Constraining accretion from coordinated multi-wavelength rapid timing observations of X-ray binaries

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Abstract

It has long been believed that the optical and infrared (OIR) fluxes of compact accreting sources will not generally show fast, stochastic variability. This is because reprocessing of high energy photons is thought to be the primer driver of the OIR fluxes. In recent work, we have found fast (sub-second) optical variations in accreting black hole and neutron star binaries. The power spectra of the source light curves show wide-band noise and even low-frequency quasi-periodic oscillations. These are characteristics very similar to those found in X-ray observations. The OIR fluxes show some clear and intriguing correlations with the X-ray fluxes on timescales of 0.1-10 s, which can place quantitative physical constraints on the accretion processes for the first time. Detailed statistical analyses including lags and rms spectrum provide key insights. These show unambiguously that at least two separate components (e.g. a jet and a corona) are interacting via some underlying connections (e.g. a strong magnetic field threading the entire inner flow regions). OIR timing studies are thus proving detailed insight on compact accreting sources, complementing X-ray constraints.

Key words: accretion: stars – individual: GX339–4 – individual: SwiftJ1753.5–0127 – stars: X-rays: binaries – stars: optical: variable – black holes

1. Introduction

The development of the X-ray timing industry has been a marvellous success story in Astronomy over the past several decades, driving our understanding of compact accreting sources in the cosmos. Timing at other wavebands, on the other hand, has been comparatively slow to catch on. This has been partly due to the general lack of availability of suitably fast instrumentation, and partly a result of the belief that timing studies in wavebands such as the optical and infrared either yield a null result, or do not provide any constraints independent from X-ray observations.

Reprocessing of high energy photons to lower energies on the outer portions of the accretion disk is thought to dominate the observed optical fluxes of low mass X-ray binaries, i.e. those systems in which the luminosity of the companion star itself is negligible (e.g. van Paradijs & McClintock 1994). The expected timing signature of such reprocessing is a delayed and smeared response of the optical lightcurves with respect to X-rays, depending upon the size of the accretion disk and system inclination.

But it has also been suspected for some time that there may be additional components to the observed optical fluxes. In the early 1980s, Motch et al. (1982, 1983, 1985) uncovered fast and strong optical flaring activity in the black hole X-ray binary GX 339–4. The flares occurred on very short (sub-second timescales) and did not seem to follow the X-ray lightcurves. If anything, there was evidence for the optical variations preceding the X-rays, and showing an opposite trend in flux changes. It is difficult to reconcile such behaviour with simple disk reprocessing scenarios, meaning that the optical flux in this case is generated by a different process.

A few other sources have since also shown evidence for fast and strong optical variations (e.g. Kanbach et al. 2001, Uemura et al. 2002). The black hole binary XTE J1118+480, in particular, has been studied in great detail due to its bright outburst magnitude and high Galactic inclination. Simultaneous optical and X-ray timing have clearly demonstrated that in this case, the optical variations do not trace the expected X-ray reprocessing behaviour (e.g. Kanbach et al. 2001, Spruit & Kanbach 2002, Hynes et al. 2003).

In order to understand the nature of this rapidly variable optical component, we observed two binaries simultaneously in optical and X-rays in mid 2007. We discuss some these results herein and show that optical timing has the potential to provide great new insight on the physics of accretion.

2. Observations

Our observations were carried out simultaneously with the ULTRACAM imager mounted on the Very Large Telescope and the Rossi X-ray Timing Explorer (*RXTE*) satellite in mid June 2007. ULTRACAM is an ultra-fast camera employing frame transfer CCDs which allow frame rates of up to 500 Hz with dramatic reduction of dead time as compared to traditional CCDs. Beam splitters allow completely simultaneous photometry in three separate filters. For full details on the instrument, we refer the reader to Dhillon et al. (2007).

ULTRACAM was mounted on the VLT for about two weeks. We chose to observe GX 339–4 and (recently discovered at that time) another black hole candidate Swift J1753.5–0127. GX 339–4 was caught just a few weeks following its return to the low/hard state after a major outburst, whereas Swift J1753.5–0127 has remained in the low/hard state ever since it was found. But it is important to realise that our observational window was entirely fixed by the mounting period of ULTRACAM, rather than any specific choice of source X-ray state or brightness levels.

