# Simultaneous optical and X-ray flickering observations of GX 339-4: correlations on sub-second timescales

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**Abstract.** We present a fast timing analysis of *VLT* (optical) and *RXTE* (X-ray) observations of the Galactic black hole GX 339-4 in the low/hard rapid-flickering state, soon after emerging from outburst. Both optical and X-ray power density spectra are qualitatively similar with a break or QPO-like feature at timescales of $\sim 10-20$ s. A cross-correlation analysis on the fastest time resolutions in the light curve ($\sim 50-100$ ms), a significant ($>10\sigma$) correlation peak is detected, with the optical lagging X-rays by $\sim$150 ms. The correlation exhibits a complex, but stable pattern, with a shallow rise, a steep decline, and anti-correlations on timescales of several seconds. The optical radiation is unlikely to be a result of reprocessed X-rays. We discuss the results in the context of cyclo-synchrotron emission. The complex variability pattern resembles that seen in another important X-ray binary XTE J1118+480, and is likely to be the result of several interacting components in the inner accreting parts of the source. We emphasize the need for further rapid multi-wavelength observations of this fascinating source.

**Keywords:** X-ray binaries, black holes, rapid time variations, optical and x-ray telescopes
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## INTRODUCTION

GX 339–4 (4U 1658–48) is currently one of the strongest candidates for a Galactic Black Hole (BH; with $M_{\rm BH} > 5.8$ $M_\odot$ [1]) and a crucial target in advancing our understanding of the importance of relativistic effects in accretion processes. Located at a distance of $\sim$ 8 kpc [2] with a probable binary orbital period of 1.75 days, the source shows several similarities with the archetypal Galactic BH candidate Cyg X–1, including rapid variability on very short timescales.

Extensive timing studies of the source have been carried out in X-rays (e.g. [3, 4, 5] and many more), but only a handful have been done simultaneously with optical observations. Such observations are especially important for GX 339–4, due to the fact that its binary companion star is very faint [6], implying that accretion dominates both the optical as well as the X-ray power output. The few rapid timing studies in optical and X-rays that were carried out in the 1980s found a complex multi-wavelength behaviour, but no obviously strong correlation between the two wavebands [7, 8].

During three nights in 2007 June, we used the rapid optical photometer ULTRACAM [9] mounted on the 8.2 m Very Large Telescope (*VLT*) in order to study the rapid variability of GX 339–4, simultaneously with pointed observations in X-rays with the *RXTE* telescope, preliminary results of which are presented herein.

# OBSERVATIONS

GX 339–4 had only just recently reverted to its typical low/hard state following an outburst that peaked around 2007 May 17. ULTRACAM[1] is a visitor instrument, mounted for brief periods at the Nasmyth focus of *VLT* Unit Telescope 3. The period of 2007 Jun 9–24, during which our observations were carried out, was only the second period that the instrument has been mounted there. We observed the target for $\sim 1$ h on each on the nights of Jun 14, 16 and 18 (hereafter, Nights 2, 3 and 4, respectively). A brighter comparison star within the instrument field-of-view was observed simultaneously for relative photometry. The time resolutions ranged between $\approx 50-130$ ms. The results reported herein refer to photometry in the Sloan $r'$ filter. Optical spectro-photometry from Night 4 shows a magnitude $V_{\rm Vega} \approx 17 \;=> \lambda L_\lambda^{0.5\ \mu{\rm m}} \approx 2.3\times10^{34} (d/8\ {\rm kpc})^2$ erg s$^{-1}$, not corrected for reddening. A Galactic extinction of $A_{\rm V}$=3.3 means that the intrinsic luminosity is $\sim 20$ times larger.

*RXTE* observed the target in its canonical `GoodXenon` and `Standard` PCA modes. A simple hard power-law with photon-index $\Gamma \approx 1.65 \pm 0.02$ provided a statistically acceptable fit to the `Standard2` PCA spectra. The source had a flux $F_{2-10} = 1.6 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$, $=> L_{2-10} = 1.2\times10^{36}$ erg s$^{-1}$, implying an optical:X-ray ($V : 2-10$ keV) luminosity ratio of about 40 per cent. The low flux and hard power-law spectrum are characteristic of the source in the low/hard state.

# RESULTS: POWER SPECTRA

Power-density spectra (PSD) were computed for the best time resolution light curves and are shown in Fig. 1. The source showed significant broad-band noise and a high rms variability in X-rays, approaching 50 per cent (above the value expected from Poisson fluctuations) on all nights of observation. In the optical, the net rms variability was $\approx 15$ per cent.

