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# Echo mapping of Swift J1753.5–0127

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## ABSTRACT

We present two epochs of coordinated X-ray–optical timing observations of the black hole candidate Swift J1753.5–0127 during its 2005 outburst. The first epoch in July occurred at outburst peak. Two consecutive nights of observations using the McDonald Observatory Argos camera with the Rossi X-ray Timing Explorer show a consistent correlation with an immediate response and an extended tail lasting  $\sim 5$  s. The properties of the variability and the correlation are consistent with thermal reprocessing in an accretion disc. The shortness of the lag suggests a short orbital period consistent with that recently claimed. The second epoch in August used the Very Large Telescope Focal Reducer/low dispersion Spectrograph 2 (FOR2) High Time resolution (HIT) mode again in conjunction with *RXTE*. Again a repeatable correlation is seen between two independent subsets of the data. In this case, though, the cross-correlation function has an unusual structure comprising a dip followed by a double peak. We suggest that this may be equivalent to the dip plus single-peak structure seen by Kanbach et al. (2001) in XTE J1118+480 and attributed there to synchrotron emission; a similar structure was seen during later activity of Swift J1753.5–0127 by Durant et al. (2008).

**Key words:** accretion, accretion discs – binaries: close – stars: individual: Swift J1753.5–0127.

## 1 INTRODUCTION

The X-ray source Swift J1753.5–0127 was the first transient black hole candidate discovered by the *Swift* mission on 2005 June 30 (Burrows et al. 2005; Palmer et al. 2005). It was also detected at high energies by the *RXTE* (Morgan et al. 2005) and *INTEGRAL* (Cadolle Bel et al. 2005). The X-ray source was associated with an optical counterpart with  $R = 15.8$  (Halpern 2005) and a blue spectrum showing H $\alpha$  and He II emission (Torres et al. 2005a,b). A variable but unresolved radio counterpart was also identified by Fender, Garrington & Muxlow (2005).

From the outset of the outburst, X- and  $\gamma$ -ray observations indicated that the spectrum and variability properties of Swift J1753.5–0127 were typical of a black hole system in the hard state (Cadolle Bel et al. 2005; Morgan et al. 2005). The presence of a compact radio component is also consistent with this (Fender et al. 2005). While canonical black hole systems often enter a soft thermally dominated state near outburst peak, there are a number of other systems that have remained in the hard state throughout (Brocksopp, Bandyopadhyay & Fender 2004).

Relatively little is known about the binary system. We identified significant optical variability and short time-scale correlations with

X-rays (Hynes & Mullally 2005a,b). Interpreting the small lags seen as due to thermal reprocessing in an accretion disc around a black hole, we suggested a relatively short period of less than 12 hours (Hynes 2006). This was subsequently supported by optical photometric observations that found a 3.24 h periodicity interpreted as a superhump modulation (Zurita et al. 2007, 2008). If this interpretation is confirmed, then the orbital period will be slightly less than this, making this the shortest orbital period black hole candidate yet discovered.

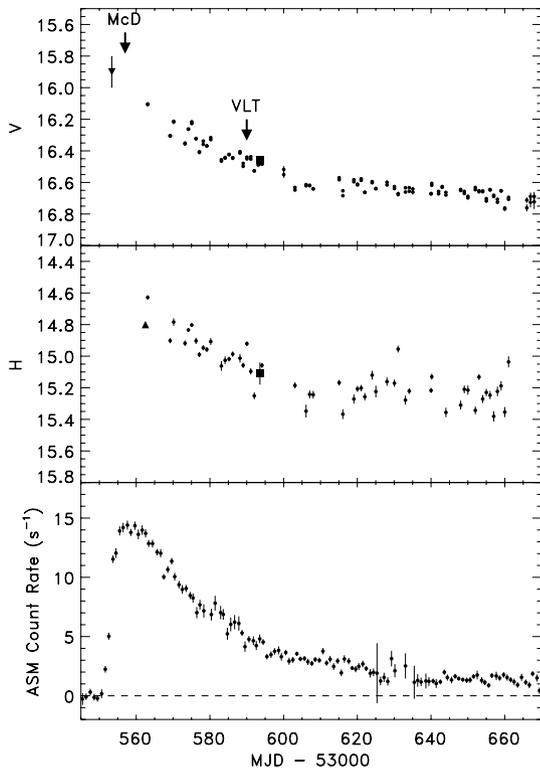
In this work, we present two epochs of coordinated X-ray and optical observations at high time resolution during the main outburst in 2005, one in early July and the other in early August. Preliminary results from this study were presented by Hynes & Mullally (2005a,b), Hynes (2006) and Hynes (2007). We note that Durant et al. (2008) reported similar, but not exactly the same, behaviour as we see in our August observation during a later phase of activity in 2007.

