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Swift J1753.5-0127: The Black Hole Candidate with the shortest orbital period

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ABSTRACT

We present time-resolved photometry of the optical counterpart to the black hole candidate Swift J1753.5-0127 which has remained in the low/hard X-ray state and bright at optical/IR wavelengths since its discovery in 2005. At the time of our observations Swift J1753.5-0127 does not show a decay trend but remains stable at $R = 16.45$ with a night to night variability of ~ 0.05 mag. The R -band light curves, taken from 2007 June 3 to August 31, are not sinusoidal, but exhibit a complex morphology with remarkable changes in shape

and amplitude. The best period determination is 3.2443 ± 0.0010 hours. This photometric period is likely a superhump period, slightly larger than the orbital period. Therefore, Swift J1753.5-0127 is the black hole candidate with the shortest orbital period observed to date. Our estimation of the distance is comparable to values previously published and likely places Swift J1753.5-0127 in the Galactic halo.

1. Introduction

X-ray transients (XRTs) are low-mass accreting X-ray binaries that display episodic X-ray and optical outbursts whose luminosity may increase by several orders of magnitude from quiescent luminosity. Most of them are believed to harbor a black hole as the compact object. Because of large changes in the effective accretion rate during the outburst, XRTs pass through certain identifiable X-ray spectral states.

XRTs at maximum brightness are often observed in a state in which the X-ray emission is dominated by thermal emission from the hot inner accretion disc (i.e., the *high/soft* or *thermal dominated* state). Once the mass accretion rate drops below a critical value, the spectrum switches to a state dominated by a hard non-thermal power law component (i.e., the *low/hard* state – LHS). At ever lower accretion rates XRTs are in quiescence, which may appear as just an extreme example of the LHS. There are, however, systems that in outburst do not reach the thermal dominated state but are instead dominated by a hard non-thermal power-law component (see e.g., Brocksopp et al. 2004). The persistence of the LHS during an outburst can be explained by a truncation of the accretion disc at some large inner radius. The interior volume is filled with a hot, optically thin, quasi-spherical accretion flow, where most of the energy, released via viscous dissipation, remains in the flow rather than being radiated away and is finally advected by the compact object (e.g., Narayan et al. 1996). The LHS of X-ray binaries has been associated with jet activity (Fender et al. 2001). In the context of the coronal evaporation model (Meyer et al. 2000) it is expected that the systems with the shortest orbital periods remain in the LHS throughout the outburst (Meyer-Hofmeister 2004). Examples of such sources are XTE J1118+480 (Hynes et al. 2000), in the Galactic Halo, and GRO J0422+32 (Sunyaev et al. 1993).

Swift J1753.5-0127 was discovered by the Swift Burst Alert Telescope on 2005 Jun 30¹ (Palmer et al. 2005) as a bright, variable γ -ray and hard X-ray transient source. It was

¹The earliest detection of Swift J1753.5-0127 in Palmer et al. 2005 should be 2005-06-30 instead of 2005-05-30 (Palmer, private communication)

also detected in soft X-rays with the Swift X-ray telescope (XRT) and in UV with the UV/Optical Telescope (Morris et al. 2005; Still et al. 2005). The optical counterpart was found with the MDM 2.4 m telescope with $R \sim 15.8$ which was not visible in the Digitized Sky Survey (Halpern 2005) nor in the USNO B1.0 catalog ($V > 21$). Optical spectroscopy of Swift J1753.5-0127 revealed double-peaked $H\alpha$ and $HeII$ emission lines (Torres et al. 2005a,b). Furthermore, the source was detected in radio likely indicating jet activity, which would usually be associated with a LHS. However Swift J1753.5-0127 does not follow the usual radio/X-ray correlation of X-rays binaries in this state (Cadolle Bel et al. 2007). INTEGRAL observations of the source indicate that the spectrum to be typical of a Black Hole Candidate (BHC) in the hard state (Cadolle Bel et al. 2007; Ramadevi & Seetha 2007). Also, its power density spectrum shows a 0.6 Hz quasi periodic oscillation with a shape typically seen in BHCs (Morgan et al. 2005). Analysis of the light curves and hardness ratios of Swift J1753.5-0127 from the RXTE All-Sky Monitor and pointed RXTE observations reveal that the source has remained in the LHS since the onset of its outburst in 2005. However, it has been suggested from fits to the 0.5–10 keV X-ray spectrum that the inner disk is not radially truncated (Miller et al. 2006), supporting a growing body of evidence that disks do not immediately recede when black holes move into the LHS, and that advective flows take hold at lower accretion rates than is marked by the state transition. Finally, Swift J1753.5-0127 might be placed in the Galactic halo if it is located at a distance of about 6 kpc, as has been estimated by Cadolle Bel et al. (2007) from its X-ray flux. The only firmly identified black hole X-ray binaries in the Galactic halo to date are XTE J1118+480 (Wagner et al. 2001) and probably BW Cir (Casares et al. 2004).

