The newly discovered Be/X-ray binary Swift J004516.6−734703 in the SMC: witnessing the emergence of a circumstellar disc

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ABSTRACT
We report on the discovery of Swift J004516.6−734703, a Be/X-ray binary system by the Swift SMC Survey, S-CUBED. Swift J004516.6−734703, or SXP 146.6, was found to be exhibiting a bright (~ 10^{37} erg/s) X-ray outburst in 2020 June 18. The historical UV and IR light-curves from OGLE and Swift/UVOT showed that after a long period of steady brightness, it experienced a significant brightening beginning around 2019 March. This IR/UV rise is likely the signature of the formation of a circumstellar disc, confirmed by the presence of strong a H\alpha line in SALT spectroscopy, that was not previously present. Periodicity analysis of the OGLE data reveals a plausible 426 day binary period, and in the X-ray a pulsation period of 146.6s period is detected. The onset of X-ray emission from Swift J004516.6−734703 is likely the signature of a Type-I outburst from the first periastron passage of the neutron star companion through the newly formed circumstellar disc. We note that the formation of the circumstellar disc began at the predicted time of the previous periastron passage, suggesting its formation was spurred by tidal interaction with the neutron star.

Key words: stars: emission line, Be – X-rays: binaries

1 INTRODUCTION
Be/X-ray Binaries (BeXRBs) consist of a Be star, a massive typically main-sequence star with B spectral type showing strong Balmer and other emission lines (Porter & Rivinius 2003), and a compact object, which is most often a neutron star (NS), but sometimes a white dwarf (WD) (Coe et al. 2020) or a black hole (Munar-Adrover et al. 2014). The compact object is often in a highly eccentric orbit, with typical orbital periods of 10s to 100s of days (Reig 2011). Notably, Be stars show excess infrared (IR) emission over regular B-stars, which is thought to be a signature of emission from a circumstellar disc (CSD) that forms around the star, although the mechanism of this formation is not clear (Rivinius et al. 2013). When the compact object approaches periastron, accretion from the CSD will occur, and seen in X-rays as a short lived (days - weeks) X-ray outburst, which are referred to as Type-I outbursts. Less frequently BeXRBs show large, sometimes super-Eddington, outbursts (e.g. as in the recent outburst of SMC X-3, Townsend et al. 2017), which can last for several orbital periods (Reig 2011). These are referred to as Type-II bursts. When a BeXRB contains a NS compact object, an X-ray pulsar is often seen.

The Small Magellanic Cloud (SMC) is an irregular dwarf galaxy, and neighbour to the Milky Way. Clearly visible by eye in the southern hemisphere, the SMC enjoys low line-of-sight absorption and a well defined distance (62.1 kpc; Graczyk et al. 2014), making it ideal for studies of X-ray binaries. The SMC is known to contain an over abundance of BeXRBs compared to the Milky Way, and as such has been extensively surveyed in order to study and catalog BeXRB systems (e.g. Haberl et al. 2000; Sturm et al. 2013).

The Swift Small Magellanic Cloud Survey (S-CUBED; Kennea et al. 2018) is a shallow, high cadence survey of the SMC performed by the Neil Gehrels Swift Observatory (Gehrels et al. 2004). S-CUBED consists of 142 tiled pointings covering the optical extent of the SMC (including the “Wing”). Excepting for observational and subscription constraints, S-CUBED is performed weekly, with each tile exposing for 60s. S-CUBED collects data utilizing the SwiftX-ray Telescope (XRT; Burrows et al. 2005) and Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005). Given the low background of the XRT, S-CUBED is sensitive to outbursts of accreting pulsars of > 1 – 2% Eddington luminosity. This makes S-CUBED a power-
ful tool for both early detection of outbursts and regular monitoring of BeXRB sources.

