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Optical and X-ray variability of two Small Magellanic Cloud X-ray binary pulsars – SXP46.6 and SXP6.85

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ABSTRACT

We present long-term optical and *RXTE* data of two X-ray binary pulsars in the Small Magellanic Cloud, SXP46.6 and SXP6.85. The optical light curves of both sources show substantial (∼0.5–0.8 mag) changes over the time-span of the observations. While the optical data for SXP6.85 do not reveal any periodic behaviour, by detrending the optical measurements for SXP46.6 we find an orbital period of ∼137 d, consistent with results from the X-ray data. The detection of Type I X-ray outbursts from SXP46.6, combined with the fact that we also see optical outbursts at these times, implies that SXP46.6 is a high orbital eccentricity system. Using contemporaneous optical spectra of SXP46.6, we find that the equivalent width of the Hα emission line changes over time indicating that the size of the circumstellar disc varies. By studying the history of the colour variations for SXP6.85, we find that the source gets redder as it brightens which can also be attributed to changes in the circumstellar disc. We do not find any correlation between the X-ray and optical data for SXP6.85. The results for SXP6.85 suggest that it is a low-eccentricity binary and that the optical modulations are due to the Be phenomenon.

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

1 INTRODUCTION

Observations of the Small Magellanic Cloud (SMC) at multiwavelengths have uncovered numerous high-mass X-ray binaries, the majority of which are Be/X-ray transients (see e.g. Haberl & Pietsch 2004; Coe et al. 2005; McGowan et al. 2007). These systems comprise of an OB star and a neutron star. As the compact object orbits the companion star in a wide and eccentric orbit it passes close to the circumstellar disc of the Be star and X-ray outbursts are seen (Okazaki & Negueruela 2001). In some cases, optical outbursts coincident with the X-ray outbursts are also detected (see e.g. Alcock et al. 2001; Coe & Edge 2004).

RXTE monitoring is providing a wealth of information on the X-ray pulsars in the SMC (see e.g. Laycock et al. 2005; Galache et al. 2007). However, to investigate the sources in detail, in particular, at multiwavelengths, more precise locations must be determined, via e.g. *Chandra* and *XMM–Newton*.

In this paper, we present observations and analysis of optical and X-ray data for two Be/X-ray binaries in the SMC, SXP46.6 and SXP6.85, whose positions have been identified recently using *Chandra* and *XMM–Newton*.

2 SXP46.6 = XTE J0053–724 = 1 WGA 0053.8 − 7226

SXP46.6 was discovered in 1997 during observations of the SMC with *RXTE* (Marshall, Lochner & Tkeshima 1997). A position for the source was obtained from follow-up *ASCA* observations, leading to the object being identified with an archival *ROSAT* source. The *ASCA* measurements also revealed possible pulsations at ∼92 s (Corbet et al. 1997). Further analysis of the *ASCA* and *RXTE* data established a pulse period for the source of 46.6 s (Corbet et al. 1998). Studies of *ROSAT* observations confirmed the transient nature of the source (Buckley et al. 2001, and references therein). Due to the uncertainty on the X-ray position, Buckley et al. (2001) proposed two optical sources as the counterpart to SXP46.6. The characteristics of both optical candidates were similar and led to the conclusion that the system was a Be/X-ray binary.

RXTE has continued to monitor SXP46.6 over the past 10 yr, the results of which are presented in Galache et al. (2007). During this time, the source has exhibited regular outbursts allowing an

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orbital period of 137.36 ± 0.35 d and an outburst ephemeris of MJD 52293.9 ± 1.4 to be derived (Galache et al. 2007, based on nine years of data). Adding the most recent data, we determine a refined period and time of maximum flux of 137.74 ± 0.42 d and MJD 52430.3 ± 1.4, respectively.