In this paper we make a detailed analysis of the long-term time-resolved photometry of the optical counterpart to the BHC Swift J1753.5-0127 updating the preliminary results presented in Zurita et al. (2007). The paper is structured as follows: In §2 we describe the observations and the data reduction procedure. In §3 we present the light curves and study their short and long-term variability. The results are discussed in §4 where we examine questions such as the origin of the periodic modulation in the light curves, the distance towards Swift J1753.5-0127 and the possible halo nature of the source.

2. Observations and data reductions

We observed Swift J1753.5-0127 for a total of 20 nights between June 3 and August 31 with three different telescopes: the 1.5-m and the 0.84-m telescopes at the Mexican Observatorio Astronómico Nacional on San Pedro Mártir, and the 80 cm IAC80 telescope

at the Observatorio del Teide, Tenerife, Spain. The data consist of time-series of R-band photometry acquired during ~ 6 h per night. The exposure time in all sets ranged from 60 to 120 s depending on the telescope and atmospheric conditions. An observing log is presented in Table 1. All images were corrected for bias and flat-fielded in the standard way using IRAF. We performed aperture or profile fitting photometry on our object and several nearby comparison stars which were checked for variability during each night and over the entire data set. Additionally on 2007 Jun 7 we obtained *BVRI* images of our target and of 6 Landolt standard fields (Landolt 1992) to perform a color-dependent calibration of a set of stars in the field of Swift J1753.5-0127 (see Fig.1 and Table 2) .

Table 1: Log of observations

Date	ΔT (h)	Exp. Time (s) / no. exposures	Mean magnitude	Telescope
3/6/2007	7.05	60 / 293	16.42	1.5m SPM
4/6/2007	6.71	60 / 275	16.41	1.5m SPM
5/6/2007	5.23	60 / 223	16.43	1.5m SPM
7/6/2007	6.13	60 / 272	16.44	1.5m SPM
8/6/2007	5.70	60 / 245	16.47	1.5m SPM
12/6/2007	6.87	60 / 281	16.53	IAC80
13/6/2007	4.72	60 / 210	16.50	IAC80
14/6/2007	6.68	60 / 300	16.50	IAC80
18/6/2007	6.93	60 / 165	16.44	IAC80
20/6/2007	6.57	60 / 295	16.51	IAC80
21/6/2007	5.07	60 / 227	16.50	IAC80
27/6/2007	5.09	90 / 166	16.43	84cm SPM
28/6/2007	6.90	90 / 205	16.44	84cm SPM
29/6/2007	7.39	90 / 235	16.42	84cm SPM
1/7/2007	7.52	90 / 191	16.40	84cm SPM
31/6/2007	6.85	90 / 211	16.40	84cm SPM
27/8/2007	4.26	60 / 222	16.43	1.5m SPM
28/8/2007	3.77	60 / 192	16.43	1.5m SPM
30/8/2007	4.52	120 / 127	16.45	1.5m SPM
31/8/2007	3.18	60 / 164	16.45	1.5m SPM

Table 2: Magnitudes for seven comparisons in the field of Swift J1753.5-0127. Errors are less than 0.01 magnitudes

Star	V	$B - V$	$V - R$	$V - I$
1	16.17	1.53	0.81	1.75
2	17.27	0.95	0.54	1.25
3	12.49	0.60	0.37	0.93
4	13.55	0.81	0.42	1.07
5	14.68	1.23	0.67	1.55
6	16.66	0.96	0.49	1.19
7	16.95	1.40	0.72	1.61

3. The light curves

3.1. Long term behaviour

The X-ray light curve of Swift J1753.5-0127 was typical of XRTs in outburst, with a Fast Rise Exponential Decay (Ramadevi & Seetha 2007). It peaked at ~ 210 mcrab on 2005 July 6 (Cadolle Bel et al. 2007). We observed the target about two years after its outburst and, at this time, the source was still bright in the RXTE ASM energy band (1.2–12 keV) with an average flux of ~ 23 mcrab.