The sources were observed for a few hours each, split across several nights during the week of 12–18 Jun 2007. A time resolution of between 40 and 140 ms was chosen, depending on real time weather conditions on each night, in order to maximise the signal:noise in each frame. Such time resolution can be easily achieved by reading out only small windows ($\sim$50–100 pixels on a side) centered on the target. An identical window placed on a random, bright comparison star in the field provided comparison and correction for any atmospheric scintillation effects. Dead times were of the order of 1–2 ms. Simultaneous light curves were obtained in the SDSS r', g' and u' filters. The last filter has lower sensitivity, and 50 consecutive frames were co-added in this case in order to achieve a gain in signal:noise, at the expense of time resolution.

3. Results

The results have been published in Gandhi et al. (2008, 2010) for GX 339–4 and Durant et al. (2008, 2009) for Swift J1753.5–0127. We refer the reader to these works for all the details. Here, we review some of the highlights. In both sources, we found strong optical flux variability in all filters. Variations in GX 339–4 are especially dramatic, with flares of strength about a factor of two above the local average on timescales of just 100 ms or shorter. This already rules out simple reprocessing scenarios for this emission.

Analysing the net optical and X-ray barycentered light curves provides some fascinating insight. Fig. 1 shows the cross-correlation functions (CCFs) between the two light curves. Though only the r' is used for the optical in this case, the bluer filters showed similar results (but for specific details, please see the above references). Both sources show an intriguing 'dip', skewed to negative times in the sense that optical precedes X-rays. This anti-correlation dip sharply cuts off at the moment of simultaneity $t = 0$ for Swift J1753.5–0127, while it is perhaps broader and more symmetric for GX 339–4. The CCF in this latter case is actually dominated by a sharp feature centered at $t \approx +150$ ms, i.e. a very fast, positive optical response delayed with respect to X-rays.

Consistent results are obtained between the nights, meaning that the main features are real and stable.

4. Implications

4.1. Arguments against reprocessing

A variety of arguments may be put forward against the hypothesis that the bulk of the observed optical emission and variations arise from reprocessing. These include:

Speedy variations and short optical delay : Significant variability power is found on timescales down to just tens of milli-seconds. GX 339–4 shows a peak optical delay of only $\sim$150 ms in the CCF with respect to X-rays, computed with the fastest light curves available. 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 behaviour : The anti-correlation dips seen in Fig. 1 imply a negative response on times of several seconds, whereas reprocessing is generally regarded as a positive, linear transfer of power to lower Fourier frequencies.

Short optical coherence times : At least for the case of GX 339–4, the *auto-correlation* functions (ACFs) of the X-ray light curves are broader than the corresponding optical ones. One way to see this is to compare the X-ray ACF shape with the optical-vs-X-ray CCF. The very fast optical variations and CCF response are much faster and narrower than the X-ray ACF for this source. This can also be confirmed by directly computing the optical ACF (see Gandhi et al. 2008). In a reprocessing scenario, the source photons ought to show faster characteristic variations as compared to derivative photons, and so we would expect the X-ray ACF to be narrower than the optical one, which is not the case. This was also found to be true for XTE J1118+480 (Kanbach et al. 2001).

