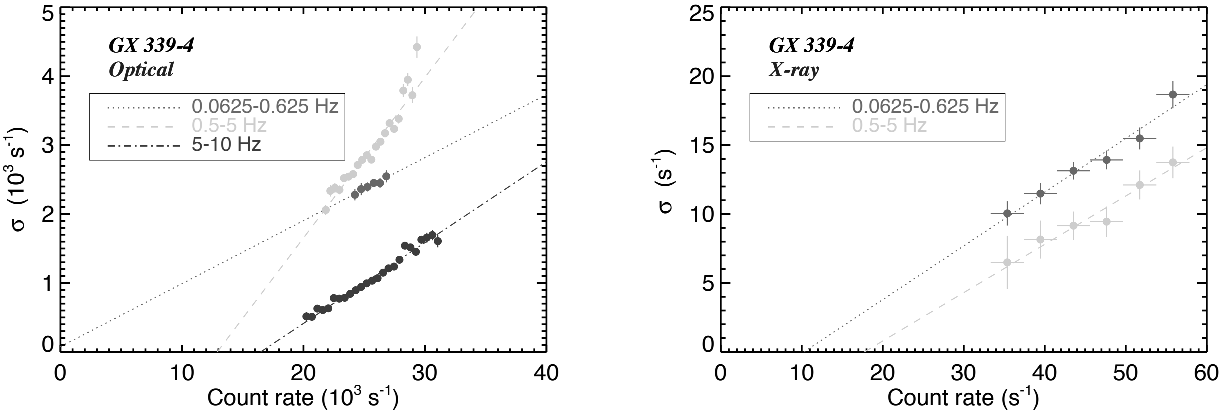

Fig. 2. Optical (*Left*) and X-ray (*Right*) rms–flux relations for GX 339–4 over various Fourier frequency ranges, as labelled. In each case, the line is a simple linear fit (Gandhi 2009).

We note that a model by Malzac et al. (2004) could prove to be consistent with all the above observations. Their study proposes that the strength of the emergent power scales in proportion to the total amount of energy stored in some ‘reservoir’. Cumulative build-up and dissipation of energy in this reservoir can result in the rms–flux relation (with only minor modification; see Gandhi 2009), while sharing of this energy between the jet and corona results in the complex optical/X-ray CCF. A good candidate for the reservoir is a large-scale magnetic field connecting various parts of the flow.

5. Summary

Fast, sub-second timing observations of GX 339–4 have been carried out simultaneously in optical and X-rays. Rapid optical broad-band noise flickering is found in the optical, as is usual for the X-ray lightcurves. Cross-correlating lightcurves in the two bands shows complex behaviour, with both positive and negative correlations. Several lines of reasoning suggest that the fast optical variations do not arise as a consequence of X-ray reprocessing. Models where variability in both optical and in X-rays is seeded by perturbations across a wide range of radii and timescales are preferred. Division of accretion energy between the various optical/X-ray generation components can lead to the complex timing correlations observed.

Fast multi-wavelength variability studies can thus give important new constraints on the physical conditions of hot plasmas around accreting black holes, and perhaps other astrophysical sources in general. Such observations remain severely limited, and this work needs to be expanded significantly.

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