A 420-day X-ray/optical modulation and extended X-ray dips in the short-period transient Swift J1753.5−0127

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Accepted 2013 May 1. Received 2013 May 1; in original form 2013 March 21

ABSTRACT
We have discovered a ~420-d modulation, with associated X-ray dips, in Rossi X-Ray Timing Explorer-All Sky Monitor/Monitor of All-Sky X-ray Image/Swift-Burst Alert Telescope archival light curves of the short-period (3.2 h) black hole X-ray transient, Swift J1753.5−0127. This modulation only appeared at the end of a gradual re-brightening, approximately 3 yr after the initial X-ray outburst in mid-2005. The same periodicity is present in both the 2–20 and 15–50 keV bands, but with a ~0.1 phase offset (≈40 d). Contemporaneous photometry in the optical and near-infrared reveals a weaker modulation, but consistent with the X-ray period. There are two substantial X-ray dips (very strong in the 15–50 keV band, weaker at lower energies) that are separated by an interval equal to the X-ray period. This likely indicates two physically separated emitting regions for the hard X-ray and lower energy emission. We interpret this periodicity as a property of the accretion disc, most likely a long-term precession, where the disc edge structure and X-ray irradiation are responsible for the hard X-ray dips and modulation, although we discuss other possible explanations, including Lense–Thirring precession in the inner disc region and spectral state variations. Such precession indicates a very high mass ratio low-mass X-ray binary, which even for a ~10 M⊙ BH requires a brown dwarf donor (~0.02 M⊙), making Swift J1753.5−0127 a possible analogue of millisecond X-ray pulsars. We compare the properties of Swift J1753.5−0127 with other recently discovered short-period transients, which are now forming a separate population of high-latitude BH transients located in the galactic halo.

Key words: X-rays: individual: Swift J1753.5-0127.

1 INTRODUCTION
Soft X-ray transients or X-ray novae (hereafter XRTs) are low-mass X-ray binaries (LMXBs) consisting of a neutron star (NS) or black hole (BH) compact object (M₁) accreting from a low-mass companion (M₂). 75 per cent of XRTs are believed to harbour a BH (McClintock & Remillard 2006), and are characterized by long periods of quiescence (years to decades) followed by X-ray outbursts which can increase the luminosity by several orders of magnitude. Black hole X-ray transients (BHXTs) have proven to be important in studying X-ray binaries (XRBs), as in quiescence they provide the opportunity to study the donor itself, which is mostly impossible in luminous, persistent XRBs (Charles & Coe 2006).

Swift J1753.5−0127 (hereafter J1753) was discovered by the Swift-Burst Alert Telescope (BAT) in 2005 (Palmer et al. 2005) as a hard-spectrum (γ-ray source) XRT at high galactic latitude (+12°). The source peaked within a week, at a flux of ~200 mCrab, as observed by the Rossi X-Ray Timing Explorer (RXTE)-All Sky Monitor (ASM; Cadolle Bel et al. 2007). The source was also detected in the ultraviolet (UV), with Swift’s Ultraviolet/Optical Telescope (UVOT; Still et al. 2005), and in the radio with Multi-Element RadioLinked Interferometer Network (MERLIN; Fender, Garrington & Muxlow 2005). An R ~ 15.8 optical counterpart was identified by Halpern (2005), who noted that it had increased by at least 5 mag [as it is not visible on the Digitized Sky Survey (DSS)], thereby establishing J1753 as an LMXB. Subsequent time-resolved photometry of the

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observed R-band modulations on a period of 3.2 h, which are now well established. By analogy with other XRTs (e.g. XTE J1118+480; see Zurita et al. 2002), these were interpreted as a superhump period ($P_{orb}$), slightly longer than the orbital period ($P_{orb}$).