Immediately after outburst the optical brightness decayed at a rate of ~ 0.1 mag per week (Torres et al. 2005). The system had $R = 16.15$ on 2005 Aug 11, $R = 16.45$ on Aug 17 and $R = 16.60$ on Aug 27 (Cadolle Bel et al. 2007). At the time of our observations Swift J1753.5-0127 remains stable at $R = 16.45$ with a night to night variability of ~ 0.05 mag. The long term light curve and its periodogram are shown in Fig.2. The magnitude of our object on the night of 2007 June 7 were: $B = 17.00 \pm 0.005$, $V = 16.60 \pm 0.005$, $R = 16.45 \pm 0.005$, $I = 15.95 \pm 0.005$.

3.2. Short term behaviour

In Fig.3 we present the R-band light curves of Swift J1753.5-0127 obtained from 2007 June 3 to August 31. The light curves are not sinusoidal, but exhibit a complex morphology with remarkable changes in shape and amplitude. Some nights they have a sawtooth shape with a ~ 0.15 mag peak-to-peak amplitude whereas other nights they show a peculiar four-peaked modulation (more clear in June 29 in Fig.3) or a flat shape with a deep

dip (as in June 12). They resemble the outburst nightly light curves of the black hole transients GRO J0422+32 (Chevalier & Ilovaisky 1995; Callanan et al. 1995), GS2000+25 (Charles et al. 1991) and Nova Mus 1991 (Bailyn 1992), all attributed to tidal perturbation of the outer regions of the disk by the companion. Peculiar superhump modulations showing several peaks and dips are also often detected in cataclysmic variables (e.g. V603 Aqr; Patterson et al. 1993).

As the light curves are non-sinusoidal, we employed the PDM algorithm (Stellingwerf 1978) to analyze the periodicities present in the data. We detrended the long-term variations by subtracting the nightly means from the individual curves. This removed the low-frequency peaks from our PDM spectrum. The periodogram was computed in the frequency range 0.1 to 30 cycle d^{-1} with a resolution of 1×10^{-3} and 20 phase bins. The deepest minimum is found at 7.3976 cycle d^{-1} which corresponds to a period of 3.2443 ± 0.0010 h (see Fig.4). The frequency uncertainty was derived from the half width at half maximum of the periodogram peak. A consistent result (3.2454 ± 0.0080 h) is obtained when calculating a Lomb Scargle periodogram. The light curves show a complex non-sinusoidal shape which explains why the PDM periodogram shows substantial power at $2P$, P and $P/2$. We folded all our data on this period selected an origin at $T_0 = \text{HJD } 2454249.853$ which corresponds to the minimum observed on 2007 Jun 3 (see Fig.5).

4. Discussion

4.1. Causes of the 3.24 h modulation

At the time of our observations Swift J1753.5-0127 had a mean magnitude of $V=16.60$, more than 4 mag brighter than in quiescence, assuming the quiescent magnitude is $V \geq 21$ as estimated from the USNO B1.0 catalog (Monet et al. 2003). Therefore, it is expected that the companion star is contributing only a tiny fraction of the luminosity and that the optical flux is dominated by the accretion disk. It rules out an ellipsoidal modulation of the secondary as responsible for the modulation. It appears very likely that the 3.24 h periodicity reflects the orbital motion of the underlying binary, through the reprocessing of X-rays by the secondary or superhump modulations. We regard the possibility of the minima occurring near phase 0 are due grazing eclipses of the disk by the secondary star as unlikely because the timing of these minima is sometimes altered (see Fig.5). Also note that no X-ray eclipses have been seen.

The modulation can be due to X-ray heating of the companion. X-ray irradiation, from the inner region of the accretion disk, can deposit energy at a modest optical depth in the atmosphere of the secondary star which is then thermalized and emerges as optical and ultraviolet flux. This has been shown to occur in a number of low mass X-ray binaries in outburst, such as the short-period neutron star transients 4U 2129+47 (Thorstensen et al. 1979) and XTE J2123-058 (Zurita et al. 2000). The optical modulation in these two systems was, however, much larger than we see in Swift J1753.5-0127. The X-ray heating of the companion is easiest to detect in the ultraviolet where the modulation can be very large. Swift J1753.5-0127 was observed in UV two days after the outburst onset (Morgan et al. 2005) but no temporal variability on 10-1000 s timescales above 1-sigma was found (Still et al. 2005). Furthermore, optical colors do not vary significantly with phase (Durant et al. in preparation), which makes this model unlikely.