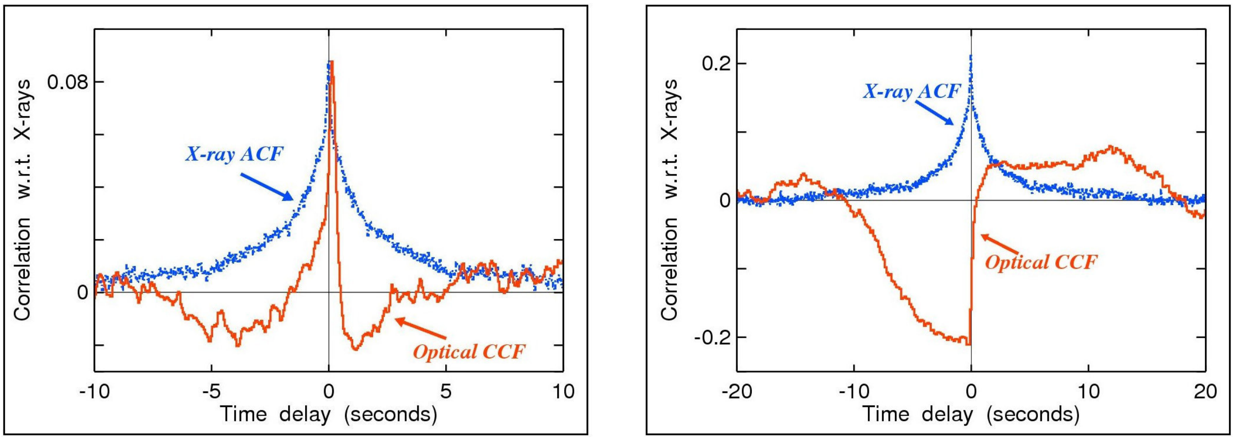

Fig. 1. Optical (VLT/ULTRACAM r' band) vs. X-ray (*RXTE* full band) cross-correlation functions (denoted 'Optical CCF') for GX 339–4 (*Left*) and Swift J1753.5–0127 (Right). A positive delay implies that optical lags X-rays. A significant anti-correlation trough is seen in both cases on timescales of ∼10 s. Note that for GX 339–4, the sharp positive component is delayed with respect to zero time by about 150 ms. Also shown in both cases are the auto-correlation functions (denoted 'X-ray ACF') of the X-ray light curves. In the case of GX 339–4, the sharp optical response is much narrower than characteristic X-ray ACF timescales. For full details, please refer to Gandhi et al. (2008, 2010) for GX 339–4 and Durant et al. (2008, 2009) for Swift J1753.5–0127.

Energetics : One may also ask what fraction of X-ray power is expected to be reprocessed to the optical. Assuming canonical disk reprocessing, a few per cent of the high energy radiation may be thermalised into the optical. On the other hand, the observed optical:X-ray flux ratios for our observations lie well above this, being as high as about 0.5 for GX 339–4 (Gandhi et al. 2010, Durant et al. 2011). A reprocessor with extremely high covering factor would be required to reproduce this. Instead, this comparison of available and observed energetics suggests the presence of emission components in addition to any underlying reprocessing.

4.2. Physical scalings

If not a result of reprocessing, what is the origin of the optical power? We may start with some simple inferences based upon order of magnitude estimates. The fastest optical flares that we observe have characteristic times of $\lesssim$100 ms. This is undoubtedly limited by the time resolution employed, and is not an intrinsic limit. In fact, faster flares on just a few tens of ms times were seen by Motch et al. (1982). This implies an upper limit to the size of the optical emission region of around 10^4 km, or $\sim 10^3$ $R_{\rm S}$ assuming a black hole mass of $\sim$10 $M_\odot$ ($R_{\rm S}$ is the Schwarzschild radius). Such a small physical size is already quite constraining, implying emission from the inner portions of the accretion flow if it is centrally located. In combination with the observed optical powers, the above size implies an emission region brightness temperature of $\sim 10^7$ K. Such high temperatures strongly argue for a non-thermal emission process.

4.3. Comparisons with XTE J1118+480

In fact, a plethora of non-thermal models have been propounded to explain the non-reprocessed optical flickering of XTE J1118+480, 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.

4.4. RMS spectrum

We may ask if there are likely to be two such interacting components in GX 339–4 as well. One way to investigate this is to compute the so-called 'rms spectrum'. This is done by multiplying the observed fluxes in all energy ranges or filters by the respective fractional variability levels (the latter being computed from the power spectra of the light curves). The result is the energy spectrum of the variable component of emission, and is shown in Fig. 2 for the case of GX 339–4. Despite optical dereddening uncertainties (which do have a systematic effect), the slopes of the lines connecting the various energies in Fig. 2 show that the variable component is best described not as a single power law connecting the r', g' and soft and hard X-ray ranges, but as two separate components over the X-ray and the optical, respectively.

4.5. Interactions between a jet and inner accretion components

We propose a scenario for GX 339–4 in which broad X-ray flaring events occur as a result of coronal reconnection cascades. Such events deplete stored coronal magnetic energy density, leading to a drop of optical coronal (cyclo)synchrotron emission. This implies that broad X-ray flaring events ought to have similar timescales to the optical:X-ray anti-correlation dips, which is what we find (see Fig. 1; discussion in Gandhi et al. 2010, section 5.3).

