Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **505,** 4417–4421 (2021)
Advance Access publication 2021 June 7

https://doi.org/10.1093/mnras/stab1609

RX J0123.4-7321 – the story continues: major circumstellar disc loss and recovery

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Accepted 2021 May 29. Received 2021 May 29; in original form 2021 May 4

ABSTRACT

RX J0123.4-7321 is a well-established Be star X-ray binary system in the Small Magellanic Cloud. Like many such systems, the variable X-ray emission is driven by the underlying behaviour of the mass donor Be star. Previous work has shown that the optical and X-ray were characterized by regular outbursts at the proposed binary period of 119 d. However, around 2008 February the optical behaviour changed substantially, with the previously regular optical outbursts ending. Reported here are new optical (OGLE) and X-ray (*Swift*) observations covering the period after 2008 that suggest an almost total circumstellar disc loss followed by a gradual recovery. This indicates the probable transition of a Be star to a B star, and back again. However, at the time of the most recent OGLE data (2020 March) the characteristic periodic outbursts had yet to return to their early state, indicating that the disc still had some re-building yet to complete.

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

1 INTRODUCTION

Be star X-ray binary (BeXRB) are a large sub-group of the well-established category of high-mass X-ray binaries characterized by being a binary system consisting of a massive mass donor star, normally an OBe type, and an accreting compact object, a neutron star. They are particularly prevalent in the Small Magellanic Cloud (SMC) that contains the largest known collection of BeXRBs. Whilst catalogues have been produced listing such systems in the SMC (e.g. Coe & Kirk 2015; Haberl & Sturm 2016), it is clear that the complex interactions between the two stars continue to produce unexpected surprises. In particular, the behaviour of the mass donor B-type star is major driver in the observed characteristics of such systems.

The source that is the subject of this paper, RX J0123.4-7321, was identified early on as an X-ray source in the SMC (Haberl et al. 2000), but it took over another decade before its identity as BeXRB was clearly established by Sturm et al. (2013). In their paper, they not only identified the X-ray source as a partner to the Be star [M2002] SMC 81035, but also used optical photometry from the OGLE III project to show that the binary period of the system was 119 d.

Reported here are the successive 10 yr of OGLE IV data and 4 yr of X-ray observations from the *Swift* X-ray Telescope (XRT; Burrows et al. 2005) as part of the S-CUBED project (Kennea et al. 2018). The new OGLE data show a major change in the behaviour of the Be star as it appears to almost completely lose its circumstellar disc. This represents a rarely seen transition of [M2002] SMC 81035 from a classic Be star to a regular B-type star, and back again. All within a decade. The X-ray data, which are concurrent with the last few years of OGLE IV, reveal 15 detections of RX J0123.4-7321, with the detections extremely well correlated with the phase of the optical outbursts. These epochs are believed to correspond to times of periastron passage of the neutron star, and the profiles of the optical and X-ray outbursts are very similar, suggesting a common mechanism related to the periodic distortion of the circumstellar disc.

2 OBSERVATIONS

2.1 OGLE

The OGLE project (Udalski, Szymański & Szymański 2015) provides long term *I*-band photometry with a cadence of 1–3 d. The star [M2002] SMC81035 was observed continuously for nearly two decades until COVID-19 restrictions prevented any further observations from 2020 March. It is identified in the OGLE catalogue as

OGLE III (I band): smc121.2.50
OGLE IV (*I* band): smc733.26.24
OGLE III (*V* band) : smc121.2.v.18
OGLE IV (*V* band): smc733.26.v.13

The *I*-band data are shown in their entirety in the top panel of Fig. 1. The OGLE III data were previously presented in Sturm et al. (2013) who reported overwhelming evidence for the binary period of this system based upon the sharp regular outburst features seen every 119 d. However, this striking feature ended around TJD 5000 just as the OGLE III project phase also came to an end. Presented here are the OGLE IV data that add a further 10 yr to the story, and indicate a very dramatic change in behaviour pattern from OGLE III. For most

