

SWIFT J1753.5–0127: A SURPRISING OPTICAL/X-RAY CROSS-CORRELATION FUNCTION

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ABSTRACT

We have conducted simultaneous optical and X-ray observations of SWIFT J1753.5–0127 with *RXTE* and ULTRACAM, while the system persisted in its relatively bright low/hard state. In the cross-correlation function, we find that the optical emission, with a broad negative peak, leads the X-ray emission by a few seconds and has a smaller positive peak at positive lags. This is markedly different from what was seen for the similarly interesting system XTE J1118+480, and it is the first time that such a correlation function has been so clearly measured. We suggest a physical scenario for its origin.

Subject headings: binaries: general — stars: individual (SWIFT J1753.5–0127)

1. INTRODUCTION

X-ray emission and optical emission from astrophysical objects are produced by very different means, with different energetics and timescales. X-ray binaries are prolific sources of both, with measurable rapid variability. The emission modes cannot be wholly independent, so by comparing their interconnection, we can learn about the physical conditions from the main emission region: the inner disk around a neutron star or black hole.

Although a high time resolution (≤ 1 ms) for X-ray observations has been achieved from the very earliest observations, the photon rates for most sources prevented statistically significant timing work. In the optical domain, exposure times in the millisecond domain have become possible only relatively recently, with low enough noise and dead time and high enough quantum efficiency (i.e., CCDs as opposed to photometers) to achieve good signal-to-noise ratios per exposure. The final problem has been simply to schedule simultaneous X-ray and optical observations.

The black hole X-ray transient SWIFT J1753.5–0127 is a system that has been of great interest recently, following its outburst episode and detailed observations with the *Swift* satellite. It was first discovered by Palmer et al. (2005) using the Burst Alert Telescope on board *Swift*; pointed γ -ray, X-ray, UV, optical, and radio observations all detected a new bright source at this location (Morris et al. 2005; Still et al. 2005; Halpern 2005; Fender et al. 2005). Following the early report of a 0.6 Hz quasi-periodic oscillation (Morgan et al. 2005; Ramadevi & Seetha 2007), which lasted for some time after the bursting episode, we conducted simultaneous optical and X-ray observations of the system as it faded.⁷ However, the source was still relatively bright, especially in the optical, at the time of our project. Following the burst, Cadolle Bel et al. (2007) measured the spectrum from radio up to 600 keV, and Miller et al. (2006) showed

spectroscopically that a disk reaching down to small radii was likely.

Further details of our observational campaign, including spectroscopy, longer term multiband optical photometry, and detailed periodogram analysis, are to be published separately in Durant et al. (2008), and an analysis is presented in Zurita et al. (2008) of the long-term *R*-band variability and orbit-like modulation. Here we intend to make the minimum number of processing steps and assumptions to obtain the X-ray/optical cross-correlation functions (CCFs), which are a unique phenomenological hint of black hole accretion physics.

2. OBSERVATIONS

SWIFT J1753.5–0127 was observed for 53.6 minutes on 2007 June 13 with the *Rossi X-Ray Timing Explorer (RXTE)*, which provides a very high timing resolution (~ 1 μ s), a reasonable energy resolution (~ 1 keV), and a very high effective area in the 2–100 keV range. During this observation, three of the units of the Proportional Counting Array (PCA; Bradt et al. 1993) were active. We do not consider here the data from the High-Energy X-Ray Timing Experiment or the All-Sky Monitor on board *RXTE*, for which the count rates were much lower. The 2–20 keV flux was 1.6×10^{-9} ergs cm⁻² s⁻¹ (with standard background subtraction).

We produced four light curves of the data using the FTOOLS task *seextract* with standard good time filtering and standard settings. The bands were selected purely by splitting the energy channels into four equal segments. We have not attempted to calibrate these energy cuts exactly.⁸ The variability was at the $\sim 40\%$ level (in which Poissonian noise is significant).