Almost immediately after the outburst peak the X-ray flux of J1753 started declining, but it then stalled at \(\sim 20\) mCrab for over 6 months rather than returning to quiescence as might have been expected. Another well-known XRT to remain active for a significant period of time in this way is EXO 0748–676, a NS system and X-ray burster which remained active for 24 yr before finally returning to quiescence (Wolff et al. 2008). J1753 unusually showed a steady increase in flux from late 2005, eventually producing an increase in hard band activity that was noted in mid 2008 (Krimm et al. 2008) and at lower energies in late 2009 (Negoro et al. 2009). Despite this long-term trend in X-ray flux, it remained in the low-hard (LH) state for \(\sim 4.5\) yr after outburst, at which point it then underwent a complex transition to the hard intermediate state for a brief period before returning to the LH without passing through a soft state (Soleri et al. 2013).

With a large optical increase at outburst, it is not surprising that there has been no spectroscopic signature of the donor in J1753 (Durant et al. 2009), but with no detectable fluorescence features either, it has not been possible to obtain any direct indication of the compact object mass. However, INTEGRAL observations highlighted the presence of a hard power-law tail up to \(\sim 600\) keV, very typical of a black hole candidate (BHC) in the hard state (Cadolle Bel et al. 2007). Also the power density spectrum from a pointed RXTE observation revealed a 0.6 Hz quasi-periodic oscillation (QPO) with a shape that is typically seen in BHCs (Morgan et al. 2005). J1753 is therefore a BHC with the third shortest $P_{orb}$ known (after Swift J1357.2–093313; Corral-Santana et al. 2013, and MAXI J1659–152; Kuulkers et al. 2013). Given the high galactic latitude of J1753, Cadolle Bel et al. (2007) concluded that its distance is 4–8 kpc, placing it in the galactic halo, similar to the BHXRT XTE J1118+480 (Wagner et al. 2001).

In this paper we present a detailed analysis of the long-term X-ray observations of J1753, using data from the RXTE-ASM, Swift-BAT and the Monitor of All-Sky X-ray Image (MAXI) on-board the International Space Station (ISS; Matsuoka et al. 2009) as well as monitoring from various optical telescopes. We focus here on the variability of the source over the near 7 yr coverage provided by these facilities and in particular, note extended X-ray dips that are present in the BAT data.

2 OBSERVATIONS AND ANALYSIS

2.1 Observations

J1753 has been more or less continually observed by multiple X-ray to $\gamma$-ray instruments since its original outburst in 2005. Public data from MAXI, Swift-BAT and the RXTE-ASM have been used to produce the \(\sim 7\) yr light curves presented here. The data required no significant processing and are all available online.\(^1\)\(^2\)

J1753 was also observed by the two 2-m robotic Faulkes Telescope North (located at Haleakala on Maui) and Faulkes Telescope South (at Siding Spring, Australia), of the Faulkes Telescope Project (FTP), which are part of the Las Cumbres Observatory Global Telescope (LCOGT) network (e.g. Lewis et al. 2010). Photometry was performed in the $I$, $R$ and $V$ bands and the data were reduced using the FT pipeline. We also have optical data from the 80-cm IAC-80 telescope at the Observatorio del Teide on Tenerife, and both the 1.5-m and 0.84-m telescopes at the Mexican Observatorio Astronómico Nacional on San Pedro Mártir (Zurita et al. 2008). J1753 has also been monitored in the $H$, $I$ and $V$ bands with the Small and Moderate Aperture Research Telescope System (SMARTS) at Cerro Tololo (Hynes et al. 2009; Soleri et al. 2010).

2.2 Light curves

The 7-yr X-ray light curve of J1753 is shown in 5-d bins in Fig. 1 and exhibits a profile typical of XRTs in outburst, i.e. a fast rise and exponential decay (FRED) profile, with a peak at \(\sim 200\) mCrab (Ramadévi & Seetha 2007). However, after the initial outburst the flux stalled at \(\sim 20\) mCrab for several months before it then started gradually increasing. This behaviour is present in both the BAT and ASM light curves, although we note that it is slightly steeper in the higher energy data. Then, just after MJD \(\sim 54500\), there is a significant increase in flux, following which the light curve begins to exhibit a modulation with a period of \(\sim 400\) d. The sudden increase in X-ray flux has been noted before (Krimm et al. 2008; Negoro et al. 2009), but the long-term variability has not previously been investigated.