Such reconnections would also energise particles in the corona, accelerating them along the jet field lines (GX 339–4 is a prototype of strongly jetted binaries; e.g. Gallo et al. 2005). Emission along the jet is stratified, becoming optically-thin to lower energies farther away from the acceleration region. Hence, optical emission is expected to be delayed with respect to X-rays, exactly as is seen. Such a model is qualitatively similar to that of Malzac et al. (2004), who proposed a jet–corona reservoir model for XTE J1118+480.

Whether or not our model proves to be correct, it illustrates the fact that optical:X-ray CCFs provide some key characteristic timescales, which can then be used to constrain the dimensions of, or dominant accretion processes within, the various physical components.

4.6. The case of Swift J1753.5–0127

Unlike GX 339–4, Swift J1753.5–0127 shows a very strong anti-correlation component without any obvious, single positive response (Fig. 1). This is clearly very different behaviour and requires further detailed study. But we note that this is at least qualitatively consistent with the jet–corona model described above. This is because Swift J1753.5–0127 is known to be radio weak, atypically so given its X-ray flux (see Durant et al. 2009, and references therein). The source is thought to have a weak radio jet.

In our model above, it is the jet which is responsible for the positive CCF feature. So it is not surprising to find this feature lacking in the case of Swift J1753.5–0127 (see discussion in Gandhi et al. 2010, section 5.5). On the other hand, a strong inner hot flow (or corona) must be present in this source for it to produce the observed bright X-ray emission, and this is the component responsible for the anti-correlation, according to the scenario that we outline above.

5. Summary and future prospects

The results of fast, sub-second timing of two X-ray binaries, GX 339–4 and Swift J1753.5–0127, simultaneously observed in optical and X-rays have been presented. Rapid optical flickering is found in the optical. Cross-correlating lightcurves in the two bands shows complex patterns, 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. The complex shape of the correlations suggest that there is division of accretion energy between various optical/X-ray generation components, and we suggest that the jet plays an important role in giving rise to a fast and positive optical response delayed with respect to X-rays. The corona, on the other hand, may be responsible for the observed anti-correlation component, which is a general characteristic of X-ray binaries, including at least two neutron star systems Cyg X-2 and Sco X-1 (see, e.g. Durant et al. 2011).

Much more analysis than can be reviewed here is possible. For instance, power spectra yield important clues as to the nature of the underlying variations. Both sources show broad-band noise over a wide Fourier frequency range, and even evidence of low-frequency quasi-periodic variability (e.g. Gandhi et al. 2010, Durant et al. 2009). The broad band noise seems to have underlying connections arising from correlated variations over the whole inner accretion flow regions, favouring so-called propagating perturbation models (Lyubarskii 1997, Uttley & McHardy 2001). This has been known for some time in X-rays, and is now revealed in the optical (Gandhi 2009). Such behaviour cannot be produced by isolated shot flaring events.

What we are finding is that the optical lightcurves show characteristics usually ascribed to X-ray lightcurves. This opens up a whole new window on accretion studies via optical variability. But much of the above behaviour is probably not exclusive to the optical. Casella et al. (2010) have carried out simultaneous near-infrared and X-ray observations of GX 339–4 in the low/hard state, and uncovered a similar fast and delayed near-infrared response at $\sim$100 ms with respect to X-rays. Broad-band spectral models imply that the jet should dominate the infrared, whereas the optical may be a mixture of various components (see references in Gandhi et al. 2010). In this sense, extending fast timing analysis to the infrared holds great promise.

Fast multi-wavelength variability studies can thus give important new constraints on the physical conditions of accretion and outflows. Such observations remain severely limited, and this work needs to be expanded significantly on all scales. We still do not fully understand the underlying driver for the observed multi-wavelength variability. Nor can we predict which sources, and under which source states, can we expect to uncover fast multi-wavelength variations. The fact that we found the observed behaviour without any particular pre-selection suggests that such rapid optical flickering may be ubiquitous.

MAXI provides an excellent opportunity for high cadence, very long term monitoring of X-ray light curves.