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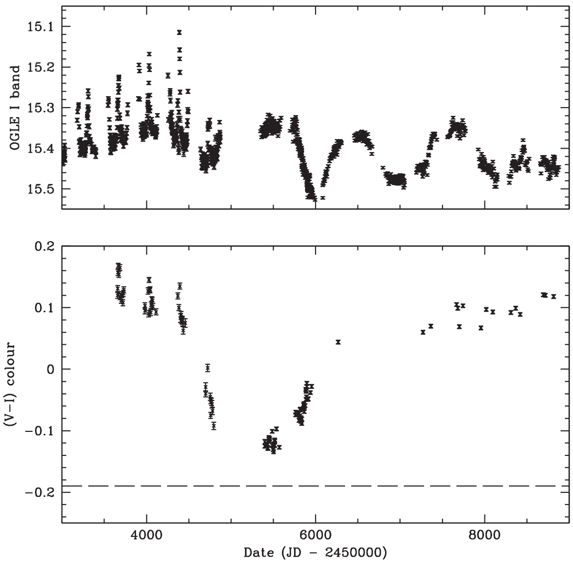

Figure 1. Upper panel : OGLE III and IV data – the transition between the two observing phases occurred around TJD 5000. Lower panel: OGLE *(V – I)* colour measurements. The dashed horizontal line indicates the predicted observed colour of a B0.5 III star in the SMC.

of this last decade, the regular outbursts are missing completely and only just start to re-emerge around TJD 8500, though not as strongly as before. None the less, the presence of these features 10 yr later permit a small refinement to be made to the binary period ephemeris that was originally presented in Sturm et al. (2013). The updated ephemeris for the time of the optical outbursts, T_{opt}, is

$$T_{\mathrm{opt}} = 54387.1 + N(119.59)\ \mathrm{MJD}. \quad (1)$$

The optical counterpart [M2002] SMC 81035 is reported to be a B0.7 IIIe star by Massey (2002) and Ramachandran et al. (2019). The exact intrinsic colours of such a spectral type are not readily tabulated, but the *(V – I)* colour of an almost identical B0.5 V star is given in Pecaut & Mamajek (2013) as −0.338. They do not quote the colours of a giant of the same type, but this difference is given in Wegner (1994) as 0.08. Thus, it is expected that the intrinsic colours of a B0.5III will be $(V-I) = -0.258$.

The OGLE dust maps of the SMC (Skowron et al. 2021) enable the precise reddening correction to be made for such an object in the SMC and that is $E(V-I) = 0.067$. Thus, the predicted observed colours of [M2002] SMC 81035 if it were a B-type star B0.5II with no circumstellar disc will be $(V-I) = -0.19$. The difference between a B0.5 and B1 star is less than 0.01 (Pecaut & Mamajek 2013), so any difference between a B0.5 and B0.7 will be negligible for the purpose of this discussion. Thus, the calculated colour is indicated in the lower panel of Fig. 1 as the horizontal dashed line. From this figure, it is immediately clear that all the observed OGLE colours for this object lie significantly above the baseline, strongly suggesting the presence of a circumstellar disc adding further reddening to the observed colours.

Clearly, if the red excess in the colour of [M2002] SMC 81035 is interpreted as the existence of a circumstellar disc, then the huge variations in the *(V – I)* colour seen in Fig. 1 must also be indicating significant changes in the disc size over the last 20 yr. From a substantive disc at the start of this period, through to almost nothing around TJD 5000. Then, the star went through a series of re-growth phases to reclaim some of its original status as a probable Be type. This is further discussed below.

Table 1. Table of X-ray detections of RX J0123.4-7321 by S-CUBED over the range 0.3–10 keV.