We selected X-ray data for timing analysis by excluding the initial outburst/FRED portion, i.e. we used all data after MJD 54000 (see Fig. 1). The periods and their errors were determined using a Lomb–Scargle (LS) analysis to determine a central peak frequency, and then performing a Monte Carlo simulation based on ‘bootstrapping with replacement’ to repeatedly extract a subset of the light curve to re-perform the periodogram analysis on. The distribution of peak frequencies resulting from 10 000 iterations of this process was used to determine the error on the peak frequency. A LS power spectrum was also calculated using the available optical data in the combined $R$-band and FTP $I$-band data, as observations of the source in both these filters exhibited almost identical values. As seen in Fig. 2, there is a clear peak in both X-ray periodograms at 416.4 ± 2.1 d (BAT) and 422.8 ± 2.3 d (combined MAXI/ASM). The power spectrum of the combined optical data also exhibits a peak at a period of 419.2 ± 3.5 d; however, whilst the peak power is still significant, it is lower than that in both X-ray power spectra, and the periodogram is noisier. Nevertheless, it should be noted that these data sets are entirely independent of each other.

When the light curves are folded on $P = 422.8$ d (Fig. 3) it becomes clear that the peak of the hard X-ray light curve (Swift-BAT) precedes that at lower energies (MAXI/ASM) by \(\sim 0.1–0.2\) phase (\(\sim 40–80\) d). There is also evidence of potential dipping structure in the folded Swift-BAT light curve, which we explore further in Section 2.3. The folded optical light curve shows evidence of a tentative anticorrelation between the optical and the hard X-ray flux, with a correlation coefficient $r \approx -0.3$ (at 95 per cent confidence), with a similar value of $r$ being calculated for the optical versus MAXI data. The confidence level was determined from the two-tailed $p$-value calculated alongside the Pearson $r$ coefficient.

2.3 X-ray dips

One of the most remarkable features of the Swift-BAT light curve of J1753 is the presence since MJD \(\sim 55500\) of two extended X-ray dips, which are separated by 420 d, an interval that is fully consistent

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\(^1\) http://maxi.riken.jp/top/
\(^2\) http://heasarc.nasa.gov/docs/swift/results/transients/
\(^3\) http://xte.mit.edu/
with the long-term modulation discussed in Section 2.2. These dips last for ≈25 d and are almost a full eclipse of the hard X-ray flux, and occur at the maximum of the MAXI/ASM modulation. The dips in the Swift-BAT light curve at MJD ≈ 55625 and ≈ 56045 are clearer in the more detailed in Fig. 4, where related, but weaker, features in the lower energy MAXI light curve can also be seen. The MAXI feature is more significant in the first dip (∼30 mCrab) than in the second. Dips on this time-scale are not visible anywhere else in the near 7 yr light curves of the source in either energy band, which is why they are not immediately obvious in the folded Swift-BAT light curve in Fig. 3. Fig. 4 also includes contemporaneous optical monitoring data that have been obtained with FTP and IAC-80. Evidence of optical dips in these data is marginal, although there may be a tentative dip of ∼0.15 mag, coincident with the second hard X-ray dip, in the FTP R-, V- and i′-band data. However, this variation is within the broad range of fluctuations seen on long time-scales, so cannot be considered significant.

3 DISCUSSION

3.1 The 420-d modulation

J1753 is a unique candidate BHXRT in that the source has not returned to quiescence like most transients, but instead is now exhibiting a substantial long-term modulation over a wide range of energies on a period of ∼420 d. Since we know $P_{\text{orb}} \approx 3.2 \, \text{h}$ (Zurita et al. 2008), this modulation is a ‘superorbital’ periodicity of the kind that has now been seen in a significant fraction of XRBs. There are a variety of mechanisms that can give rise to long-term (tens to thousands of days) variations in all types of XRBs (see e.g. Charles, Kotze & Rajoelimanana 2010; Kotze & Charles 2012), but the most likely cause in this case is disc precession as a result of the high mass ratio in BH LMXBs. Such behaviour is well established in the cataclysmic variable (CV) analogues of LMXBs, the SUMa systems, which exhibit ‘superhumps’ on periods very slightly longer than $P_{\text{orb}}$ (see e.g. Warner 1995), as a result of the disc expanding outside its tidal stability radius (for full details see e.g. Whitehurst & King 1991). More importantly, Patterson et al. (2005) have demonstrated an observational link between the period difference (i.e. $P_{\text{sh}} - P_{\text{orb}}$) and mass ratio $q = M_2/M_1$, and this relationship has been extended from CVs to LMXBs. Indeed, it was applied by Zurita et al. (2002) in their analysis of XTE J1118+480.