We have analysed archival *Chandra* AXAF CCD Imaging Spectrometer (ACIS) data covering the region of SXP46.6 (see also McBride et al. 2007). The ACIS observations were taken on 2002 July 20, 2006 April 25 and 2006 April 26, and had exposure times of 7.7, 49.3 and 47.4 ks, respectively. We processed the data using the *Chandra* analysis package CIAO v3.4. The event files were filtered to restrict the energy range to 0.5–8.0 keV and we searched for sources using the wavelet analysis algorithm. We detect an X-ray source coincident with one of the optical candidates, Star B from Buckley et al. (2001), in all three *Chandra* observations. The X-ray position of the source is RA = $00^{h}53^{m}55\overset{s}{.}22$, Dec. = $-72°26'45\overset{''}{.}7$. The measured counts in the three *Chandra* observations are 7, 38 and 28 counts, respectively, corresponding to X-ray luminosities of 4.6×10^{33}, 4.1×10^{33} and 3.1×10^{33} erg s^{-1}, assuming a distance to the SMC of 60 kpc (based on the distance modulus, Westerlund 1997). Using the most recent orbital period and ephemeris from *RXTE*, we find that all three *Chandra* observations were taken at outburst phase ∼0.3 (see also Fig. 4). The low flux detected with *Chandra* can be explained by the phases at which the measurements occurred. A search for pulsations was not possible due to the lack of source counts.

2.1 Optical light curve

While the source is not in the OGLE II or Massive Compact Halo Object (MACHO) catalogues, it is clearly detected in the more extensive OGLE III survey. OGLE III, whose data are not yet public, is a continuation of the OGLE project (Udalski, Kubiak & Szymański 1997; Szymański 2005). We show in Fig. 1 OGLE III photometry for Star B, from 2001 June 26 to 2007 January 28. The optical light curve displays a large variation in brightness (∼0.5 mag) over the six years of observations, typical of Be stars (Mennickent et al. 2002).

As the large-scale modulations present in the OGLE III light curve are clearly not periodic, before we searched for coherent variations we removed the long-term changes. The data were split into eight sections and each section was detrended separately by subtracting a linear fit. We then searched the detrended light curve (see Fig. 2, top panel) for periodicities in the range 2–1000 d using Lomb–Scargle (LS) and phase dispersion minimization (PDM) periodograms.

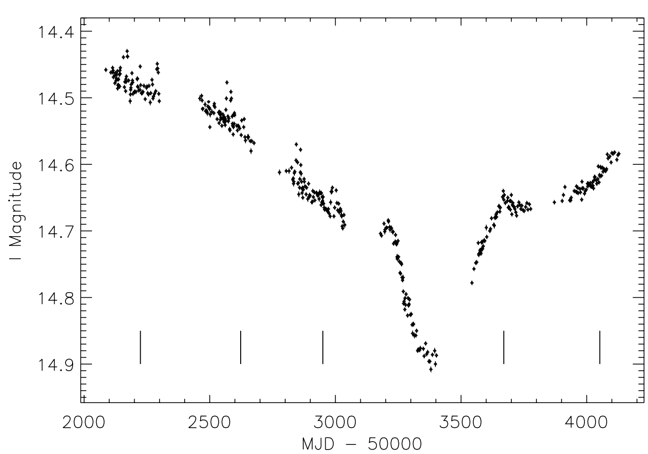

Figure 1. The OGLE III light curve of SXP46.6. The times when optical spectra were taken are marked with solid lines.

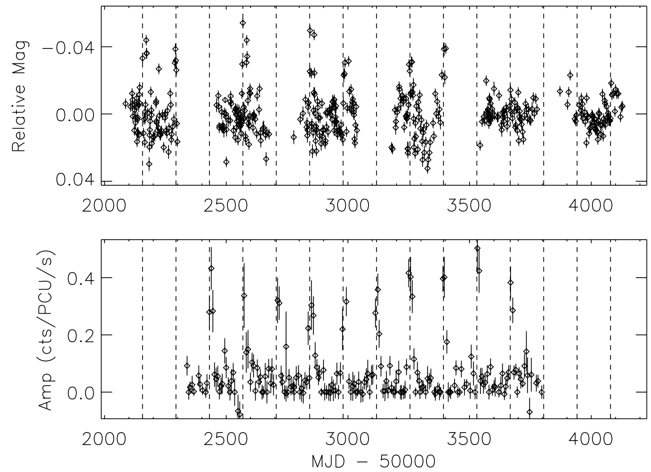

Figure 2. The detrended OGLE III light curve (top panel) and *RXTE* light curve (bottom panel) for SXP46.6. Only X-ray data with identical collimator responses (see the text) and covering the time of overlap with the optical data have been plotted. The times corresponding to the orbital period determined from the *RXTE* data, P = 137.74 d, are marked (dashed lines).