Date MJD	X-ray flux	X-ray error	Binary phase
	10^{-12} erg per (cm^2 s^{-1})		
57722.37	2.76	1.34	0.88
57736.24	3.02	1.49	0.00
57966.38	3.50	1.54	0.93
57973.62	2.85	1.42	0.99
58078.46	7.96	2.54	0.86
58218.41	7.82	4.46	0.03
58225.97	3.54	2.03	0.09
58344.77	4.57	2.66	0.09
58344.78	3.63	2.08	0.09
58939.04	6.54	2.83	0.06
58953.16	1.85	1.35	0.18
59052.03	8.26	3.27	0.01
59059.00	3.45	2.00	0.07
59093.00	5.26	3.07	0.35
59296.41	3.52	2.04	0.05

2.2 S-CUBED

RX J0123.4-7321 was detected by the S-CUBED survey (Kennea et al. 2018), a shallow weekly X-ray survey of the optical extent of the SMC by the *Swift* XRT (Burrows et al. 2005). Individual exposures in the S-CUBED survey are typically 60 s long, and occur weekly, although interruptions can occur due to scheduling constraints. Starting with the S-CUBED observation taken on MJD 57722 (29 Nov 2016), S-CUBED-detected RX J0123.4-7321 on several subsequent occasions over the following 4–5 yr and internally numbered it SC379. The occasions on which it was detected are listed in Table 1 and shown in the top panel of Fig. 2, together with the flux measured on each occasion. Non-detections have upper limits in the range $(5-10) \times 10^{-12}\,\mathrm{erg\cdot cm^{-2}\cdot s^{-1}}$.

S-CUBED observations taken with the UV/Optical Telescope (UVOT; Roming et al. 2005) were also analysed, utilizing the standard `uvotmaghist` tool. The middle panel of that figure shows the UVOT measurements in the *uvw1* band (2600 Å); it also indicates all the occasions when the source was observed. Broadly speaking, the UV tracks the *I* band, but not in the same detail. This is partially because the UVOT measurements lack the same precision as the OGLE data, but also because the circumstellar disc radiates predominately in the red end of the spectrum. These UVOT observations seem to confirm that [M2002] SMC 81035 has not yet returned to the earlier much brighter state, but has levelled off at some intermediary phase.

Assuming no spectral changes, one can sum all the detections together to obtain an average flux value of $(5.63 \pm 0.90) \times 10^{-12}$erg $\cdot$ cm^{-2} $\cdot$ s^{-1}. Using a standard SMC distance of 62 kpc (Scowcroft et al. 2016) and correcting for absorption fixed at the value derived from Willingale et al. (2013), this corresponds to a 0.5–10 keV luminosity of $(2.5 \pm 0.4) \times 10^{36}$ erg$\cdot$ s^{-1}.

3 DISCUSSION

The OGLE *V*- and *I*-band behaviour is shown in Fig. 1. It is obvious that a fundamental change occurred in this emission pattern around TJD 5000. The source changed from clear regular outburst behaviour to one showing long time-scale fluctuations. The *(V – I)* colour record is hugely important in interpreting this change as it shows the bluest colour around the time of this switch in behavioural patterns. It suggests that the Be star lost almost all its circumstellar disc around