## 2 OBSERVATIONS

### 2.1 SMARTS 1.3-m Andicam data

We performed daily monitoring, where possible, using the Small and Moderate Aperture Research Telescope System (SMARTS) 1.3-m telescope at Cerro Tololo, Chile, for the first three

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**Figure 1.** Light curves of the early outburst. The upper two panels are from SMARTS data, the lower from *RXTE*/All Sky Monitor (ASM) monitoring. The downward pointing triangle shows the *Swift*/Ultraviolet and Optical Telescope (UVOT) measurement of Still et al. (2005). The upward pointing triangle is from Torres et al. (2005b), and square points are from Cadolle Bel et al. (2007). Times of coordinated observations are shown.

months of the outburst until visibility became compromised. Observations used the Andicam dual-channel optical/infrared (IR) camera. Two 130 s *V*-band observations were performed together with five 50 s dithered *H*-band images each night.

All data reduction used standard procedures in *IRAF*. Optical data were supplied with satisfactory pipeline reduction. IR data from each night were median filtered to create a sky image which was then subtracted from each frame before shifting and coadding the individual images. In both bands, aperture photometry was performed relative to a comparison star in the field.

The optical comparison star was calibrated relative to several standard stars in the field of T Phe (Landolt 1992). The IR comparison star was calibrated relative to Two-Micron All-Sky Survey photometry. In both cases, the uncertainty in the calibration was  $\sim 0.04$  mag.

Our *V* and *H* light curves are shown in Fig. 1. We have supplemented these light curves with additional points from Still et al. (2005), Torres et al. (2005a) and Cadolle Bel et al. (2007).

## 2.2 McDonald 2.1-m Argos data

Fast optical photometry was obtained on 2005 July 6 and 7 for approximately 1.5 hours each night using the Argos CCD photometer on the McDonald Observatory 2.1-m telescope (Nather & Mukadam 2004). Observations on each night were performed as an uninterrupted time series of 1 s exposures using a *V* filter; there was no dead time between exposures. Absolute timing was synced to Global Positioning System (GPS) 1 s ticks and multiple Network Time Protocol (NTP) servers.

Custom IDL software written for the instrument was used to subtract dark current and bias and flat-field the data before performing aperture photometry of Swift J1753.5–0127 and a brighter comparison star using a 2 arcsec radius aperture.

## 2.3 Very Large Telescope 8-m FORS2/HIT data

Further rapid observations were performed on 2005 August 9 using the HIT fast imaging mode (O’Brien 2007) of the FORS2 instrument on the European Southern Observatory’s Unit Telescope 2 (UT2)/Very Large Telescope (VLT) telescope on Cerro Paranal, Chile. The observation was taken with the *V*-band Bessel filter. The HIT mode uses a slit to allow only a small fraction of the CCD to be exposed to light. It then shifts the charge from this exposed region at regular intervals and stores it on the unexposed regions of the CCD. Once the masked region is full (after accumulating data for 64 s), the shutter is closed and the CCD read out in the usual manner. The slit width used in the observations was 3 arcsec, which projects on to 12 (binned) pixels implying a time resolution of 0.5 s. The image was very stable, with an rms deviation of 0.14 pixels during the entire run. The image quality was equally stable with a mean full width at half-maximum (FWHM) of 2.44 pixels (0.61 arcsec) and an rms of 0.2 pixels. The flux was extracted using a variable one-dimensional aperture along the slit on the bias subtracted images. The width of the aperture was set to be  $5 \times \text{FWHM}$ , as measured from a fit to the comparison star profile. The sky was measured in symmetric regions around this. An identical aperture was used to extract the flux from the comparison star.

## 2.4 *RXTE*/PCA data

All high time-resolution observations were coordinated with public *RXTE*/Proportional Counter Array (PCA) observations. For this analysis, we used Standard 1 mode light curves with 125 ms time resolution and all energy channels merged into a single bin. Each light curve was extracted from final data products using standard tools.