Consequently, the presence of such long-term time-scales in BHXRTs is taken as evidence of a precessing accretion disc, and hence can be extremely important in being able to provide an indication of $q$ without any direct kinematic measurements. Zurita et al. (2008) claimed a tentative precession period of 29 d from their R-band photometry. This can be interpreted as the beat between the orbital and superhump frequencies, i.e. $P_{\text{prec}} = (P_{\text{sh}}^{-1} - P_{\text{orb}}^{-1})^{-1}$, giving $P_{\text{prec}} = 3.23 \, \text{h}$ for the observed $P_{\text{sh}} = 3.2443 \, \text{h}$. This would imply $q = 0.025$, using $\Delta P = (P_{\text{sh}} - P_{\text{orb}})/P_{\text{orb}} = 0.18q + 0.29q^2$ (Patterson et al. 2005). If we instead re-apply the Patterson relation using our ∼420-d modulation as $P_{\text{prec}}$, we find that this gives a much more extreme $q \sim 0.002$. If the compact object is a typical ∼10 $M_\odot$ BH (Farr et al. 2011), then the donor has a mass of ∼0.02 $M_\odot$, and hence is itself highly evolved.
Such an extreme $q$ suggests a comparison of J1753 with SAX J1808.4–3658, the first accreting millisecond X-ray pulsar (AMXP), with $P_{\text{orb}} = 2\,\text{h}$ (Chakrabarty & Morgan 1998). With an estimated donor mass $M_2 \approx 0.05\,M_\odot$ (Bildsten & Chakrabarty 2001), we suggest that J1753 is a BH analogue to this AMXP system, taking the mass ratio to new extremes. If this is the case, a 0.02$M_\odot$ brown dwarf (BD) donor would require a radius of $\approx 0.14\,R_\odot$ to sustain Roche lobe overflow, and this is consistent with the $M$–$R$ relation of low-mass stars and substellar objects detailed in fig. 2 of Chabrier et al. (2009). This relation is approximately constant below masses of $\sim 0.1\,M_\odot$, which may account for the extended duration of the J1753 outburst, as the BD radius is roughly independent of mass.

Another mechanism we considered for the long-term modulation of J1753 was that of irradiation-driven warping. In this case an initially flat accretion disc is unstable to warping when irradiated by a central source, as the warp then excites the tilt of the disc continuously, thereby leading to precession (Ogilvie & Dubus 2001; Foulkes, Haswell & Murray 2006). This model was used to simulate real binary systems with observed or inferred superorbital periods by Foulkes, Haswell & Murray (2010), who found they could account for observed X-ray luminosities for a given superorbital period ($P_{\text{sup}}$). However, high $q$ systems were found to have the shortest $P_{\text{sup}}$ out of all XRBs examined, and knowing that the donor of J1753 must be very low mass (it is not visible on the DSS), it is unlikely that this scenario applies to J1753.

### 3.2 Properties of the 420-d modulation

The folded light curves in Fig. 3 show that the hard X-ray emission leads at lower energies, but the hardness ratio (HR) modulation (Fig. 3, panel C) shows that this could also be interpreted as a smooth spectral variation. This is reminiscent of that seen in 4U 1636–536, an LMXB with a 3.8-h period that displays long-term variability on time-scales of 30–40 d (Belloni et al. 2007). Remarkably, while the long-term variability was found at both soft (2–12 keV, RXTE-ASM) and hard [20–100 keV, INTEGRAL-Imager on Board INTEGRAL Satellite (IBIS)] X-ray energies, it was also found to be anticorrelated (Shih et al. 2005). The long-term variation was initially suggested to be due to a tilted or warped precessing accretion disc (Shih et al. 2005), and the measured mass ratio allowed for this hypothesis (Casares et al. 2006). However, the variations were not stable and coupled with the anticorrelation between soft and hard X-rays, it is difficult to interpret as a precessing disc (Shih, Charles & Cornelisse 2011). Regardless of the nature of the long-term variations, the soft/hard X-ray anticorrelation seen in the 4U 1636–536 light curves suggests physically separate emission regions responsible for hard and soft X-rays, a hypothesis we believe can be applied to J1753. This theory is further strengthened by the presence of strong X-ray dips in the Swift-BAT light curve of J1753, but only weak dips in the softer MAXI light curve.