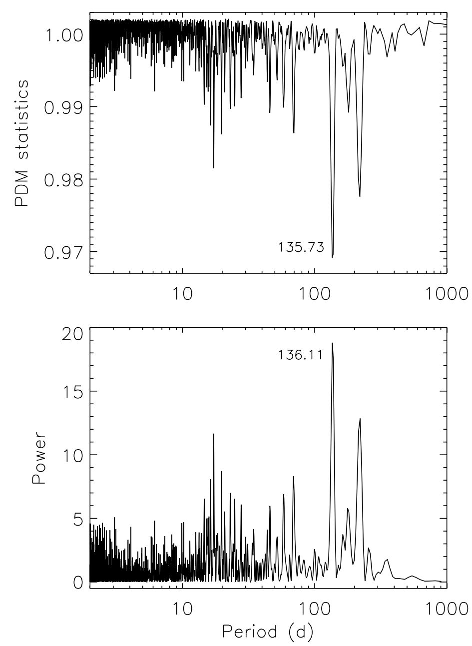

Figure 3. PDM (top) and LS periodograms (bottom panel) for the detrended OGLE III data of SXP46.6. The strongest dip in the former corresponds to a period of 135.73 d, with the highest peak at 136.11 d in the latter.

The results of the temporal analysis are shown in Fig. 3. The dominant peak in the LS periodogram occurs at P = 136.11 ± 2.27 d, with a corresponding dip in the PDM periodogram at P = 135.73 ± 2.26 d. The second largest peak (dip) in the periodograms (at ∼220 d) is due to this frequency beating with the one year sampling. The ∼136 d period from the LS and PDM searches is, within errors, consistent with each other and the period found using the most recent *RXTE* data. This confirms that Star B is the correct counterpart to SXP46.6.

2.2 X-ray light curve

Before analysis of the *RXTE* light curves can be performed the raw data are filtered to include only *Good Xenon* measurements from the top anode layer. Light curves are generated in the 3–10 keV energy band with 0.01 s time bins and the detected count rate is divided by the number of Proportional Counter Units (PCUs) that were active at each time-stamp. Each PCU has a collimator, the result of which is that each unit has approximately the same field of view. Due to small variations between the PCUs, the source count rates must be corrected for the collimator response. Only observations with the same pointing position have been used in the following analysis. For more details on the data reduction see Galache et al. (2007).

To investigate possible correlations between the optical and X-ray data, we show in Fig. 2 the detrended OGLE III light curve for SXP46.6 (top panel) and the *RXTE* light curve (in units of counts $PCU^{-1}\ s^{-1}$, bottom panel). Only X-ray data with identical collimator responses and covering the time of overlap with the optical data have been plotted. We have also plotted, as dashed lines, the times of expected X-ray outburst using the orbital period and ephemeris found using the most recent *RXTE* data. It is clear from the figure that the optical light curve displays outbursts, with amplitudes of ∼0.04 mag, coincident with the X-ray outbursts.

We have folded the detrended OGLE III data and the *RXTE* data on $P = 137.74$ d using $T_0 =$ MJD 52430.3. The folded light curves show that the modulation is highly non-sinusoidal, with the peak emission in the X-ray data coinciding with the peak in the optical data (Fig. 4). It is also apparent that both the X-ray and optical outbursts are short lived, occupying only a small fraction of the orbital phase. There is a suggestion that the optical peak is actually split in two. To investigate this, we divided the light curve into two parts, MJDs 52086–53037 and MJDs 53179–54128, and then folded the two data sets using the period and ephemeris given above. We find that the double peak is prominent in the first half of the data, with little evidence of the same structure in the second half.