The shape of the light curves suggests that the 3.24 h periodicity is a superhump modulation. Superhumps are periodic variations in the luminosity of an accreting binary system, first discovered in the SU UMa class of dwarf novae, with a period slightly longer than the orbital period. The most probable explanation for superhumps is they are due to the effect of tidal stresses on a precessing, elliptical accretion disk. The changing shape and amplitude of the light curves can be explained by changes in the shape or size of the disk and resonance between the Keplerian orbits and the orbital motion of the companion. Superhumps only occur in extreme mass-ratio systems, which can form elliptical accretion disks (see eg. Whitehurst & King 1991) and they have been seen in XRTs, both in outburst (O’Donoghue & Charles 1996) and near quiescence (Zurita et al. 2002). In the case of Swift J1753.5-0127 a M2 type, or later, main sequence star is needed to fit within the Roche lobe of a 3.24 h period orbit. Giving $M_2 \leq 0.3 M_\odot$ for the secondary star, the mass ratio may be $q = M_2/M_1 < 0.1$ if the primary is a black hole ($M_1 > 3 M_\odot$). With such low value, the eccentric disk should be forced to precess by perturbations from the secondary. Furthermore, superhumps show no changes in colors redder than U, as is the case here (eg. Haefner et al. 1979). For a superhump, one can estimate the orbital period using the following expression, empirically derived by Patterson et al. (2005): $\Delta P = 0.18 q + 0.29 q^2$, where $\Delta P = (P_{sh} - P_{orb})/P_{orb}$ with P_{sh} and P_{orb} the superhump and the orbital period respectively and q the mass ratio. For Swift J1753.5-0127 $\Delta P < 2\%$ and thus $3.18 h < P_{orb} < 3.2443 h$. Therefore, this is the black hole candidate with the shortest orbital period observed to date (a summary list of orbital periods in black hole binaries can be found in McClintock & Remillard 2006).

Since the superhump is the beat frequency between the orbital and disk precession

frequency, the disk precession period P_{prec} is given by $P_{prec} = (P_{orb}^{-1} - P_{sh}^{-1})^{-1} > 7$ d (for a main sequence M secondary and a $> 3 M_{\odot}$ black hole). In our long term light curve, a ~ 0.1 mag modulation is visible (Fig. 1) so we have tentatively searched for periodicities during this epoch by calculating a Lomb Scargle periodogram of our entire data set in the frequency range 0 to 3 cycled^{-1} . The highest peak is found at 0.034 cycled^{-1} which corresponds to a period of ~ 29 day (Fig.2 – bottom panel). This periodicity, if real, could be associated to the precession of the accretion disk. A sinusoidal fit with 29 d period is shown with the long-term light curve in Fig.2 (top panel). Given the orbital period implied by $P_{prec}=29$ day, i.e., $P_{orb}=3.23$ h, we infer $q = 0.025$ and $M_1 = 12 M_{\odot}$ for a M2 type secondary star. The confirmation of the orbital period and of the secondary star nature will come from radial velocity variations and from observations in quiescence.

4.2. A new black hole candidate in the Galactic halo?

We can estimate the distance d to the source by comparing the quiescent magnitude V_{quiet} with the absolute magnitude of a M2 type main sequence star. The quiescent magnitude is unknown although $V_{quiet} > 21$ according the nearby faint USNO B1.0 catalog (Monet et al. 2003). With $A_V \sim 1.05$ (Cadolle Bel et al. 2006) the system has a distance $d > 1$ kpc.

Futhermore, Shahbaz & Kuulkers (1998) determined an empirical relation for the absolute magnitude of the accretion disk during XRT outburst, from which we can estimate the distances to the sources. For systems having $P_{orb} < 12$ h:

$$5 \log d_{kpc} = V_{out} - A_v - 2.5 \log f - 12.34 + 3.47 \log P_{orb}(h) \quad (1)$$

where d_{kpc} is the distance in kpc and f is the fraction of light arising from the secondary star in quiescence. If we assume $f=1$ then the distance estimate is a lower limit. Using this relation we estimate $d_{kpc} > 7.2$ for Swift J1753.5-0127.

Alternatively, in the context of King & Ritter (1998) the X-ray exponential decay indicates that irradiation is strong enough to ionize the entire accretion disk. Also, a secondary maximum is expected, one irradiated-state viscous time after the onset of the outburst. This can be used to calibrate the peak X-ray luminosity and hence the distance to the source.

$$d_{kpc} = 4.3 \times 10^{-5} t_s^{3/2} \eta^{1/2} r^{1/2} F_p^{-1/2} \tau_d^{-1/2} \quad (2)$$

where F_p is the peak X-ray flux, t_s the time of the secondary maximum after the peak of the outburst in days, τ_d the e-folding time of the decay in days, η the radiation efficiency parameter and r the ratio of the disk mass at the start of the outburst to the maximum possible mass (Shahbaz et al. 1998). In our case $F_p=7.19 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 3–25 keV energy range, $\tau_d=31$ (Ramadevi & Seetha 2007) and $t_s=53$ from the X-ray light curve. Assuming $\eta=0.05$, and $r=0.5$ we find $d_{kpc}=5.6$. For η between 0.01–0.05, and f between 0.5–1 d_{kpc} varies between 2.5 and 7.9 kpc.