### 3.3 Hard X-ray dips

The hard X-ray dips could be attributed to a warped disc structure that obscures the hard X-ray emitting region entirely whilst leaving the softer region mostly visible. We presume that the dips do not appear earlier in the overall light curve as the warp was not yet established at that time. The dip light curves can be used to place constraints on the size of the hard X-ray emitting region if we adopt our derived value of $q$. Assuming that the obscuring material is located at the edge of the disc ($R_1 \approx 1.8\,R_\odot$), the angle swept out...
Figure 4. Panel A: Swift/BAT light curve (15–50 keV) of J1753 with 1-d binning. Panel B: 2–20 keV light curve of J1753 from MAXI, also in 1-d bins. Panel C: HR defined as BAT count rate/MAXI count rate. Panel D: optical photometry of J1753 from the IAC-80 [yellow (R) and green (V) squares] and FTP [red (R), black (V) and white (i′) circles]. In panels A, B and C, the dash–dotted line marks the zero-point and the vertical dotted lines highlight the minimum of the dips. A colour version of this figure is available in the online edition.

by the warp would be ∼21°, from which we roughly estimate a hard X-ray emitting region size of ∼0.3 R⊙. However, we note that the lack of similar scale dips at lower energies implies that the latter is from a significantly more extended region.

We also note that the dips are prominent in the HR light curve (Fig. 4, panel C), which shows similar behaviour in the more extended, but shallower dip at MJD ∼ 55300. Interestingly, this is the interval when Soleri et al. (2013) observed spectral state changes, and so these dips could all be related to such behaviour, although it is not clear why this would be periodic.

Finally, we note that the 420-d separation of the two dips may be consistent with Lense–Thirring precession at the Bardeen–Petterson radius (Bardeen & Petterson 1975). It is at this radius that frame dragging effects from the rapidly rotating BH can give rise to twisted, warped structure in the inner disc, which has been linked to the QPOs seen in many XRBs (Fragile, Mathews & Wilson 2001), and could offer an explanation for the hard X-ray dips. Linking the 0.6 Hz QPO seen in J1753 with the Bardeen–Petterson radius would place it at ∼200 R⊙ (where R⊙ is the Schwarzschild radius of the BH) for a typical BH mass, which could have a Lense–Thirring precession period comparable to our observed 420 d. However, these values are highly dependent on the scaling and spin parameters of the BH as described in equation (4) of Fragile et al. (2001) and such effects have never been seen at these time-scales.

### 3.4 Comparison with other high-latitude X-ray transients

Remarkably the last decade has seen the emergence of a number of short period BHXRTs which we can compare with J1753. Interestingly these are all at high Galactic latitude and hence located in the halo (Table 1), and may represent a subclass of BHXRTs which are difficult to find in soft X-ray surveys, but are seen by Swift-BAT in the LH state.

It is interesting to note that four of the six sources listed show dipping structure. Swift J1357.2−093313 exhibits very fast optical dips (∼2–8 min) and these cannot be Keplerian at the outer disc, but must be in the inner disc region (Corral-Santana et al. 2013). Swift J1357.2−093313 shows no X-ray dips and thus must have a very high i, requiring that the central BH is hidden from view completely, and thus we only see scattered X-rays, accounting for the low peak $F_x ∼ 30$ mCrab, making such systems hard to detect.

On the other hand, MAXI J1659−152 exhibits X-ray dips suggestive of a disc edge structure, hence the range in i shown in Table 1. This highlights the importance of considering the geometry of such systems, as we would not expect this high a fraction of dipping sources within the sample.