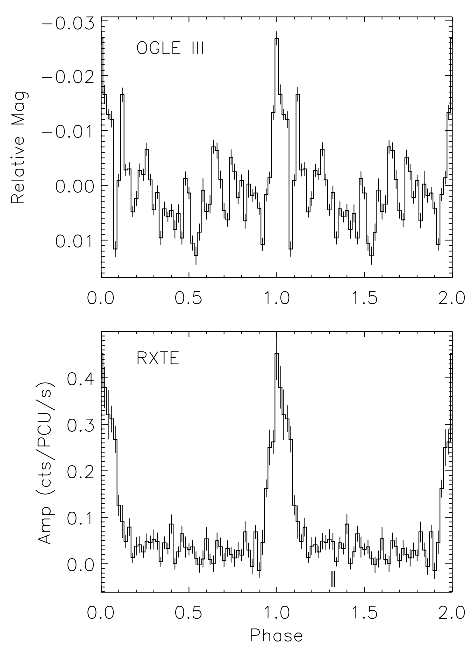

Figure 4. Detrended OGLE III (top panel) and *RXTE* data (bottom panel) for SXP46.6. The data are folded in 50 phase bins using $P = 137.74$ d and $T_0 =$ MJD 52430.3. The phases of the three *Chandra* observations are marked in the bottom panel (solid lines).

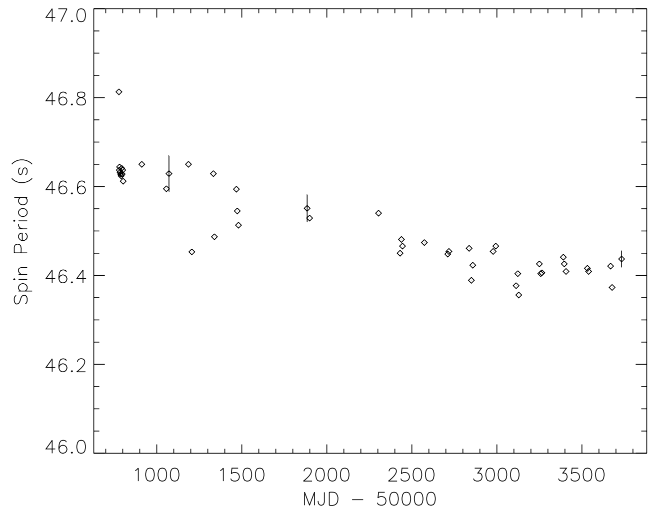

Figure 5. Spin-up of SXP46.6 over the last 10 yr, from *RXTE* monitoring.

2.3 Spin period

We show in Fig. 5 the pulse period history of SXP46.6 over the past 10 yr of *RXTE* monitoring. In general, the source has been spinning-up over that time frame, with an overall rate of change of spin period of $\dot{P} = -1.2 \times 10^{-9}\ \mathrm{s\,s^{-1}}$. The transfer of angular momentum to the neutron star from orbiting material as it is accreted is thought to be responsible for the spin-up (Ghosh & Lamb 1979). The luminosity required to achieve the measured spin-up is $1.2 \times 10^{36}\ \mathrm{erg\,s^{-1}}$. There is evidence that the rate of spin-up has slowed, with a notable flattening off in period change, since MJD 53000 (see Fig. 5). This coincides with the lower Hα equivalent widths measured in the optical spectra (see Section 2.4) and the diminishing size of the optical outbursts (see Fig. 2).

2.4 Optical spectra

Spectra of the optical counterpart of SXP46.6 have been taken on several occasions using the 1.9-m telescope at South African Astronomical Observatory, South Africa. A log of the observations is given in Table 1. The unit spectrograph was used with a 1200 line mm^{-1} grating, giving a dispersion of ∼0.4 Å/pixel. We also obtained a lower resolution spectrum of the source using the European Southern Observatory (ESO) faint object spectrograph and camera (EFOSC2) mounted on the 3.6-m telescope at La Silla, Chile. A 600 line mm^{-1} grating was used giving a dispersion of 2 Å/pixel. The SAAO and ESO data were reduced using standard IRAF packages. The SAAO spectra are plotted in Fig. 6. It is clear that the profile of the Hα emission is changing with time; the equivalent widths are

Table 1. Observation log of the optical spectra for SXP46.6.