The Galactic latitude of Swift J1753.5-0127 is $b^{II} = 12^\circ.2$ so, taking a central value for the distance of $d=5.4$ kpc, the source should be at $z=1100$ pc above the Galactic plane, rather large compared to the distribution of the BHCs, for which the mean is about 625 pc (Jonker & Nelemans 2004). Among the BHCs, Swift J1753.5-0127 shows the strongest similarities with XTE J1118+480 and GRO J0422+32. These latter two systems have also been observed in the LHS, exhibit superhump modulations (O’Donoghue & Charles 1996; Uemura et al. 2000; Zurita et al. 2002), have the shortest orbital periods: 4.1 h (McClintock et al. 2001; Wagner et al. 2001) and 5.1 h (Filippenko et al. 1995) respectively and have also high Galactic latitudes. It is hence interesting to consider whether Swift J1753.5-0127 belongs to a population of Galactic high- z . The discovery of such a population of halo BHCs in the Galaxy could impose new constraints on the formation and evolution of the black hole XRTs.

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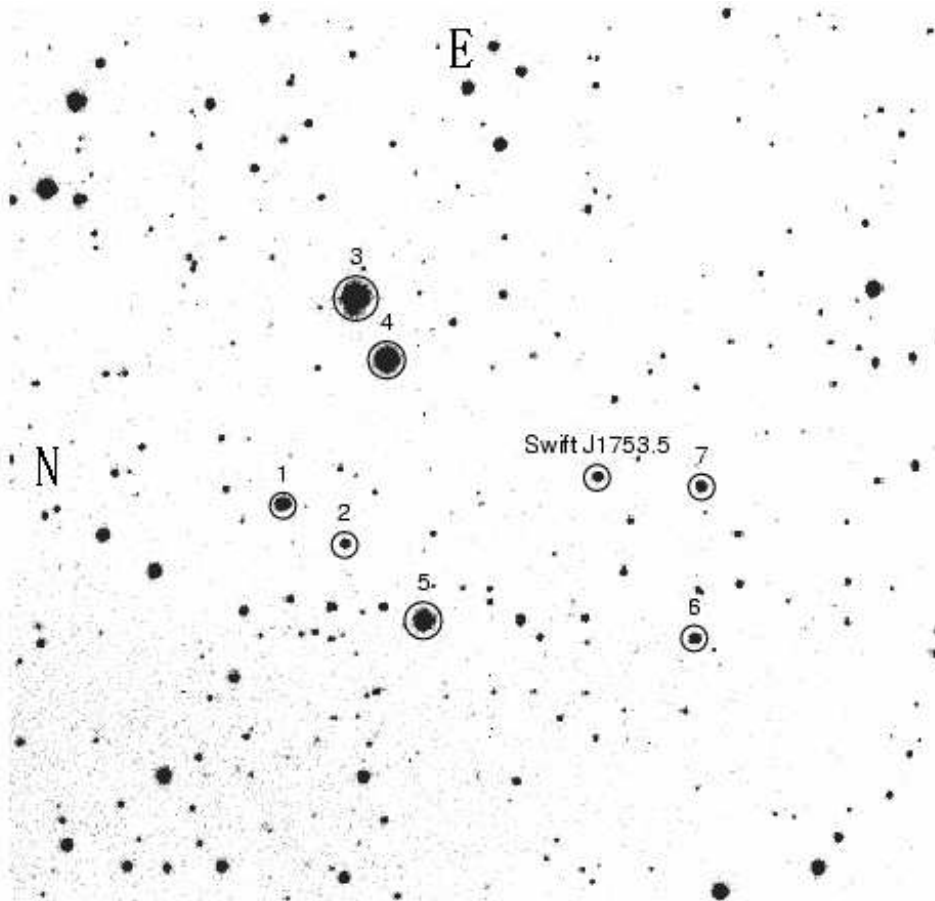


Fig. 1.— R-band 60-s image of Swift J1753.5-0127. The field of view is 4.2×4.2 arcmin. The magnitudes of stars 1-7 are listed in Table 2.