### 3.5 Future work

If the hard X-ray dips are indeed a periodic phenomenon, then we predict that the next dip will occur in 2013 June, with the minimum being reached ∼June 18. We will monitor both the Swift-BAT and the MAXI light curves during this time. We also intend to obtain pointed observations with both optical and X-ray telescopes in order to determine the structure of the dips at multiple wavelengths. An ideal instrument to cover the dip structure would be Swift, as a pointed observation would allow simultaneous use of the X-ray Telescope (Swift-XRT) and UVOT, as well as the continued hard

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**Figure 4.** Panel A: Swift/BAT light curve (15–50 keV) of J1753 with 1-d binning. Panel B: 2–20 keV light curve of J1753 from MAXI, also in 1-d bins. Panel C: HR defined as BAT count rate/MAXI count rate. Panel D: optical photometry of J1753 from the IAC-80 [yellow (R) and green (V) squares] and FTP [red (R), black (V) and white (i') circles]. In panels A, B and C, the dash–dotted line marks the zero-point and the vertical dotted lines highlight the minimum of the dips. A colour version of this figure is available in the online edition.
Table 1. Black hole X-ray transients in the galactic halo.

| Source       | $F_x$  | $b$ | $d$ | $v_{dp}$ | $P_{orb}$ | $P_{sup}$ | $q$ | $M_1$ | $i$ | $M_2$ |
|--------------|-------|-----|-----|----------|-----------|-----------|-----|-------|-----|-------|
|              | (mCrab)| (kpc)| (kpc) s$^{-1}$ | (h) | (d) | (d) | (M$_\odot$) | (°) | (M$_\odot$) | |
| GRO J0422+32$^1$ | 3000 | −12$^*$ | ~2.5 | 400 | 5.1 | ? | 0.075 | ~4 | 45$^*$ | 0.3 |
| XTE J1118+480$^2$ | ~40 | +62$^*$ | ~1.8 | 600 | 4.1 | ~52 | <0.025 | 8 | 68$^*$ | 0.2 |
| MAXI J1305−704$^3$ | ~30 | −7$^*$ | ? | 500$^*$ | ? | ? | ? | ? | ? | ? |
| Swift J1357.2−093313$^4$ | ~30 | +50$^*$ | ~1.6 | 900 | 2.8 | ? | <0.06 | >3 | >70$^*$ | 0.2 |
| MAXI J1659−152$^5$ | ~50 | +16$^*$ | 8.6 | ? | 2.4 | ? | <0.08 | >3 | ~65−80$^*$ | 0.15−0.25 |
| Swift J1753.5−0127 | ~200 | +12$^*$ | ~8 | 600 | 3.2 | ~420 | ~0.002 | ~10 | ? | ~0.02 |

Note: $^*$peak X-ray flux; $^*$disc velocity estimated from H$_\alpha$ double peak separation (Warner 1995); $^*$denotes that $v_{dp}$ was estimated from He II data archive.

X-ray monitoring with BAT. Contemporaneous soft and hard X-ray and UV/optical monitoring will allow us to provide constraints on the nature of the dips.

ACKNOWLEDGEMENTS

We would like to thank the anonymous referee for the helpful comments provided. RC acknowledges a Ramon y Cajal fellowship (RYC-2007-01046). RC and JC acknowledge support by the Spanish Ministry of Science and Innovation (MICINN) under the grant AYA 2010-18080. DMR acknowledges support from a Marie Curie Intra-European Fellowship within the 7th European Community Framework Programme (FP7) under contract no. IEF 274805. TD acknowledges funding via an EU Marie Curie Intra-European Fellowship under contract no. 2011-301355. The Faulkes Telescopes (North and South) are maintained and operated by LCOGT. This research has made use of MAXI data provided by RIKEN, JAXA and the MAXI team. We acknowledge results provided by Swift, NASA’s GSFC. We acknowledge the use of public data from the ASM/RXTE teams at MIT and at the RXTE SOF and GOF at NASA’s GSFC. This paper has been typeset from a TeX file prepared by the author.