In this letter we present the discovery, by S-CUBED, of the BeXRB system Swift J004516.6−734703. We present results from both long term monitoring of this new source with S-CUBED data from the Swift XRT and UVOT, along with post outburst follow-up observations with Swift and the South African Large Telescope (SALT; Buckley et al. 2006). In addition we present long term monitoring observations of this source by Optical Gravitational Lensing Experiment (OGLE; Udalski 2003; Udalski et al. 2015). Discussion of the apparent onset of Be activity, and the later onset of X-ray emission are discussed.

2 OBSERVATIONS

2.1 Discovery by S-CUBED and Swift/XRT follow-up

Swift J004516.6−734703 was first discovered in outburst by the S-CUBED survey. Utilizing an automated transient pipeline set up to detect outbursting X-ray sources, we were alerted to the presence of a new X-ray source in the S-CUBED observation taken on 2020 June 18. The source was internally designated SC1774 by S-CUBED, and with the standardized Swift name of Swift J004516.6−734703.

Examination of the automatically generated X-ray light-curve of Swift J004516.6−734703 showed that it was detected on 2020 June 18, at a count rate of 0.289 ± 0.075 count s\(^{-1}\), and a week earlier on 2020 June 11, at a lower count rate of 0.037\(^{+0.036}\)\(^{-0.026}\) count s\(^{-1}\), showing almost an order of magnitude brightening. Although S-CUBED began on 2016 June 8, no previous X-ray detection of the source had been made by the survey.

After discovery we requested a rapid turn around Swift Target-of-Opportunity Request (TOO) for 2 ks monitoring observations with a 2 day cadence with XRT in Photon Counting (PC) mode in order to obtain a high quality spectrum and short term light-curve. UVOT was configured to obtain images in the 6 optical and UV filters. These observations commenced on 2020 June 19. These data were analysed utilizing standard XRT analysis tools provided by HEASoft 6.27.2 and using the methods described by Evans et al. (2009).

We calculated a X-ray position for Swift J004516.6−734703, utilizing the method described by Goad et al. (2007), using UVOT data to correct for the systematic errors in astrometry. We find a position of RA(J2000) = 00\(^{h}\) 45\(^{m}\) 17.91\(^{s}\), Dec(J2000) = −73\(^{\circ}\) 47\('\) 05.5\(\arcsec\), with an error radius of 1.9\(\arcsec\) (90% confidence). This position does not match any previously known X-ray source, but is consistent with an optical source, 2dFJ0556, with a spectral type of B1-3(III) (Evans et al. 2004). Analysis of the UVOT data finds a counterpart at the position RA(J2000) = 00\(^{h}\) 45\(^{m}\) 17.77\(^{s}\), Dec(J2000) = −73\(^{\circ}\) 47\('\) 05.59\(\arcsec\), which lies 6\(\arcsec\) from the center of the XRT error region, and 1\(\arcsec\) from 2dFJ0556.

In the first TOO observation the source was well detected at an average brightness of 0.387 ± 0.021 count s\(^{-1}\) in XRT data. The PC mode X-ray spectrum is well described by an absorbed power-law model, with \(N_H\) fixed at a standard value of 5.9 × 10\(^{20}\) cm\(^{-2}\) (Dickey & Lockman 1990), we find a photon index \(\Gamma = 0.50 ± 0.16\) with a reduced \(\chi^2 = 0.89\) (14 degrees of freedom). We note that the hard X-ray spectrum is consistent with other High Mass X-ray Binaries (HMXB) and BeXRBs in the SMC. Given the companion is a B-star, the onset of X-ray emission is this highly suggestive that Swift J004516.6−734703 is a newly discovered BeXRB system.

The fitted peak flux, corrected for absorption is 3.0 ± 0.4 × 10\(^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) (0.5−10 keV). Assuming a standard SMC distance of 62.1 kpc, this corresponds to a 0.5−10 keV luminosity of 1.5 × 10\(^{37}\) erg s\(^{-1}\).