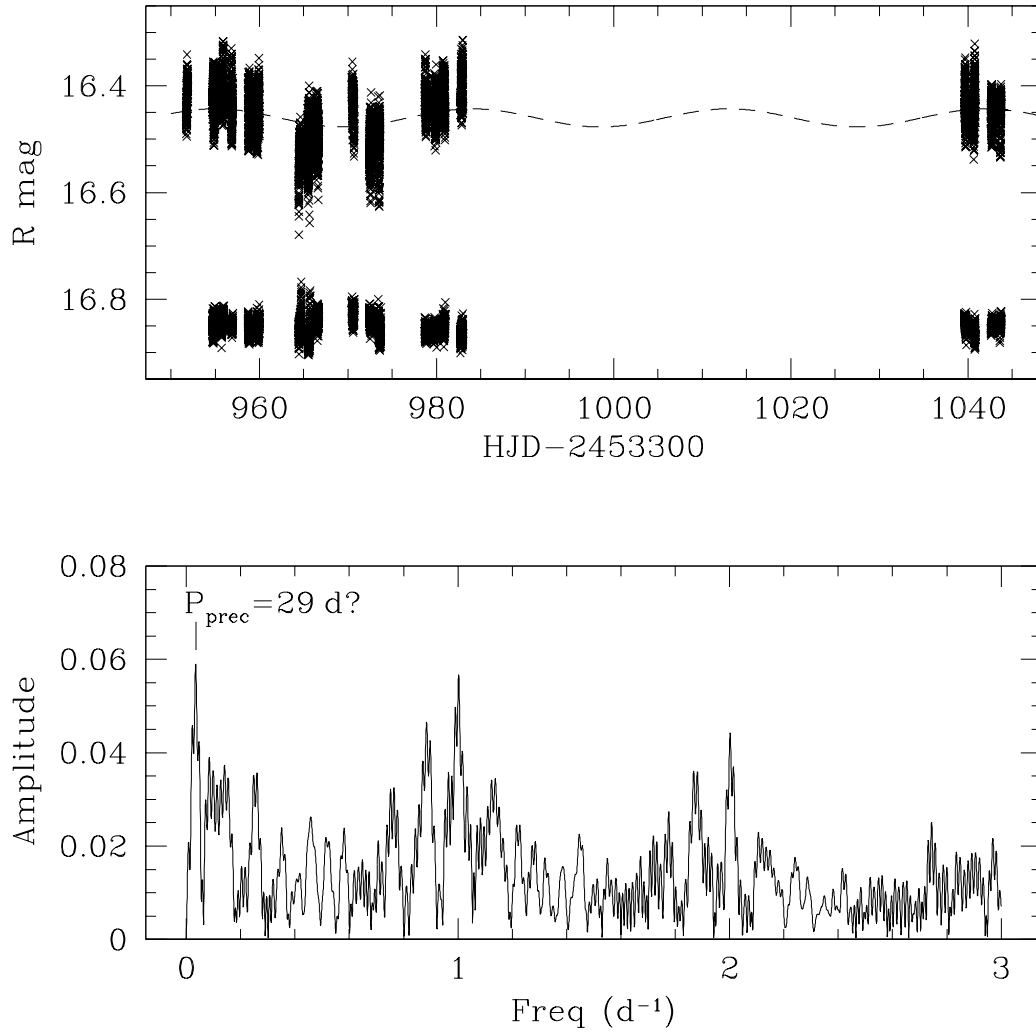


Fig. 2.— Long term R-band light curve of Swift J1753.5-0127 and of a comparison star of similar brightness. We have overplotted a sinusoidal fit with 29 d period (top). Lomb Scargle periodogram of all our data set from Jun 3 to August 31 UT. There are also clear signatures of 1-day alias periodicities.