SWIFT J1753.5–0127 was simultaneously observed with ULTRACAM, an ultrafast, triple-beam CCD camera mounted on VLT-UT3 (Melipal). Of the 75 minutes of observation, ~ 50 minutes were simultaneous with the *RXTE* observation. ULTRACAM is an instrument employing dichromatic beam splitters, frame-transfer CCDs, and a Global Positioning System, in order to make simultaneous multiwavelength light curves at very high time resolution (i.e., up to 300 Hz; Dhillon & Marsh 2001; Dhillon et al. 2007). We used two small windows on each CCD (one for the source of interest and one for a local standard), with exposure times of 140 ms (resulting in a duty cycle of 142 ms). Here we note that conditions were

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⁷ ESO and *RXTE* observation IDs 079.D-0535 and 93119-02-02-00, respectively.

⁸ The rough general mapping of channel number to energy is sufficient for our uses (see http://heasarc.nasa.gov/docs/xte/e-c_table.html).

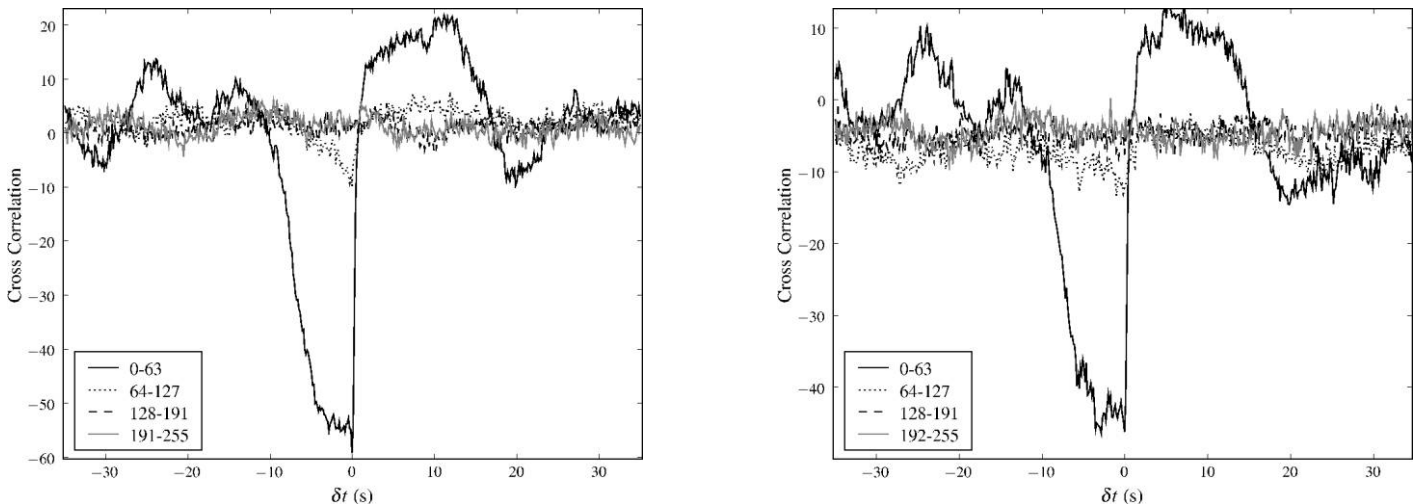


FIG. 1.—Cross-correlation of *RXTE*/PCA and ULTRACAM light curves of SWIFT J1753.5–0127; $\delta t < 0$ represents optical light arriving earlier than X-rays. Each plot shows four X-ray energy ranges, by PCA channel number, for the r' band (left) and for the g' band (right). Scaling is relative to the noise in each CCF (see text).

fairly poor, with a thin cloud causing transparency and seeing variations, mostly on timescales longer than 10 minutes. Fluxes were extracted by aperture photometry, with a variable aperture size scaled to the FWHM of the reference star on each image. This enabled some optimization for the signal-to-noise ratio under the variable conditions. Short-term variability in the optical band was at the $\sim 10\%$ level.

3. CROSS-CORRELATION

We calculated the CCFs of each of the X-ray light curves with each optical light curve produced above.⁹ The results can be seen in Figure 1. The curves have been scaled such that one unit equals the typical difference between one point and the next—it is therefore a simple measure of the random (“white”) noise, as seen in the cross-correlation. The scale is therefore a simple measure of significance.