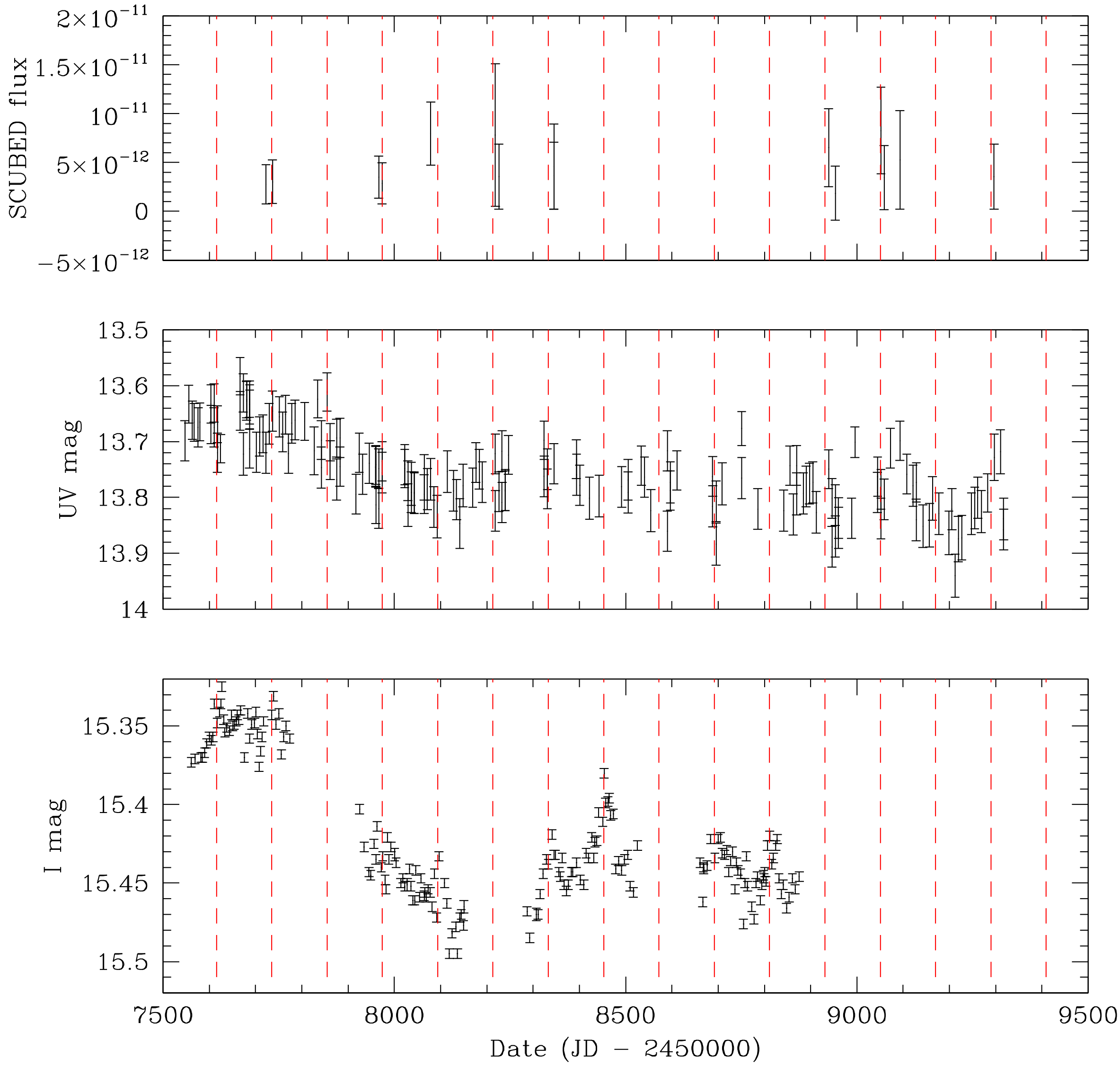

Figure 2. Comparison of the X-ray, UV, and optical detections. Upper panel S-CUBED X-ray detections of RX J0123.4-7321 in flux units of erg · cm^{-2} · s^{-1}. Centre panel : UVOT magnitudes in uvw1 filter of [M2002] SMC 81035. Bottom panel : OGLE IV I-band data of [M2002] SMC 81035. The vertical red-dashed lines indicate the dates of expected optical outburst given by equation (1).

TJD 5000–5100, and then took 5–6 yr to gradually re-build it. It is only around the end of the OGLE IV data that we see the re-commencement of the OGLE III outburst phenomenon, but still only weakly compared to the early years.

Fig. 3 shows the colour changes occurring between OGLE III and IV as a function of the *I*-band magnitude. In this figure, the pathway taken by [M2002] SMC 81035 over this ∼20 yr period is indicated. The source begins this time interval in the top right-hand corner, at maximum brightness and maximum redness. It then substantially changes over the course of OGLE III heading towards the lower left-hand corner – faintest and bluest emission almost reaching the state of a B0.7 III star with no circumstellar disc. In other words, we infer that it has transitioned from a Be star to a normal B-type star. This has occurred on a time-scale of just ∼5 yr.

During OGLE IV, we then see the star reverse its position on the colour−magnitude diagram, and in a series of, presumably, mass ejection phases re-builds its circumstellar disc and it resumes its Be-type classification. It is interesting to note that the re-building process exhibits itself as large-scale fluctuations on a time-scale of ∼1000 d. Such a behaviour could be described as a superorbital modulation, such as that described by Rajoelimanana, Charles & Udalski (2011) and Townsend & Charles (2020). In fact, the time-scales observed here of a binary period of 119 d and a superorbital period of ∼1000 d would fit comfortably in fig. 1 of Townsend & Charles (2020) in the region occupied by other Be stars in X-ray binary partnerships.