There is a clear QPO (quasi-periodic oscillation)-like feature in the optical PSD around 0.05 Hz, followed by a high frequency roll-over above 0.1 Hz. Any QPO in the X-ray data is weaker, and the broad-band PSD is consistent with a double power-law that breaks at $\sim 0.1$ Hz. No high-frequency QPOs are evident in either of the PSDs upto 10 Hz.

# RESULTS: CROSS-CORRELATION FUNCTION

The net optical and X-ray light curves were translated to a common time frame, and cross-correlated. The main result of our work is shown in Fig. 2. The CCF shows a single, significant peak at an optical lag of $\sim 150$ ms. The peak itself has a narrow core, with a shallow rise from $\sim -1.5$ s to 0 s, and a steep decline from 150 ms to $\sim 0.5$ s. Weaker, but significant anti-correlation troughs are centred at $\sim -4$ s and 1 s. Each

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[1] `http://www.shef.ac.uk/physics/people/vdhillon/ultracam/`

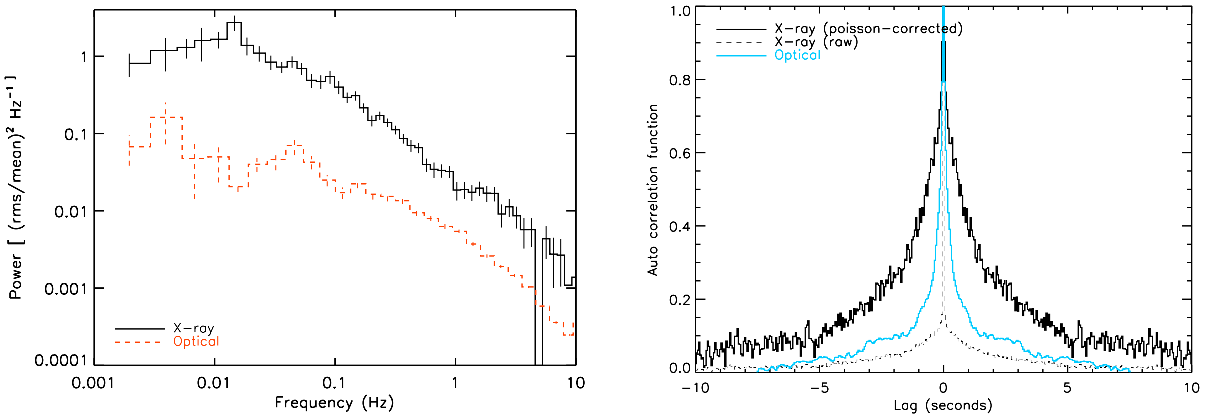

**FIGURE 1.** *(Left)* White-noise corrected power spectra from Night 4. The higher X-ray (full band PCA) variability is reflected in the higher PSD power, as compared to the optical. The optical shows a QPO-like feature around $\sim 0.05$ Hz ($\equiv 20$ s), while the X-ray PSD breaks at $\sim 0.08$ Hz. *(Right)* X-ray and optical auto-correlation functions (ACF). The X-ray ACF has been corrected for Poisson noise that severely affects the zero-lag bin, and is broader than the optical ACF, arguing against re-processing as the origin of the optical power.

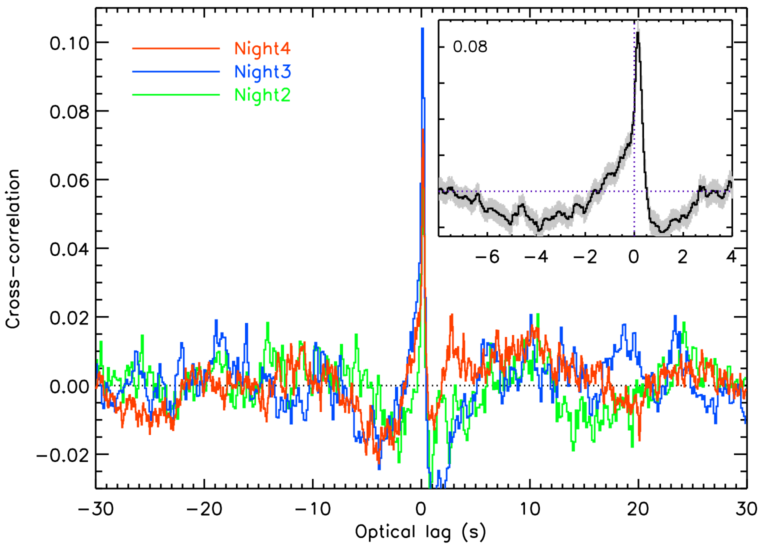

**FIGURE 2.** Optical vs. X-ray cross-correlation function. A positive delay (in this case $\approx 150$ ms) implies that optical lags X-rays on this plot. The inset shows the zoom-in average CCF of Nights 3 and 4, and the shaded region is the average scatter computed from an ensemble of light curve sections.

of these structures is visible in all the observations (in spite of some clear inter-night variation), suggesting that each of them is real. The peak narrowness and position are constant between the three nights, within the $\sim 50-130$ ms resolution available.