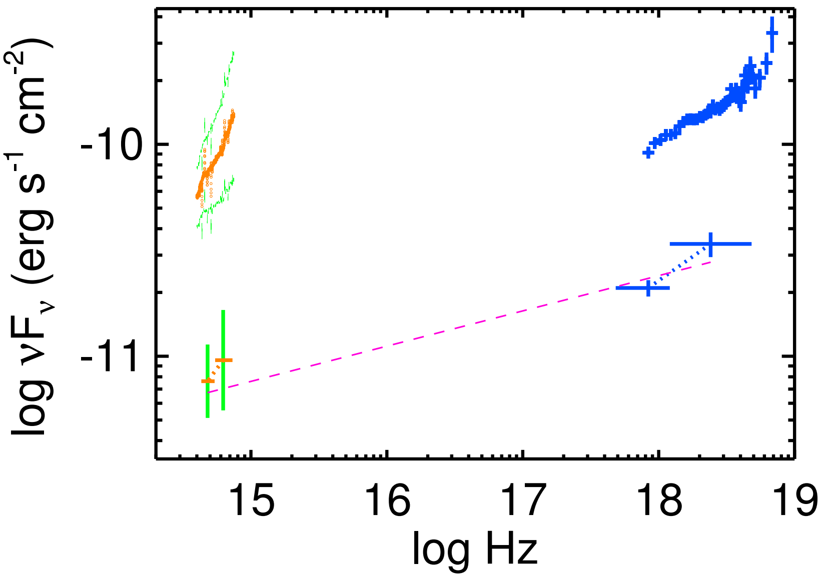

Fig. 2. RMS spectrum for GX 339–4, reproduced from Gandhi et al. (2010). The optical and X-ray total observed spectral fluxes (upper points) are multiplied by the fractional rms values obtained from power spectral analysis (in this case, over 0.4–4 Hz) of the r' (centred at the effective wavelength of 6250 Å), g' (4800 Å), 2–5 keV (3.5 keV) and 5–20 keV (10 keV) light curves, from left to right, respectively. This yields the four lower points, which represent the energy spectrum of the variable component. Systematic dereddening uncertainties to the optical are shown in green (upper and lower spectra, and the error bar on the rms points). The pink long–dashed line is a fit to these four points and has a slope of 0.17±0.04 in the plotted log-log units. The orange and blue dotted lines connect the two optical and two X-ray rms points respectively. The key point is that the slopes of these two are flatter than that of the long dashed line, implying separate optical and X-ray variable components.

This could be a first opportunity to study longer physically interesting timescales such as the thermal and viscous timescales in the outer parts of the accreting systems. We are following up particularly interesting MAXI sources in the optical for variability (e.g. Russell et al. 2010). But dedicated programs of continuous optical monitoring (using Robotic telescopes, for instance) are required for providing multi-wavelength datasets complementary to MAXI lightcurves.

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References

Casella P. et al. 2010 MNRAS., 404, L21
Dhillon V. S. et al. 2007 MNRAS., 378, 825
Durant M. et al. 2008 ApJ., 682, L45
Durant M. et al. 2009 MNRAS., 392, 309
Durant M. et al. 2011 MNRAS., 410, 2329
Esin A. A. et al. 2001 ApJ., 555, 483
Gallo E., Fender R. P. and Pooley G. G. 2003 MNRAS., 344, 60
Gandhi P. et al. 2008 MNRAS., 390, L29
Gandhi P. 2009 ApJ., 697, L167
Gandhi P. et al. 2010 MNRAS., 407, 2166
Hynes R. I. et al. 2003 MNRAS., 345, 292
Kanbach G., Straubmeier C., Spruit H. C. and Belloni T. 2001 Nature, 414, 180
Lyubarskii Y. E. 1997 MNRAS., 292, 679
Malzac J., Merloni A. and Fabian A. C. 2004 MNRAS., 351, 253
Merloni A., Di Matteo T. and Fabian A. C. 2000 MNRAS., 318, L15
Motch C., Ilovaisky S. A., Chevalier C. 1982 A&A., 109, L1
Motch C. et al. 1983 A&A., 119, 171
Motch C., Ilovaisky S. A., Chevalier C., Angebault P. 1985, Space Science Reviews, 40, 219
Russell D.M. et al. 2010, The Astronomer's Telegram, #2884
Spruit H. C. and Kanbach G. 2002 A&A., 391, 225
Uemura M. et al. 2002 PASJ., 54, L79
Uttley P., & McHardy I. M. 2001 MNRAS., 323, L26
van Paradijs J. & McClintock J. E. 1994, A&A., 290, 133
Yuan F., Cui W. and Narayan R. 2005 ApJ., 620, 905