It was noted that the this new transient lies close (2.4\('\)) from the recently discovered candidate Be/WD X-ray Binary system, Swift J004427.3−734801 (Coe et al. 2020), therefore detailed monitoring of this source will contain pre-outburst observations of Swift J004516.6−734703. We analyzed these observations and found that the source was detected in these observations between 2020 April 14, and 2020 May 20, albeit at a much fainter level. Combining the data from the 25 observations of the source over this time period, with a combined exposure time of 38.4 ks, we created a light-curve of Swift J004516.6−734703 (Fig. 1). This light-curve shows that the luminosity (assuming that the spectrum has not varied) ranged between 3.6−6.7 × 10\(^{34}\) erg cm\(^{-2}\) (0.5−10 keV) before the S-CUBED detection, and showed a steady rise before the first detection by S-CUBED. The combined X-ray light-curve in Fig. 1 is consistent with the rise, peak and fall of a BeXRB Type-I outburst.

We searched the three post-outburst TOO observations for the presence of pulsations using a Z\(^2\) search (Buccheri et al. 1983), and find a significant detection of a pulsar period of \(P = 146.6 ± 1.1\) s (error estimated using the Monte-Carlo method of Gotthelf et al. 1999), detected in both combined TOO data, and in the observation of 2020 June 21. The pulsation is detected, albeit with a lower significance in the observations of 2020 June 17 and 2020 June 19. Utilizing the nomenclature defined by Coe et al. (2005), we suggest an alternative name for Swift J004516.6−734703 of SXP 146.6.

Combining all S-CUBED data taken before 2020, we do not detect the source, and calculate a 3\(\sigma\) upper limit on the average count rate of 2.1 × 10\(^{-3}\) count s\(^{-1}\), which assuming the spectral fit above, is the equivalent to an upper limit on the pre-outburst luminosity of \(< 8 \times 10^{34}\) erg s\(^{-1}\) (0.5−10 keV).

2.2 Optical, IR and UV observations

2.3 OGLE data

The OGLE project provides long term I-band photometry with a cadence of 1-3 days. It was possible to retrieve many years of photometric monitoring from OGLE III & IV in the I-band. The optical counterpart to Swift J004516.6−734703 was identified with the
Figure 2. Long term 20-year light-curve of Swift J004516.6−734703 from OGLE. 

OGLE source smc128.3.12493 in OGLE III and smc720.12.13583 in OGLE IV. As a result it is possible to construct a 20 year light-curve in the $I$-band - see Fig. 2. This striking light-curve reveals a source that has been in a low state for at least 17-18 years with no evidence of flaring activity throughout this time. Then around MJD 58500 (2019 January 16) it began to brighten and continued this dramatic change through to the end of the current OGLE data coverage, with no sign that this increase was levelling off.

If the data prior to the start of the outburst are analysed for possible periodicities using the Lomb-Scargle technique then a very strong peak emerges in the power spectrum at a period of 426.4 ±1.8 days. Because of the 18 year length of this data run it is easy to distinguish this peak from the smaller, annual one rising from the data sampling. If the data are folded at this period then a sinusoidal profile is revealed with an amplitude of ~0.005 magnitudes - see Fig. 3. This small modulation is only detectable because the multi-year length of the data run.

It seems very probable that this is the binary period of the system with the NS partner inducing small regular changes in the structure of outer envelope of the star, or in a minimal CSD. Using the profile shown in Fig. 3 it is possible to determine an ephemeris for the brightest part of the 426d cycle of:

$$T_{\text{peak}} = n(426.4 \pm 1.8) + 52133.5 \text{ MJD}$$

(1)

It is likely that this brightest phase corresponds to the closest approach of the NS each orbit, though there may be some phase delay in the response of the B-type star and the brightest time may not be precisely at periastron.

2.4 Swift/UVOT data

UVOT observations of Swift J004516.6−734703 have been taken by S-CUBED since it began in June 2016, approximately weekly with 60s exposures utilizing the $uvw1$ filter.