Although the functions are clearly very similar between the optical bands (except that the g' band is much noisier), there is a marked difference between the X-ray bands:

1. For the 0–63 channel range, which in epoch 5 corresponds roughly to 2–27 keV, a strong signal is seen at negative lags (optical-leading X-rays), followed by a somewhat weaker inverted signal. The width of these signals is of the order 10 s. There is further, less significant structure in the CCF apart from the two main features mentioned. This could hint at some oscillatory interaction between the optical and X-ray emission.

2. In the 64–127 channel range (~ 27 –55 keV), a weaker but significant signal is seen, as in the 0–63 channel range, but this signal is notably narrower in its response.

3. For the two remaining curves at higher energies (~ 55 –118 keV), no significant signal is seen at all.

In every CCF, no further significant features are seen for $|\delta t| > 30$ s. The g' band may show a broader response than the r' band. With the poorer data in the former, we regard this as merely a suggestion.

Significantly, the cross-correlations here do not change noticeably during the window of simultaneous observations, when con-

structed for sections of the data, despite the window lengths (~ 50 minutes) being significant compared to the orbital-like modulation period of 3.2 hours (Zurita et al. 2008).

To investigate what features of the light curves are responsible for the CCFs in Figure 1, we performed the following check. For each of the brightest 1% of bins of the X-ray total light curve, we averaged the windows of the optical light curve that is centered on these bins. The resulting average looks like the solid line in Figure 1 (the X-ray light curve is, of course, dominated by the lower energy range in terms of counts). Conversely, for the average of the windows of the optical light curve centered on the *faintest* 1% of X-ray bins, the average function is again like the solid line, but with the y -axis flipped. In other words, the optical light curve, some seconds before the X-ray light curve, tends to be going in the opposite direction; yet the optical light curve, a few seconds after the X-ray light curve, tends to be going in the same direction, but the tendency is somewhat weaker. Since neither light curve can be decomposed into discreet events or flares, this relationship only comes out over an average of the whole light curve.

We constructed minimum-assumption spectra from the data, to investigate further which component is varying. Figure 2 shows the count rate per energy channel for the brightest and faintest $\sim 10\%$ of bins, along with the spectrum for all bins. One sees that from the lowest energies measured (~ 2 keV) to about channel 70 (~ 30 keV), the spectrum maintains the same form, fluctuating by about a factor of 2. Up to channel 130 (~ 60 keV), some variation is seen, but none at higher energies. Thus, it is not surprising that the higher energy bands do not correlate at all with the optical. Note that the count rates are clearly much lower in this upper energy range, and furthermore note that the background rate becomes dominant. It is not surprising, therefore, that Figure 1 shows no relationship in comparison to the white noise above ~ 60 keV. There are, however, still some counts above the background for this hard source. We compared the ratio of the sum of background-subtracted counts in the high and low curves above and below channel 127, and we found that they were very similar, with perhaps the high-energy part showing an even higher ratio (i.e., it varies more). In general, it seems that the spectrum varies in amplitude only and not in shape. However, the modeling of background

⁹ The light curves themselves, the periodograms, and the autocorrelations will be published separately (Durant et al. 2008).

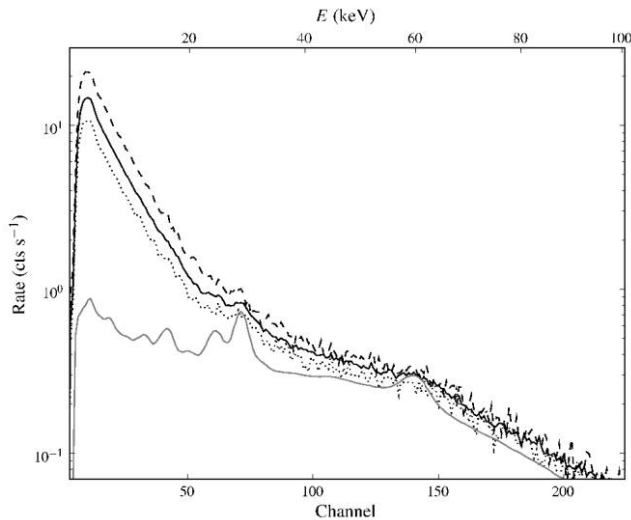


FIG. 2.—Count spectrum extracted for the *RXTE/PCA* observation of SWIFT J1753.5–0127, uncalibrated: mean spectrum (solid line), high count rate bins (dashed line), and low count rate bins (dotted line). Note the logarithmic vertical scale. For comparison, we also plot the estimated background spectrum (gray line; see text). Note how the background curve approaches but does not exceed the average spectrum.

spectra has been a rapidly changing calibration issue,¹⁰ so we regard this as suggestive. We used the latest calibration data available in 2008 April and May.