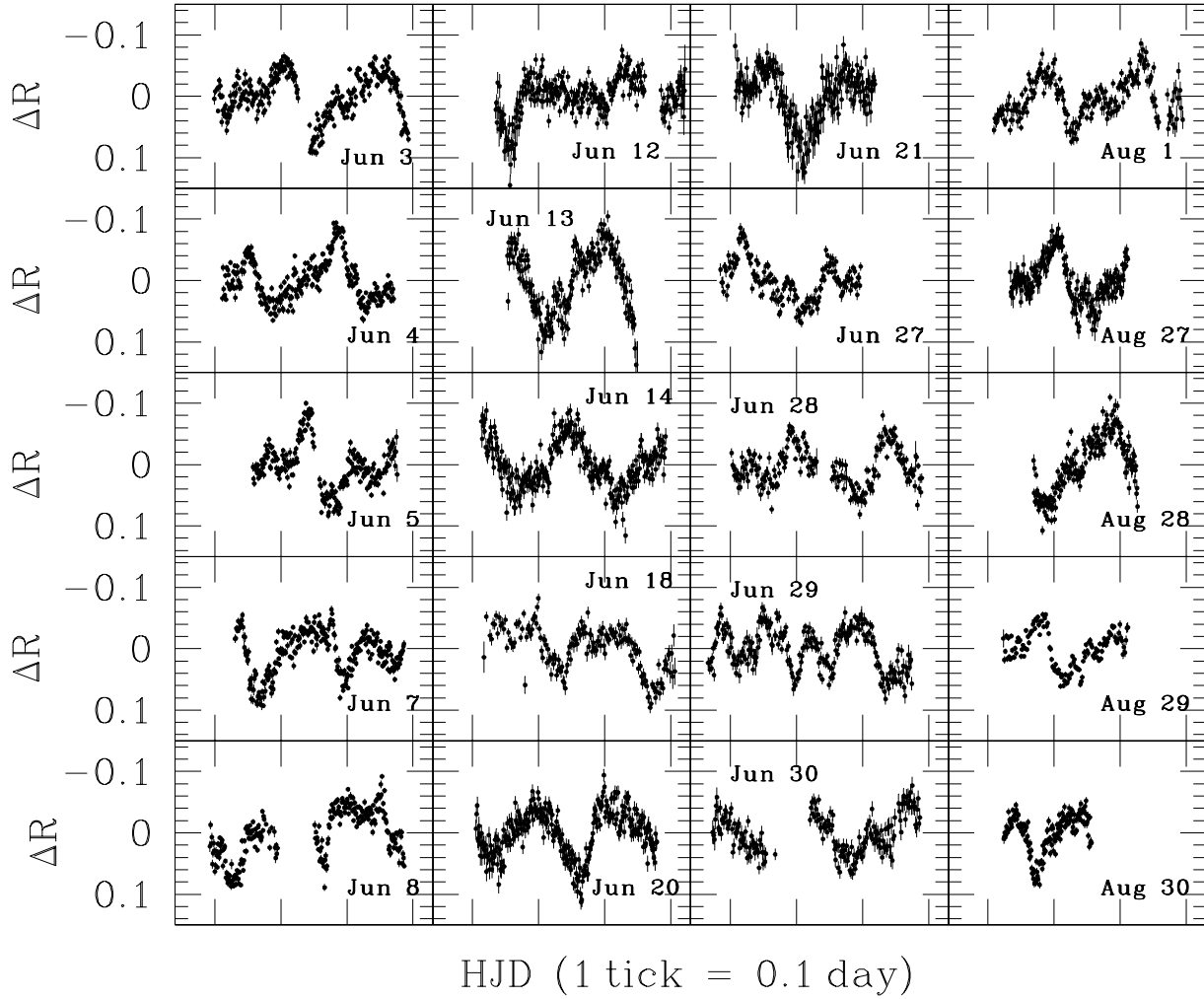


Fig. 3.— R-band light curves of SWIFT J1753.5-0127 for the individual nights. We subtract the nightly means from the individual curves. One tick interval in time is 0.1 day

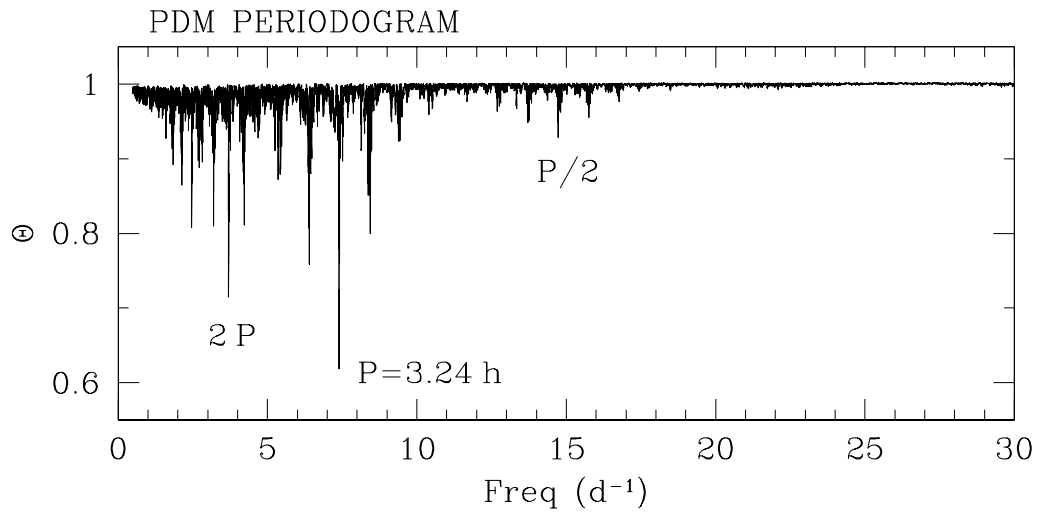


Fig. 4.— PDM periodogram of the R-band light curves of all our data set from Jun 3 to August 31 UT after detrended the long term variations by subtracting the nightly means from the individual light curves. The deepest peak at 3.24 ± 0.001 h and its multiples $2P$ and $P/2$ are marked.