# DISCUSSION

What is the origin of the rapidly variable optical power? The peak of the CCF time delay (150 ms) corresponds to a light-travel distance of 5000 $GM/c^2$ for $M \approx 6$ $\mathrm{M}_\odot$, much too large for typical hot electron coronae, but too small for reprocessing on the binary companion star. An auto-correlation function (ACF) analysis of the individual light curves (Fig. 1) shows that the X-ray ACF is broader than the optical one. If the optical flux was due to reprocessing of X-rays, the opposite would have been expected [10].

In addition to any simple reprocessing model, bremsstrahlung radiation can also be ruled out as an origin for the optical power, since this would imply a corresponding X-ray flux $\sim 10^3$ times larger than observed. The most likely mechanism that generates the optical radiation is cyclo-synchrotron radiation [11], as also envisaged by many workers for another X-ray binary XTE J1118+480 [12, 13, 14, 15, 16]. In fact, XTE J1118+480 also shows a complex CCF with fast time variability [10]; its CCF has several features that closely resemble our GX 339–4 CCF shown in Fig. 2. The models cited above for XTE J1118+480 can all fit the spectral properties well, and can qualitatively describe the timing properties. But all of them agree that the details of the full variability behaviour are likely to be complex. This may well be the case for GX 339–4 as well.

A plausible scenario can be inferred from the timescales highlighted by the PSDs and correlation analyses of the previous sections. The steep decline that follows the CCF peak (Fig. 2) suggests the presence of some mechanism that cuts off the optical flux suddenly – like infall into the BH, say. In such a picture, flares begin in X-rays (e.g. a reconnection of magnetic field lines) resulting in an increase in coronal temperature and perhaps causing an increased evaporation of disk material into the corona. We may imagine that dense, magnetized blobs suddenly break off and fall towards the BH. Small blobs will possess a high $B$ field density, and should be strong synchrotron sources. The emission of an ensemble of blobs should peak on timescales of the order of the infall time. A free-fall time of 150 ms for a 6 $\mathrm{M}_\odot$ BH corresponds to a physical scale of $\sim 250$ $R_\mathrm{G}$ ($1R_\mathrm{G} = GM/c^2$). The thermal timescale of the disk at this radius is $\sim 15$ s (for a viscosity parameter $\alpha = 0.05$), which also corresponds well to the characteristic timescales highlighted by the optical and X-ray QPOs. Typical parameters such as a field strength $B \sim 10^6$ G, electron temperature $kT_e \sim 200$ keV and a blob size $\sim$ Schwarzschild radius can account for the broad-band spectrum [17, 12].

However, if this radius of 250 $R_\mathrm{G}$ corresponds to some physically-meaningful scale, e.g. the disk truncation radius ($r_\mathrm{trunc}$), the above argument suggests a very large value of $r_\mathrm{trunc}$ – much larger than that inferred during previous [18] or even the present [19] low/hard state. An alternate possibility is that the optical flux is a result of optically-thin synchrotron radiation that results from a jet, while the X-rays originate in the corona. Feedback between a jet/corona system may also explain the anti-correlations observed, if both of them feed off a common energy reservior [14, 12, 15]. Simultaneous radio observations during future transitions to the low/hard state will provide a crucial test for this hypothesis.

# SUMMARY

The optical flux seen in GX 339–4 is dominated by accretion power. Previous simultaneous studies at optical and X-ray wavelengths detected a complex emission structure, but found no strong correlation between the two energies [20, 7, 21, 8]. This optical/X-ray behaviour remains, arguably, the least explored and least understood of the source properties.

We thus carried out the first simultaneously rapid timing observations of GX 339–4 at optical and X-ray wavelengths in its optically-faint low/hard state. A clear positive correlation was found, with the optical lagging X-rays by $\sim 150$ ms. The optical power is unlikely to be reprocessed X-rays, and may be described as cyclo-synchrotron emission. The cross-correlation between the two energies shows a complex behaviour reminiscent of that seen in another important X-ray binary XTE J1118+480. Interactions between multiple components including the disk, jet and the corona can plausibly describe the broad-band spectral and timing properties. Tracking any evolution of the optical/X-ray cross-correlation simultaneously with radio observations will be an important test of the synchrotron emission hypothesis, and will better constrain the physical location of the emitting particles. Multi-wavelength rapid timing studies are beginning to open up new parameter space to explore the innermost structures of accreting Galactic X-ray sources.

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