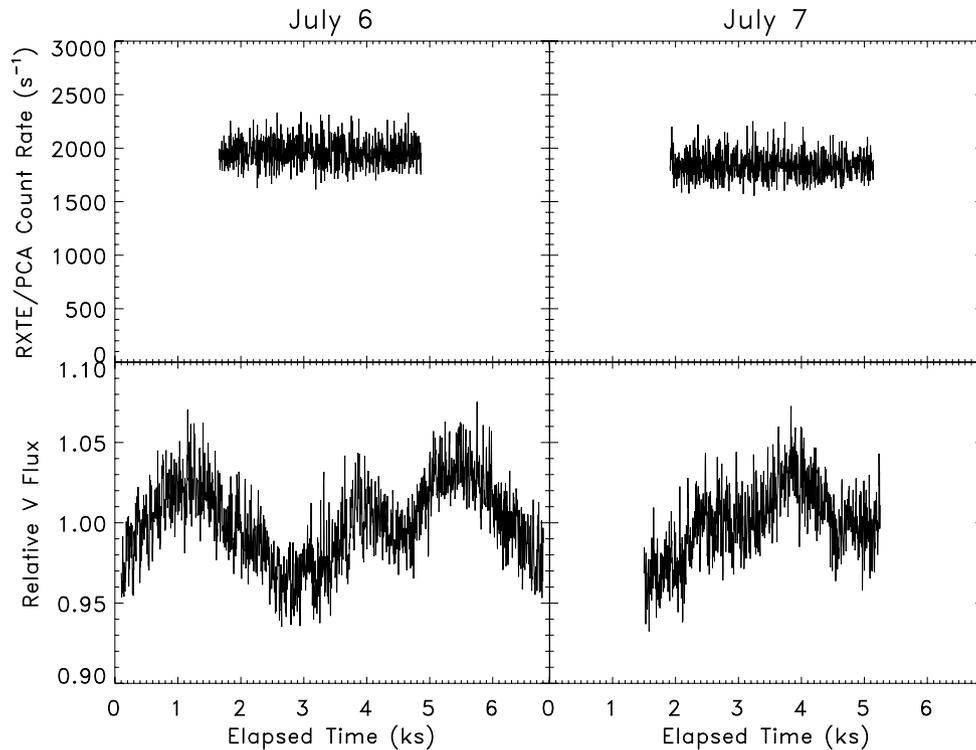
## 3 THE OUTBURST LIGHT CURVE

In Fig. 1, we show optical, IR and X-ray light curves spanning the first three months of outburst. The source followed a fast rise, slow decay pattern with a plateau seen around 60 days after the outburst peak. This is a very common morphology for a transient black hole outburst (Chen, Shradar & Livio 1997). We also indicate the times of our rapid optical observations. The first occurred almost exactly at the outburst peak, the second about a month later on the decline, somewhat before the plateau. The optical observations of Zurita et al. (2008) and Durant et al. (2008) were obtained much later, beyond the coverage here.

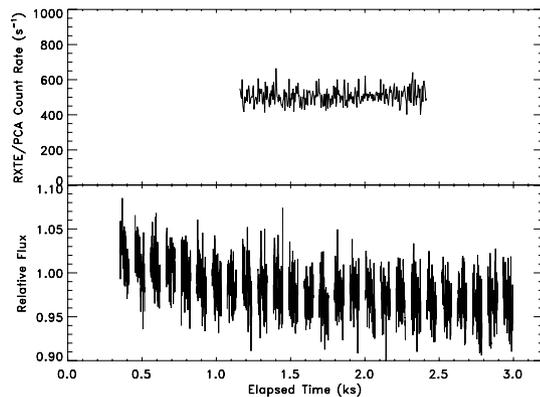
## 4 LIGHT CURVES

### 4.1 Outburst peak

The light curves from July 6 and 7, near the outburst peak, are shown in Fig. 2. The X-ray light curves show no long-term variations, but considerable rapid variability (rms  $\sim 12$  per cent on time-scales longer than 1 s compared to a statistical uncertainty of 2 per cent). The optical data, on the other hand, show substantial lower frequency variability. The data appear consistent with a 1.2 h period, although they are insufficient to prove that these observations are truly periodic rather than stochastic. If real, this periodicity



**Figure 2.** Light curves from our first coordinated observations. All have been binned to 4 s time resolution for clarity, and an arbitrary offset in time has been applied (while preserving the relative timing of the X-ray and optical light curves.)