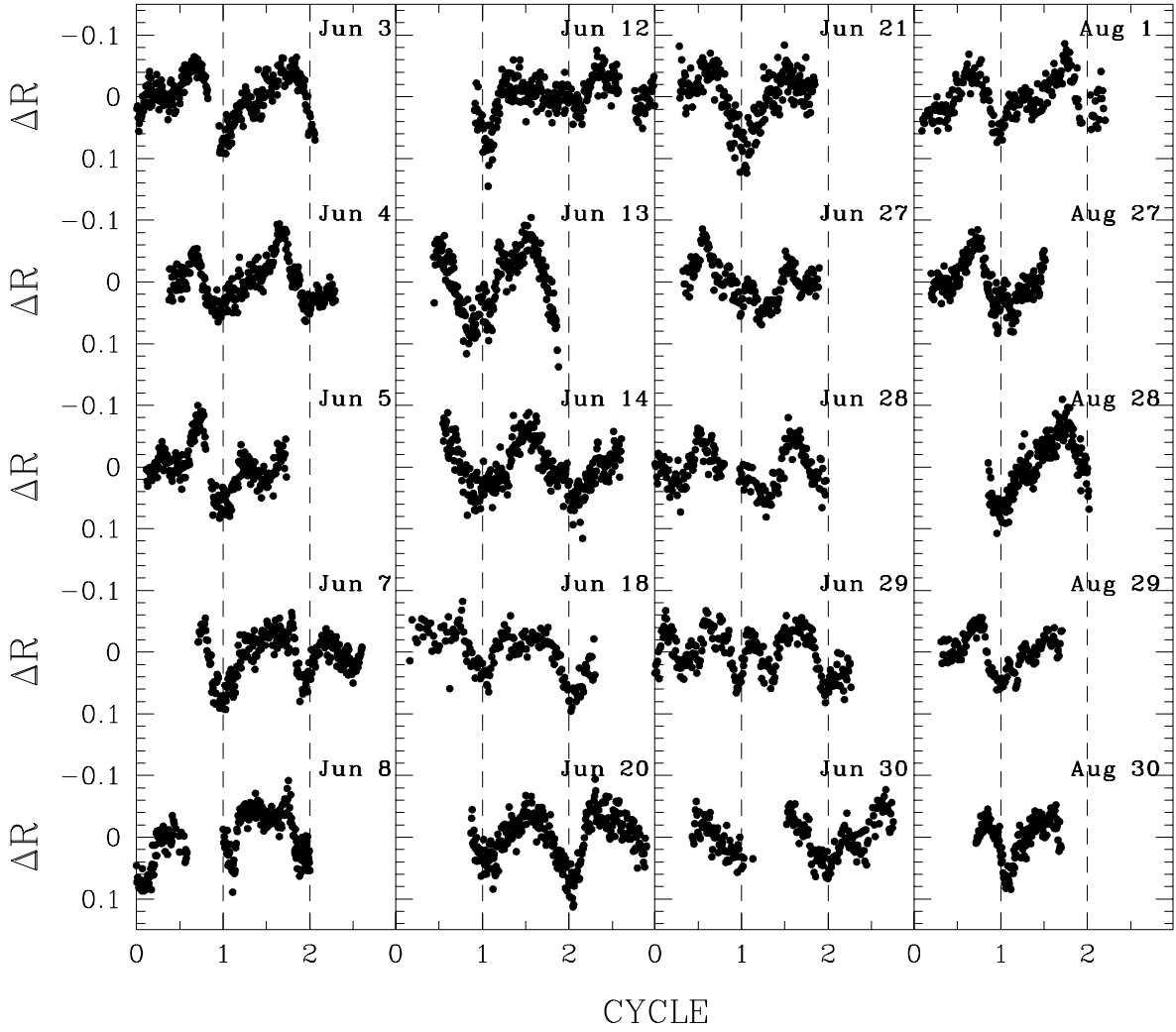


Fig. 5.— R-band light curves of SWIFT J1753.5-0127 for the individual nights folded on the 3.24 h period. We selected an origin at $T_0 = \text{HJD } 2454249.853$ which corresponds to the minimum observed on 2007 Jun 3.