Date	MJD	Telescope	Exposure (s)	Hα EW (Å)
1998 August 19/20	51044/5	SAAO 1.9 m	2 × 600	-15.3 ± 0.9^a
2001 November 11	52224	SAAO 1.9 m	1000	-2.6 ± 1.0
2002 December 15	52623	SAAO 1.9 m	1500	-20.2 ± 0.5
2003 November 07	52950	SAAO 1.9 m	1000	-23.2 ± 0.6
2005 October 27	53670	SAAO 1.9 m	2000	-8.3 ± 0.4
2006 November 13	54052	SAAO 1.9 m	1500	-11.2 ± 0.5
2007 September 17	54360	La Silla 3.6 m	500	-12.8 ± 0.2

[a]Buckley et al. (2001)

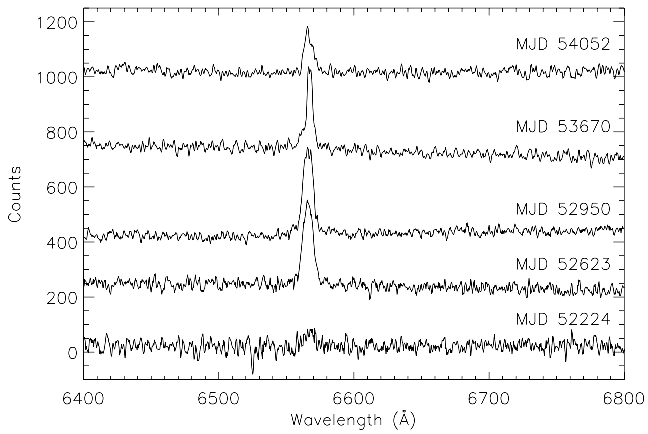

Figure 6. Optical spectra for SXP46.6 taken with the SAAO 1.9-m telescope, plotted in order of ascending date. The spectra have been smoothed with a boxcar average of three and offset for clarity. Note the variable Hα emission.

given in Table 1. The variations in Hα are likely due to variations in the circumstellar disc of the Be star.

3 SXP6.85 = XTE J0103–728

X-ray emission, pulsed at 6.8482 s, was first detected from SXP6.85 in 2003 with *RXTE* (Corbet et al. 2003). Continued *RXTE* observations spanning two months in 2003 displayed the transient nature of the source (Corbet et al. 2003). A further five detections have been made during the 10 yr monitoring campaign of the SMC with *RXTE* (see Galache et al. 2007). Temporal analysis of the X-ray data by Galache et al. (2007) revealed a period at 112.5 d, but it is not clear if this represents a true modulation or if this value is driven by the interval between two major outbursts. SXP6.85 was detected in an *XMM–Newton* observation in 2006 leading to the identification of the source with a $V = 14.6$ Be star (Haberl, Pietsch & Kahabka 2007). Independently, Schmidtke & Cowley (2007) analysed MACHO and OGLE II data for the source finding that the optical brightness varied over a time-scale of ∼658 d. They also find a possible period in the OGLE II data of 24.82 d.

3.1 Optical light curve

A search of the MACHO (Alcock et al. 1999) and OGLE II data bases (Udalski et al. 1997; Szymański 2005) provided optical photometry for SXP6.85. The MACHO project generated simultaneous photometry in two passbands, a *red* band (∼6300–7600 Å) and a *blue* band (∼4500–6300 Å), both measured in instrumental magnitudes. We have also obtained the OGLE III data for the source. In Fig. 7 (top panel), we show the combined MACHO *blue*, OGLE II and OGLE III light curves of the source, from 1992 August 18 to 2007 January 28. In order to display the data on the same scale, we had to shift the MACHO *blue* data by +24.82 mag, and the OGLE III data by −0.3 mag, both with respect to the OGLE II data.