From Fig. 1, it can be seen that during the time of regular strong outbursts seen in OGLE III the colour *(V – I)* would change sharply by ∼0.07 mag. This changes comes from an increase in the *I* band of 0.18 mag (∼20 per cent flux increase), whilst the *V* band only increased by 0.11 mag (∼10 per cent flux increase). Assuming an optically thick disc is indicative of an increase in the surface area of a disc with an average temperature significantly cooler than that of the parent star, resulting in a redder overall appearance for the system.

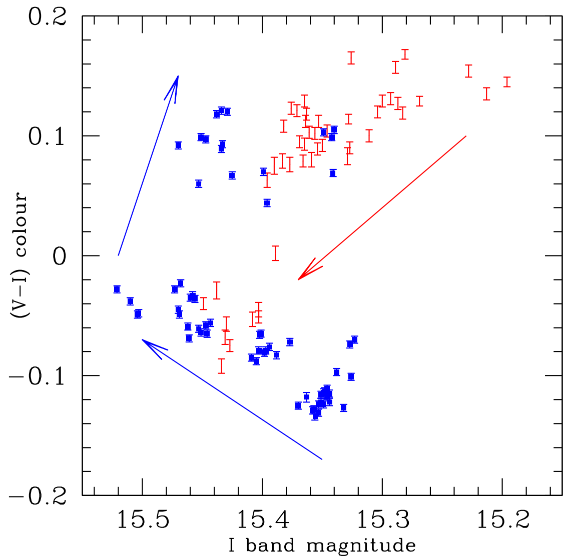

Figure 3. The colour changes observed in the optical companion to RX J0123.4-7321 from both OGLE III and IV data. The red points come from OGLE III and the red arrow indicates the direction of change with time. The blue points are from OGLE IV, and the blue arrow indicates the colour evolution with time during that phase.

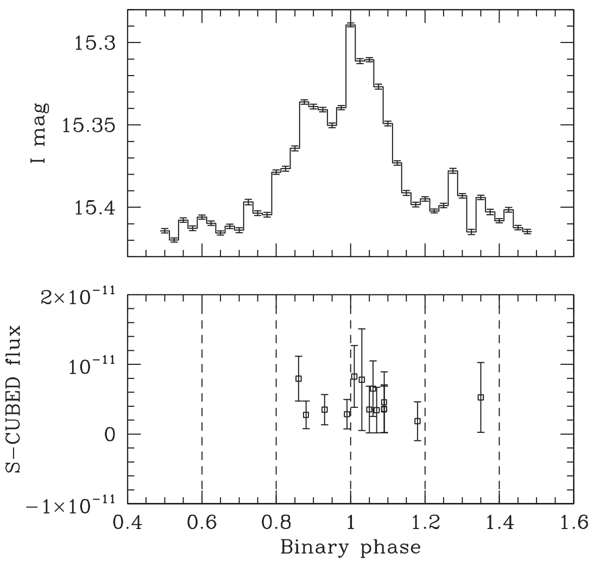

Figure 4. Upper panel: OGLE III data folded at the updated binary ephemeris – see equation (1). Lower panel: the X-ray detections of RX J0123.4-7321 as a function of the same binary ephemeris. The X-ray flux is in units of erg cm^{-2} s^{-1}.

The phases of X-ray detections are shown in Fig. 4 and compared to the OGLE III data folded with the ephemeris given in equation (1). It is immediately clear that the X-ray emission is strongly correlated in phase with the OGLE profile, both in width and peak position. The gravitational pull of the arriving neutron star distorts the surface area of the optically thick circumstellar disc increasing the *I*-band emission. At the same time, the larger disc is providing material to accrete on to the neutron star triggering the X-ray emission.