Analysis of UVOT data were performed utilizing the $uvotmaghist$ tool from HEAsoft v6.27.2. We have extracted the $uvw1$ light-curve for Swift J004516.6−734703 for the whole S-CUBED dataset. The optical counterpart is well detected in all UVOT data, with a brightness $uvw1 = 12.8 − 13.2$. The resultant light-curve is shown in Fig. 4.

The light-curve is notable in that for the period from the start of S-CUBED monitoring (2016 June 8) until approximately 2019 Feb 28, the $uvw1$ light-curve is essentially flat, with $uvw1 = 13.27 \pm 0.01$ (statistical error only). After this period the it shows a steady rise...
Table 1. Mean UVOT magnitudes for all combined data taken in 2020 for Swift J004516.6–734703 during the Type-I X-ray outburst. Note that there is no significant variability or brightening trends seen during this period.

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X-ray light-curve, no previous outburst activity was seen. The predicted periastron passage using Eq. 1 aligns well with the onset of the Type-I outburst. Additionally the previous periastron passage occurred during the period in which the OGLE-I and UVOT -uvw1 light-curves were starting to rise, suggesting that although a CSD was beginning to form during this time, there was no significant accretion on the NS at periastron, likely as the disc had not grown to sufficient size to interact with the NS.

In order to determine when the CSD began to form, we fit a simple parametric model to the OGLE and UVOT data defined as:

\[ \Delta m = A \log(1 + B(t - t_0)^2) \]

where \( t_0 \) is the start of the outburst, \( \Delta m \) is the change in brightness in magnitudes and \( A \) and \( B \) are constants. Note for \( t < t_0 \) we fixed \( \Delta m = 0 \). Utilizing this fit we are able to estimate the value of \( t_0 \), i.e. when the IR/UV brightening began. For the OGLE-I band data we find that \( t_0 = 58481.3 \pm 1.1 \) MJD. Fitting the same model to the UVOT data, we find that \( t_0 = 58532.8 \pm 1.5 \) MJD, \(~51\) days after the I-band. The reason for this lag in UV rise time is not clear, although it is suggestive that the UV emission is likely not simply the UV tail of emission from the CSD, and may be the signature of heating in the disc as it grows.

The timing of apparent appearance of the CSD is interesting, coming as it does close to the predicted previous periastron passage to the Type-I outburst. This suggests the birth of the CSD could be spurred by tidal interaction of the Be star with the NS companion, which has previously been suggested as a factor in CSD formation (Rivinius et al. 2013).

4 CONCLUSIONS

The S-CUBED survey, a weekly survey of the SMC in X-ray and UV performed by Swift, discovered a previously unknown X-ray transient in the SMC, Swift J004516.6–734703, with a pulsar period of 146.6 s. Examination of historical and catalogued data on this star revealed that it has a B-type optical companion, and post-outburst observations with SALT revealed characteristic Balmer and other line emission in the spectrum, conclusively showing that this system was a BeXRB. However, previous observations of the star did not reveal the presence of Balmer emission lines, which along with the fact that no X-ray Type-I bursts had been seen from this source before, suggest that a CSD had recently formed. Examination of the long term (~20 year) light-curve from OGLE revealed that in early 2019, after a long period of inactivity, the X band flux had started to rise. Strengthening IR emission being a signature of the presence of a CSD, this suggested that we were witnessing the birth of a CSD, and that the X-ray outburst seen by S-CUBED represented the first periastron passage of the NS though the disc since it became fully formed. Detection of a plausible long (426 day) periodicity in the OGLE light-curve further supports that this recent X-ray outburst would have been the first passage since the disc formed, and tantalisingly, the formation of the CSD is coincident to the previous periastron passage, suggesting a possible link between the onset of CSD formation and tidal interactions in the binary system.

Finally, we note that the combination of the binary period and the pulse period fits comfortably on the Corbet diagram (Corbet 1986) confirming this empirical relationship out to the longest known binary periods.

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