The combined light curve displays large variations in brightness over the ∼14.5 yr of observations. To determine whether these changes are periodic, we searched the data for coherent modulations in the range 2–1000 d using LS and PDM periodograms. Both periodograms show a strong peak (dip) at ∼620 ± 18 d, however the folded light curve indicates that the variations are quasi-periodic

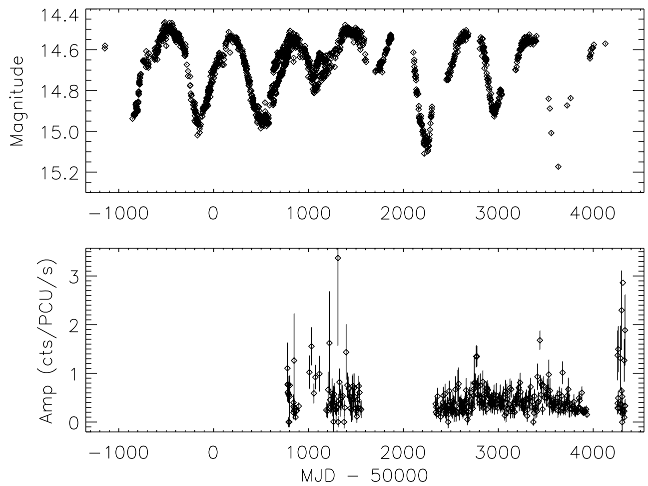

Figure 7. The combined MACHO *blue*, OGLE II and OGLE III light curves (top panel) and *RXTE* light curve of SXP6.85 (bottom panel). The MACHO blue data have been shifted by +24.82 mag and the OGLE III data by −0.3 mag, both with respect to the OGLE II data. The optical error bars are smaller than the plotted symbols.

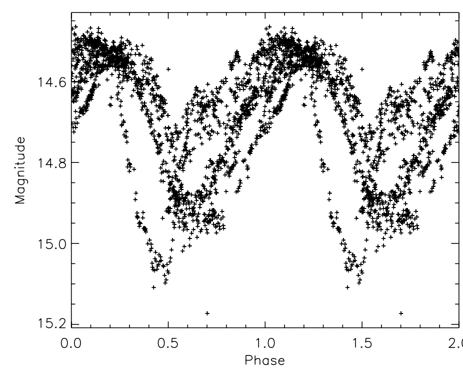

Figure 8. Combined light curve of SXP6.85 folded on $P = 620.68$ d.

(Fig. 8). This is similar to the value found by Schmidtke & Cowley (2007).

Using a similar analysis to SXP46.6, we detrended the combined light curve of SXP6.85 by splitting it into several sections and then subtracted a linear fit from each section. We then performed a period search with LS and PDM periodograms, again over the range 2–1000 d. Both periodograms show several large peaks (dips), with the highest peak in the LS periodogram occurring at 114.07 ± 0.62 d, and the corresponding PDM dip at 114.01 ± 0.62 d. There is a smaller peak (dip) at 25.86 d which is close to the value reported by Schmidtke & Cowley (2007). However, due to the large aperiodic changes in the raw data it is likely that these peaks (dips) are spurious and do not represent true periodic behaviour. We find that the amplitudes of the variations in the detrended light curves folded on these values are <0.01 mag.

3.2 X-ray light curve

The *RXTE* light curve of SXP6.85 was generated in the same way as for SXP46.6 (see Section 2.2). We show in Fig. 7 (bottom panel) the *RXTE* light curve of SXP6.85. There does not appear to be any obvious correlation between the X-ray outbursts and the raw