4. DISCUSSION

Very few X-ray/optical CCFs are recorded in the literature, and they are mostly of systems in low states, where the optical emission lags behind the X-ray emission, which is assumed to be the reprocessing signature, possibly from the large inner radius of a truncated accretion disk. This can be used for the tomography of the disk and the companion by tracking the lag evolution with spectral range and orbital phase (see particularly Hynes 2005). The dearth of cross-correlations is in part due to the logistics of arranging simultaneous observations with the few instruments capable, within the short window following an outburst. In this respect, SWIFT J1753.5–0127 has been unique, by persisting in its low/hard state (relatively bright) for years after outburst (Zurita et al. 2008). We may find that similar relationships exist in other systems, which have gone undetected for technical reasons. Notably, Hynes (2006) report the optical emission lagging behind the X-ray emission in this system by $\delta t < 10$ s during outburst, so clearly it was in some different mode during our observations.

Most typically, one expects X-ray flaring to occur in the innermost, hottest regions, and one expects the power optical emission by the reprocessing of the X-ray flux to occur farther out in the optically thick accretion disk or on the surface of the companion. This picture is a natural consequence of the typical geometry of an advection-dominated accretion flow (ADAF) model, where the disk is truncated at a large inner radius, inside of which the material is hot and of low density (the ADAF itself, where X-rays are produced). One would expect from this a CCF-positive response, with a steep rise and a slower fall. The positive

part of our CCFs does not show this, so simple reprocessing does not dominate over the positive lag region.

Alternatively, the X-ray emission may be from a magnetically driven corona around the dense accretion disk, where reconnection produces energetic particles and where the energy release is dominated by hard X-rays from the upscattering of photons by these highly energetic coronal particles. The different energy outputs can thus be coupled and interrelated in a complex manner (see, e.g., the jet-disk coupling model of Malzac et al. 2004). The corona can form a self-limiting feedback system (see, e.g., Uzdensky & Goodman 2007, 2008) wherein particles can evaporate from the disk to the corona or can condense back to the disk, and the reconnection rate is determined by the density of the corona and the movement of the magnetic loop. Reconnection occurs preferentially in a *marginally collisionless* coronal medium where free magnetic and particle kinetic energies are comparable, which results in a stable equilibrium for a given parameter set (energy transfer rate, sheering, etc.).

If the emission is composed of localized microflares (*flickering*), each flare might proceed as follows: between flares, a patch of the accretion disk cools, and particles from the corona are able to condense; as the coronal density drops, it becomes less collisional and less dominated by magnetic energy during the marginally collisionless state, where particle density cannot inhibit magnetic reconnection. At a critical point, cool X-rays flash at the moment of reconnection, decreasing the stored magnetic energy; the disk is heated again, and the coronal particle population is replenished by evaporation. Thus, the X-ray emission of the microflare is timed after a period of condensation, when the optical emission would be decreasing as more particles are shielded behind cyclotron absorption (indeed, free particles in the corona may also radiate by cyclotron/curvature); immediately afterward, the population of corona particles (and possibly the surface area of the disk patch) becomes larger, and so the optical emission is enhanced again. Only a fraction of the released X-rays and accelerated particles heat the disk; most escape or are emitted at higher energies. The X-ray luminosity acts in the opposite sense and reverses a dip in the optical (i.e., it is self-regulating); the magnetic energy driving and the evaporation/condensation of the disk do seem consistent with our CCF. How the magnetic field is transmitted from the disk to the corona is not known.

This agrees roughly with the model by Fabian et al. (1982), in which the emission is controlled by the expansion and contraction of optically thick, cyclotron-emitting plasma clouds. This model fitted well with the early measurements of GX 339–4 (see below). Since the energy emitted via the cyclotron process depends on the electron number and magnetic energy density, as the magnetic field is expelled from dense regions, the optical emission would decrease while the energy available for reconnection increases. If the cyclotron emission is predominantly optically thick, then the emitted luminosity in the optical depends on the surface area of these clouds—as they contract and expel the magnetic field to the more tenuous, hot medium, the optical emission decreases as the X-ray emission increases, and they are naturally anticorrelated.