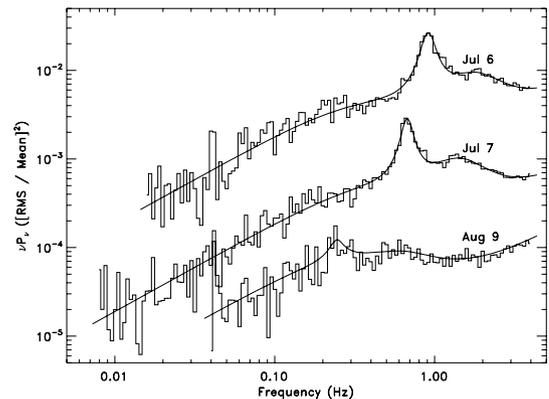


**Figure 3.** Light curves from our second coordinated observation. All have been binned to 4 s time resolution for clarity, and an arbitrary offset in time has been applied (while preserving the relative timing of the X-ray and optical light curves.)

does not correspond to either the proposed orbital period  $\sim 3.2$  h (Zurita et al. 2008) or the first harmonic of it. Spurious apparent periods are not unusual in outburst (e.g. Leibowitz et al. 1991), so we do not believe that the 1.2 h ‘period’ is real and disregard it.

#### 4.2 Outburst decline

The light curves from August 9 are shown in Fig. 3. The source is clearly considerably fainter in X-rays, but considerable variability is still present (rms  $\sim 15$  per cent on time-scales longer than 1 s). It is hard to directly compare these with the July optical observations due to the very different characteristics of the data. Both slow and rapid optical variations do appear to be present, however, as in the previous data sets.



**Figure 4.** PDS of *RXTE* data from the three simultaneous observations. The fits, each of three Lorentzians plus white noise, are described in the text. The July 7 PDS has been scaled down by a factor of 10 and the August 9 one by a factor of 100 for clarity.

### 5 POWER DENSITY SPECTRA

To better characterize the temporal properties at each epoch, we have calculated power density spectra (PDS) of each *RXTE/PCA* light curve and show them in Fig. 4. The general form of each PDS is band-limited noise (BLN), resembling a broken power law, characteristic of the hard state. The data from July additionally include a strong low-frequency quasi-periodic oscillation close to 1 Hz. We fit these PDS with a multi-Lorentzian decomposition following Belloni, Psaltis & van der Klis (2002). The band-limited noise is represented by a zero-centred Lorentzian (i.e. one with zero centroid frequency) and the Quasi-Periodic Oscillation (QPO) by a peaked one (i.e. one with non-zero centroid frequency). Even when white noise is included, we find pronounced residuals at a few Hz,

**Table 1.** Characteristic frequency ( $\nu_{\max}$ ) and amplitude ( $r$ ) of multi-Lorentzian fits to X-ray PDS.

| Date     | Component | $\nu_{\max}$ (Hz) | $r$               |
|----------|-----------|-------------------|-------------------|
| July 6   | BLN       | $0.46 \pm 0.04$   | $0.136 \pm 0.004$ |
|          | QPO       | $0.940 \pm 0.014$ | $0.098 \pm 0.006$ |
|          | QPO2      | $2.5 \pm 0.2$     | $0.10 \pm 0.02$   |
| July 7   | BLN       | $0.67 \pm 0.06$   | $0.141 \pm 0.005$ |
|          | QPO       | $0.685 \pm 0.005$ | $0.089 \pm 0.003$ |
|          | QPO2      | $1.88 \pm 0.06$   | $0.106 \pm 0.006$ |
| August 9 | BLN       | $0.64 \pm 0.12$   | $0.20 \pm 0.02$   |
|          | QPO       | $0.251 \pm 0.014$ | $0.045 \pm 0.010$ |
|          | QPO2      | $0.87 \pm 0.13$   | $0.06 \pm 0.02$   |

so include a second broader QPO. This is a similar model to that adopted by Cadolle Bel et al. (2007) except that we allow the third Lorentzian to be a peaked QPO rather than a band-limited noise component.