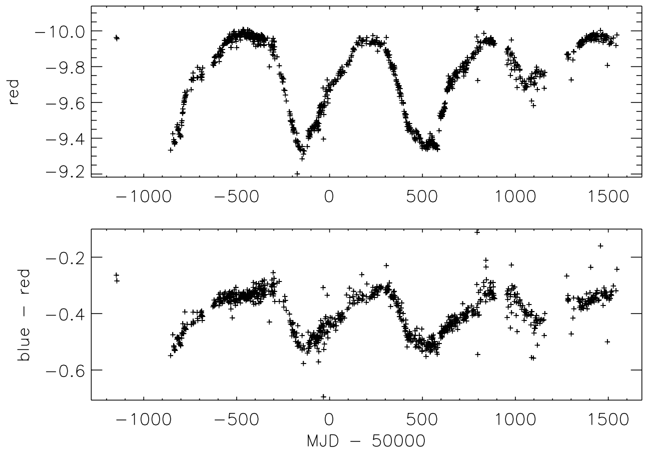

Figure 9. MACHO *red* light curve (top panel) and MACHO *blue–red* colour variations over time (bottom panel) for SXP6.85. Note that the source gets redder as it gets brighter.

optical data (Fig. 7, top panel) or with the detrended optical data (not shown).

3.3 Colour variations

We show in Fig. 9 how the colour of SXP6.85 varies over time compared to the MACHO red data. It can be seen that as the source brightens it gets redder. This indicates that the variations in the light curve are likely to be caused by changes in the structure of the circumstellar disc around the Be star. This is due to the disc being redder in $B - V$ (i.e. cooler) than the Be star (Janot-Pacheco, Motch & Mouchet 1987). Thus, the formation of the circumstellar disc will increase the optical brightness of the system by the addition of red light, or it will make the system appear fainter by masking the Be star, behaviour that is dependant on the inclination of the system. It is interesting to note that the shape of the colour changes do not exactly mirror the variations in the red light curve.

4 DISCUSSION

4.1 SXP46.6

The optical light curve of SXP46.6 displays long-term variations that are most likely due to the formation and depletion of the Be star's circumstellar disc. It is reasonable to assume, if the equatorial plane of the Be star coincides with the orbital plane of the compact object, that as the neutron star orbits close to this disc at periastron X-ray outbursts should be observed. Our results show that not only do we detect X-ray outbursts, but optical outbursts are also seen. SXP46.6 is therefore one of only a handful of systems that displays optical bursts at the binary period (see e.g. Alcock et al. 2001; Cowley & Schmidtke 2003; Schmidtke, Cowley & Levenson 2003; Coe & Edge 2004; Edge et al. 2005). We find that the amplitude of the optical outbursts (∼0.04 mag) is similar to those of other sources (see e.g. Cowley & Schmidtke 2003; Schmidtke et al. 2003).

In Be/X-ray transients, in general, the depletion of the circumstellar disc leads to a decrease in the optical brightness of the system. For SXP46.6, even when the optical light curve goes into a sharp decline there must be a residual disc present as outbursts, both at optical and X-ray wavelengths, are seen. In contrast, as the optical brightness recovers, which would normally be attributed to the disc reforming, an X-ray outburst is evident but there does not appear to be a corresponding burst in the optical. The reason for this is unclear, but could possibly be related to the amount of material in the circumstellar disc available for accretion and the quantity that is transferred to the neutron star. If less matter is accreted the optical outbursts could have a lower amplitude and may not be detectable above the intrinsic variability in the optical light curve. Another possibility for the lack of an optical outburst at this time is that there remains a wind that is sufficient to generate X-ray outbursts only.

Using the Hα equivalent width as an indicator for the circumstellar disc size (Dachs et al. 1986), we find that for the first three years of OGLE III monitoring the disc size is increasing, anticorrelated with the optical brightness. Unfortunately, we do not have spectra during the optical minimum. After the optical minimum, the equivalent width of the Hα emission line seems to reflect the recovery of the circumstellar disc, with the width of the line increasing as the optical brightness increases. The anticorrelated behaviour initially may be due to the disc covering part of the Be star leading to a reduction in brightness. This has been seen in another source, A 0538-66 (Alcock et al. 2001). It is unfortunate that we do not have multiband data that would allow us to investigate the colours of the source at these times.