To estimate the probable dimensions of the disc and neutron star orbit, some assumptions are needed. In the absence of any direct H α equivalent width measurements it is necessary to assume that [M2002] SMC 81035 is a typical Be star, and we can estimate the circumstellar disc size from its spectral classification, B0.7III. Rivinius, Carciofi & Martayan (2013) quotes the size of the H α emitting disc for a very similar B0.5IVe star as having a typical radius of $7.1R_*$. This translates into a disc size of $(3-7)\times10^{10}$ m for such a star with luminosity class in the range III–V. Also assuming, for simplicity, that the neutron star is in a circular orbit, then the period of 119 d permits an estimate of the orbital radius to be 2×10^{11} m. That is ∼10 times larger than the H α disc size, but as Rivinius et al. (2013) points out the actual disc size may well extend beyond the H α-emitting region by a significant amount. But, broadly speaking, this is what Smooth Particle Hydrodynamic simulations of such systems predict (Okazaki & Negueruela 2001; Brown et al. 2019) – the neutron star orbiting just outside the disc and constraining further disc expansion.

However, the orbital behaviour of the neutron star in this system clearly is not circular, but rather it must exhibit a high degree of eccentricity. Fig. 4 shows that both the optical and X-ray outburst behaviour is restricted to binary phase range 0.8–0.2. Though it is not possible to quantify the degree of eccentricity from those profiles alone, it is obviously very similar to that seen in another system SXP 756 (Coe & Edge 2004). That system has a much longer binary period of 394 d, but the optical behaviour is remarkably similar to the source in this paper. The optical outbursts are even sharper, extending over a binary phase range of just 0.2. It is therefore highly likely that both of these systems are clear examples of high-eccentricity orbits. Townsend et al. (2011) demonstrated a significant correlation between the binary period and the eccentricity (where that had been reliably measured as part of an orbital solution) for BeXRB systems. From their fig. 6, it can be predicted that the eccentricity of RX J0123.4-7321 could be in the range 0.4–0.5. Such a high eccentricity would comfortably explain the behaviour seen in this system.

Finally, we note from Fig. 2 that though X-ray detections are reported for many periastron passages of the neutron star, there are some missed occasions. They are missed even though S-CUBED clearly carried out observations at the appropriate times. This is almost certainly just indicative that the X-ray flux levels emitted during these Type I outbursts from RX J0123.4-7321 are close to the detection threshold of the XRT telescope on *Swift* with just a 60 s exposure. A small reduction in the X-ray strength could easily lead to a missed detection. In fact, Fig. 2 clearly shows evidence for X-ray activity during many binary cycles, even when the *I*-band flux had diminished around MJD 58000–58400. So, though the circumstellar disc was obviously greatly reduced at these times there was always enough material in the vicinity of the neutron star orbit at periastron to trigger accretion. This is further evidence that the eccentricity of this system must be very high indeed, permitting the neutron star to approach exceptionally close to the Be star each periastron passage.

4 CONCLUSIONS

Though RX J0123.4-7321 was previously well established as a member of the BeXRB family in the SMC, its behaviour has dramatically changed since it was last studied. The new OGLE optical colour data *(V – I)*, combined with the *I*-band magnitude, strongly indicate a major disc loss episode in this Be star lasting several years. This was followed by a slow recovery over a similar amount of time as the circumstellar disc was gradually rebuilt. Throughout the last few years of this process, the X-ray observations reported here were able to detect Type I outbursts around what is believed to be the time of periastron. Despite the almost complete disc loss, these X-ray detections continued over a 4 yr period up to the present. They point strongly to a very eccentric orbit bringing the neutron star in close to the Be star and thereby enabling the accretion of material from the limited remains of the circumstellar disc. It will be interesting to see if the characteristic sharp optical outbursts return in the future once the COVID-19 restrictions permit the resumption of OGLE monitoring.

ACKNOWLEDGEMENTS

The OGLE project has received funding from the National Science Centre, Poland, grant MAESTRO 2014/14/A/ST9/00121 to AU. PAE acknowledges UKSA support. JAK acknowledges support from NASA grant NAS5-00136. This work uses data supplied by the UK *Swift* Science Data Centre at the University of Leicester.

DATA AVAILABILITY

All X-ray data are freely available from the NASA *Swift* archive. The optical data in this article will be shared on any reasonable request to Andrzej Udalski of the OGLE project.

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