If the optical emission is not predominantly jetlike, then there is no longer a reason to expect radio emission to correlate with luminosity. Cadolle Bel et al. (2007) noted (confirmed by Soleri et al. 2008) that the radio emission was unusually low, and that its synchrotron-like spectrum fell below the optical emission. Furthermore, reprocessing of the emitted X-rays will be affected by the acceleration of plasma in magnetic reconnection

¹⁰ Available at <http://www.universe.nasa.gov/xrays/programs/rxte/pca/doc/bkg/bkg-2007-saa/>.

events. If there is mildly relativistic bulk motion away from the denser matter, then the reprocessing would be weakened and would show a different time response (Beloborodov 1999).

Liu et al. (2007) show that SWIFT J1753.5–0127 and also GX 339–4 can be modeled as cool inner disks, in which thermal conduction and Compton cooling are important in the disk’s interaction (condensation and evaporation) with the surrounding low-density corona. They do not specifically consider timescales and driving in their model, but their model is at least consistent with the results here and is similar to the picture presented above and to the dynamic picture presented in Fabian et al. (1982). It will be interesting to see the further development of their model.

In our source, the high-energy emission dominates the total luminosity (up to *INTEGRAL* energies; see, e.g., Cadolle Bel et al. 2007). The picture is, therefore, of emerging magnetic flux from the disk, releasing its energy in the corona in a self-regulating way. Optical emission is from the dense, hot, magnetically active disk (by cyclotron/synchrotron) and by particles in the corona (by cyclotron and curvature). We believe this scenario accounts qualitatively for what is seen but is short of a proof.

4.1. Comparison with XTE J1118+480 and GX 339–4

The two objects that have been extensively studied are XTE J1118+480 and GX 339–4, including the simultaneous optical and X-ray observations of SWIFT J1753.5–0127 with *RXTE* and *ULTRACAM*.

XTE J1118+480 and SWIFT J1753.5–0127 have very similar persistent low/hard states, high galactic latitudes, and X-ray spectral and timing characteristics. Kanbach et al. (2001) found that the optical emission lags behind the X-ray emission by a small amount (~ 0.5 s), but there is an interesting “precognition dip” in the CCF that is difficult to explain. This is in contrast to our case, in which the main feature has a strong anticorrelation (i.e., optical before X-ray). The alternative view would be that we see the same precognition dip and response signal, but with very different intensities. Interestingly, Kanbach et al. (2001) also found that the dip was stronger for longer wavelength optical data, which would also fit our data (with the caveat on the quality of the g' -band observations

above). It was to describe this system that Malzac et al. (2004) developed their jet-disk coupling model.

In the earliest such measurement made that we are aware of, Motch et al. (1983) derived the X-ray/optical CCF for GX 339–4. From a very short observation window (96 s), they suggested an optical-leading anticorrelation, but only at energies $E < 13$ keV. It was in this context that the model of Fabian et al. (1982) was fairly successful. The CCF was not independently confirmed, but it appears similar to our work. Later, Gandhi et al. (2008) repeated these measurements over a longer time baseline, for the source presumably in quiescence, and found the CCF to be similar to that of XTE J1118+480, with the strongest feature being a weak positive peak showing the optical emission slightly lagging behind the X-ray emission (by ~ 0.2 s), but the peak has a shallow rise and a steep fall, followed by a negative correlation in the 1–3 s lag range.

These comparisons suggest that the CCF we find is symptomatic of the accretion mode in our object, at the time of observation.

4.2. Conclusions

Notwithstanding the technical difficulties of constructing X-ray/optical cross-correlations, using the few capable instruments and simultaneous scheduling, this work presents the CCFs for SWIFT J1753.5–0127 that challenge our understanding of the physical processes in the immediate vicinity of a black hole. We find a strong anticorrelation, with the optical emission preceding the X-ray emission on timescales of 1–10 s. This demonstrates that there exists a causal link between the optical emission and the X-ray emission, aside from simple reprocessing, and detailed dynamical modeling will be required to describe the system more fully.

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