The shape of the optical and X-ray outbursts for SXP46.6 is both asymmetric, with a faster rise and slower decline, reminiscent of other Be/X-ray binaries (see e.g. Alcock et al. 2001; Coe & Edge 2004). We propose that the optical bursts could be due to the circumstellar disc being perturbed at each passage causing the disc to grow slightly, leading to an enhancement in the optical brightness. We can calculate a rough estimate for this increase in brightness. If we assume that the 0.5 magnitude global change in the light curve represents the difference between no disc and a full disc, then this corresponds to an increase in light of 58 per cent. The optical outbursts we detect have an amplitude of ∼0.04 mag, which equals a total increase from no disc of 64 per cent. Assuming that the increase in brightness is equivalent to the disc size, then during outburst the disc grows by ∼10 per cent. We note that the increase in optical brightness at outburst may not be due to geometric effects alone. We find that the luminosity of the optical outbursts is $\sim 3 \times 10^{34}$ erg s^{-1} and the luminosity of the X-ray outbursts is $\sim 2 \times 10^{36}$ erg s^{-1}. This implies that reprocessing could be contributing to the change in the optical light.

Stella, White & Rosner (1986) distinguished between the various kinds of X-ray behaviour observed from Be/X-ray binaries, placing them into three groups: (i) persistent, low-level (quiescent) emission, (ii) relatively bright, short-lived outbursts recurring on the orbital period at the time of periastron passage, known as Type I, and (iii) large, long-lived (weeks to months) outbursts that occur irregularly, known as Type II. We are most likely detecting quiescent emission from SXP46.6 in the *Chandra* observations. Okazaki & Negueruela (2001) have shown that the class of X-ray outbursts detected from a Be/X-ray transient, Type I and/or Type II, is dependent on the orbital eccentricity of the system, and the viscosity of the disc. The disc in binaries with low eccentricity is truncated at the 3:1 resonance radius. This means that too little material is captured (if any) by the compact object as it orbits the Be star as the disc is too far away. Therefore, regular Type I outbursts cannot be produced by these systems, but they may show infrequent Type II outbursts. In contrast, periodic Type I outbursts are generated in high-eccentricity binaries as the disc is truncated at a larger resonance radius, which permits material to be accreted by the neutron star every orbit. The detection of Type I X-ray outbursts from SXP46.6, and the corresponding optical outbursts, and its similarity to other sources that have shown optical outbursts on the orbital period, implies that SXP46.6 has a high orbital eccentricity.

4.2 SXP6.85

The long-term optical light curve of SXP6.85 is similar to that of SXP46.6 in the fact that the large changes observed are not periodic, leading to the conclusion that they are related to the Be phenomenon. The variations in the source's colour support this. Even after detrending, we find little evidence for any coherent modulations in the optical light curve of SXP6.85.

Analysis of SXP6.85's X-ray light curve does not firmly demonstrate the presence of periodic behaviour either (Galache et al. 2007). More data are needed to confirm the tentative orbital period proposed. There is a lack of correlation between the optical and X-ray data. By comparing the two data sets, we find that one X-ray outburst occurs just prior to optical maximum, while another two seem to occur as the optical source is fading. This implies that the neutron star is not accreting directly from the stellar wind, and could indicate that the X-ray emission is triggered by discrete episodes of disc material being lost radially (see e.g. Clark et al. 1999).

The characteristics of SXP6.85 are very similar to those of EXO 0531-66 and H 0544-665 (McGowan & Charles 2002). All three sources are highly variable in the optical over long time-scales but do not show variations that are orbital in origin, they become redder as they brighten in the optical and no strong correlation is found between the X-ray and optical measurements. Due to the similarities of these sources, and with comparison to SXP46.6, we therefore propose that SXP6.85 is a low-eccentricity system.

5 SUMMARY

We find that the long-term optical light curve of SXP46.6 displays regular outbursts that are coincident with the X-ray outbursts, both modulated on a period of ~137 d. The behaviour of SXP46.6 indicates that it has a high orbital eccentricity. Our results from optical spectra of SXP46.6 imply that the Be star's circumstellar disc varies in size over the years. We do not find any periodic modulations in the optical light curve of SXP6.85, but our analysis does show that as the source brightens it gets redder. It is therefore likely that the changes in the light curve and the colour variations are due to the formation and depletion of the circumstellar disc. The lack of correlated X-ray and optical activity for SXP6.85 suggests that it is a low-eccentricity system.

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