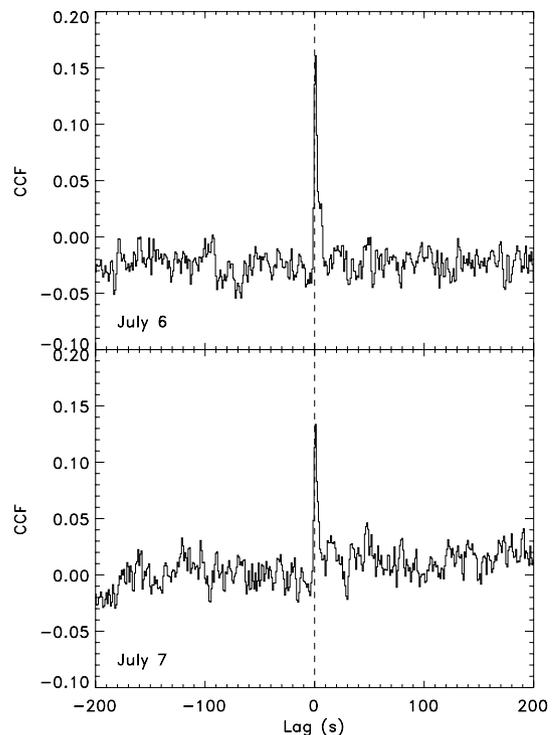
With these components, good fits can be obtained for all three nights. We summarize the characteristic frequency and amplitude of each component in Table 1. The QPOs were less pronounced on August 9 than they were in July, but with lower amplitudes the same model provides a good fit, and a QPO does still appear to be required. We did have to fix the widths of the QPOs on August 9 to the average values of the July observations to adequately constrain the fit. The most important quantity for our later correlation analysis is the characteristic period of the primary QPO. This is 1.06 s for July 6, 1.46 s for July 7 and 4.0 s for August 9. Since the Argos time resolution is only 1 s, we would not expect the QPOs to be resolved in the July optical data and their main effect is likely to be indistinguishable from an excess of white noise. The 4.0 s QPO in August could have a much more significant effect on our analysis.

## 6 CROSS-CORRELATION FUNCTIONS

### 6.1 Outburst peak

Cross-correlation functions (CCFs) for the July 6 and 7 observations near the outburst peak are shown in Fig. 5. Although correlations were not obvious in the light curve, they are clearly present at high significance, with a strong response at or close to zero lag and an extended tail lasting for a few seconds.

The obvious interpretation of the correlation is that it arises from thermal reprocessing either in an accretion disc or on the surface of the companion star. The lag of the companion star response modulates with orbital phase with an average of approximately the binary separation in light-seconds. With the parameters discussed in Section 7, the binary separation would be about 5 light-seconds and so the companion peak lag would modulate in the 0–10 s range. Since our observations span 1.5 hours each night and the orbital period is estimated to be 3.2 hours (Zurita et al. 2008), we cover about half an orbit on each night. On both nights, we observe a peak lag close to zero, so it is unlikely that the companion is dominating the response, which instead appears to originate from the accretion disc. Additionally, black hole systems are expected to usually have small mass ratios, and the presence of likely superhumps (Zurita et al. 2007) supports this expectation in this case. If the mass ratio is indeed small, then the companion star will subtend only a small solid angle as seen by the X-ray source, and hence would be expected to reprocess much less light than the accretion disc.



**Figure 5.** CCFs for July data from the outburst peak. Positive lags indicate that the optical lags behind the X-rays. No detrending or filtering has been done to the data.

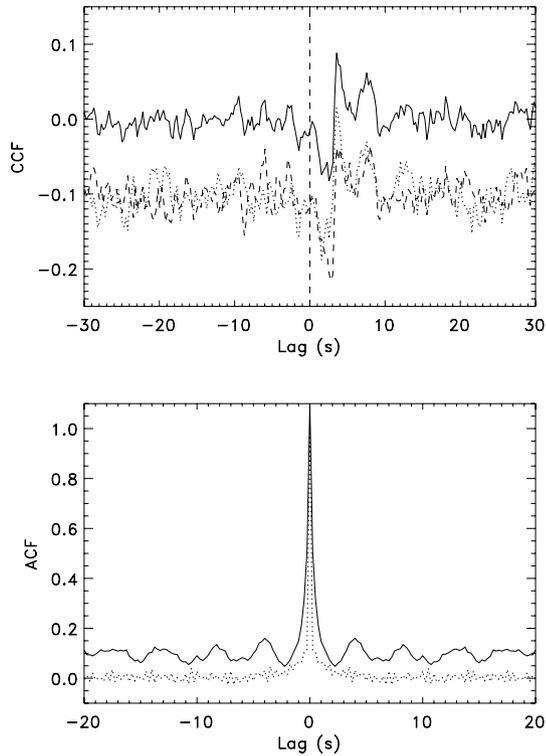
We should be somewhat cautious, however, as similar CCFs were seen in the ultraviolet in XTE J1118+480 (although not in the optical), where they may be associated with jet emission. This seems less likely in this case, however, as the correlations are observed at the peak of an apparently normal outburst, and the optical spectrum is blue and can be fitted by that of an accretion disc (Still et al. 2005). In addition, the optical autocorrelation function is found to be broader than the X-ray one as expected for thermal reprocessing, and unlike that seen in XTE J1118+480. We cannot conclusively rule this possibility out, however, especially as the CCFs seen in August (at lower luminosity) do resemble those of XTE J1118+480.

### 6.2 Outburst decline

We have similarly calculated CCFs for August 9 using VLT data. We do not then have two independent observations; however, we can compute independent CCFs by using odd and even segments of the optical data. For these data, we computed CCFs for each optical segment separately and coadded them. We show both the odd and even CCFs, and the combined CCF in Fig. 6.

The results are somewhat puzzling. A correlation is clearly present, with the structure of the feature well reproduced in both independent CCFs. The two observatories are obviously themselves completely independent, so instrumental effects cannot be responsible, and this feature must be intrinsic to the source. The shape of the CCF is strange, exhibiting a dip followed by two pronounced peaks. This general structure is not unprecedented. A similar dip followed by peak structure was seen by Kanbach et al. (2001) in XTE J1118+480, and later in the activity of Swift J1753.5–0127 Durant et al. (2008) found a strong dip followed by a weak peak.

The overall dip plus peak structure, and indeed the time-scales involved, are rather similar to those seen in XTE J1118+480, and



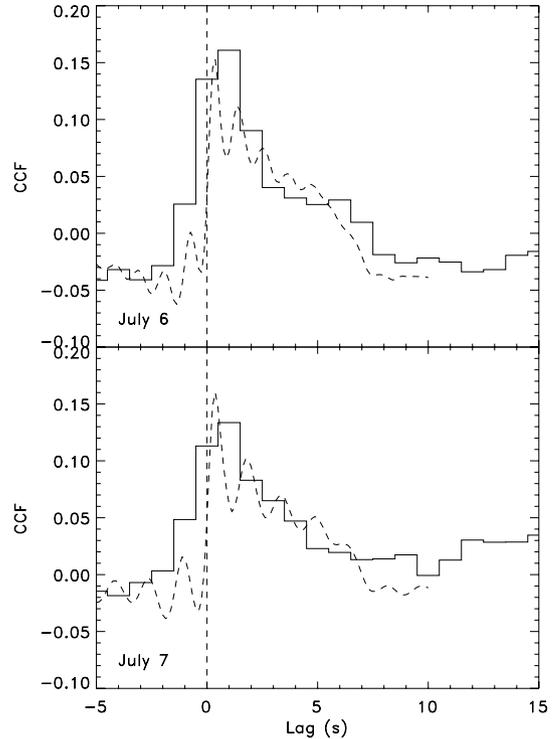
**Figure 6.** Cross- and auto-correlation functions for August 9 data from the outburst decline. In the upper panel CCFs, the upper solid line is computed from the full data set, the lower dashed and dotted lines separate odd and even optical observations to demonstrate the repeatability of the structures seen. In the lower ACFs, the solid curve is the X-ray ACF which has been offset by +0.1 and the dotted curve is the optical ACF. The latter includes a large component of statistical noise at lag 0, and may also be affected at small lags by the blurring of the data in the time-axis introduced by the data acquisition method (see Section 2.3).

less so to the later observations of Swift J1753.5–0127. The double peak has not been seen in other sources. One possible explanation is that this is actually related to the weak QPO seen at this epoch. We deduced a 4.0 s periodicity for this, and the two main CCF peaks in Fig. 6 are separated by 4.0 s. We therefore interpret the splitting of the peak as a result of the QPO aliasing the CCF structure.

## 7 MODEL TRANSFER FUNCTIONS

If we interpret the July correlations as arising from thermal reprocessing, we can investigate them further by comparing them with predicted disc transfer functions from O’Brien et al. (2002). We are of course at a disadvantage in not having a full set of system parameters. As a starting point, we can however make plausible assumptions. The most reasonable is that the orbital period is indeed close to 3.2 hours as suggested by Zurita et al. (2008). Others are largely guesses. We assume a representative black hole mass of  $7 M_{\odot}$ , a mass ratio of 0.1 (reasonable for a short-period system believed to exhibit superhumps), an inclination of  $60^{\circ}$  (the most probable inclination to be drawn from a random distribution) and a tidally truncated disc.

We calculate the transfer function following the methods of O’Brien et al. (2002). As done by Hynes et al. (2003), we then convolve the transfer function with the X-ray autocorrelation function to obtain a predicted CCF. This is more useful than attempting to compare with the light curves themselves when correlated fea-



**Figure 7.** CCFs for July data from the outburst peak (shown as histograms) compared with those expected for disc transfer functions (shown dashed).

tures cannot be directly seen in the light curves and the correlation only emerges when averaging many features in a CCF.

We show the results in Fig. 7. Note that both model CCFs show an oscillatory character. This is a feature of the X-ray Auto-Correlation Function (ACF), and is a consequence of the QPO in the X-ray light curves. Overall, the agreement between model and observed CCFs is good, supporting the interpretation of the correlation as arising from disc reprocessing.

## 8 DISCUSSION

We have interpreted correlations seen at the outburst peak as due to thermal reprocessing and those on the decline as instead associated with synchrotron emission as inferred for XTE J1118+480. These interpretations are obviously rather speculative and uncertain.

Thermal reprocessing at the outburst peak is eminently plausible, and the lags are in the range expected given the proposed orbital period of the binary. Other X-ray binaries have shown correlations consistent with reprocessing in the disc (e.g. Hynes et al. 1998; Hynes 2006, 2007), and the spectral energy distribution at outburst peak could be successfully modelled as due to an accretion disc (Still et al. 2005). This can be considered the most natural interpretation.

Associating the correlations seen on the decline with synchrotron emission is more tentative. Primarily we are interpreting the presence of the dip in the CCF; had this not been present, we would not have led to this conclusion. In XTE J1118+480, the presence of optical synchrotron could be associated with a very flat spectral energy distribution extending into the IR. This was clearly not the case early in the outburst of Swift J1753.5–0127 as the SED was modelled as a disc. In fact our SMARTS monitoring data show no evidence for a change in the shape of the SED during the period

observed, with the  $V - H$  colour remaining approximately constant to within the accuracy of our measurements.

The absence of a change in the optical/IR colour does call a synchrotron interpretation into question. Given the evolution of the source between the two epochs, there is no reason to expect that the origin of the correlated variability should be different. None the less, the CCFs clearly are very different, and so a change must have occurred. Of course, if the decline data are associated with synchrotron emission, and the SED has not changed, we cannot rule out synchrotron emission at the peak as well. This seems less likely, as argued above, but this possibility cannot be completely rejected.

## 9 CONCLUSIONS

We have presented a study of the correlated X-ray and optical variability in the black hole candidate Swift J1753.5–0127 at two epochs, one at the peak of the outburst (2005 July 6 and 7) and the other on the decline phase (2005 August 9). Data from July show a smeared and lagged correlation that can be readily interpreted as arising from thermal reprocessing in the accretion disc. Data in August show a dip and peak structure similar to that seen in XTE J1118+480. Much later in the outburst Swift J1753.5–0127 showed a strong dip followed by a weak peak (Durant et al. 2008) indicating that the CCF morphology varies with the source state. If it arises in the same way as in XTE J1118+480, we should interpret it as due to the optical synchrotron emission possibly associated with a jet, but in the absence of spectral evidence for a jet contribution in the optical this remains a somewhat unsatisfying explanation. As suggested by Durant et al. (2008), it is possible that the origin is synchrotron or cyclotron emission from above the disc rather than from a jet.

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