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The binary period and outburst behaviour of the Small Magellanic Cloud X-ray binary pulsar system SXP504

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ABSTRACT

A probable binary period has been detected in the optical counterpart to the X-ray source CXOU J005455.6–724510 = RX J0054.9–7245 = AX J0054.8–7244 = SXP504 in the Small Magellanic Cloud. This source was detected by *Chandra* on 2002 July 4 and subsequently observed by *XMM–Newton* on 2003 December 18. The source is coincident with an Optical Gravitational Lensing object in the light curves of which several optical outburst peaks are visible at ∼268-d intervals. Timing analysis shows a period of 268.6 ± 0.1 d at >99 per cent significance. Archival *Rossi X-ray Timing Explorer* data for the 504-s pulse-period have revealed detections which correspond closely with predicted or actual peaks in the optical data. The relationship between this orbital period and the pulse period of 504 s is within the normal variance found in the Corbet diagram.

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

1 INTRODUCTION

The Magellanic Clouds are a pair of satellite galaxies which are gravitationally bound to our own but which have structural and chemical characteristics differing significantly from each other, and from the Milky Way. These differences are likely to be reflected in the properties of different stellar populations. The Small Magellanic Cloud (SMC) is located at a distance of about 60 kpc (Harries, Hilditch & Howarth 2003) and centred on a position of RA $1^{\rm h}$, Dec. -73°. It is therefore close enough to be observed with modest ground-based telescopes while at the same time providing an opportunity to study and compare the evolution of other galaxies.

Intensive X-ray satellite observations have revealed that the SMC contains an unexpectedly large number of High Mass X-ray Binaries (HMXB). At the time of writing, 47 known or probable sources of this type have been identified in the SMC and they continue to be discovered, although only a small fraction of these are active at any one time because of their transient nature. All X-ray binaries so far discovered in the SMC are HMXBs (Coe et al. 2005).

Most HMXBs belong to the Be class, in which a neutron star orbits an OB star surrounded by a circumstellar disc of variable size and density. The optical companion stars are early-type OB-class stars of luminosity class III–V, typically of 10–20 solar masses that at some time have shown emission in the Balmer series lines. The systems as a whole exhibit significant excess flux at long (IR and radio) wavelengths, referred to as the infrared excess. These characteristic signatures as well as strong Hα line emission are attributed to the presence of circumstellar material in a disc-like configuration (Coe 2000; Okazaki & Negueruela 2001).

The mechanisms which give rise to the disc are not well understood, although fast rotation is likely to be an important factor, and it is possible that non-radial pulsation and magnetic loops may also play a part. Short-term periodic variability is observed in the earlier type Be stars. The disc is thought to consist of relatively cool material, which interacts periodically with a compact object in an eccentric orbit, leading to regular X-ray outbursts. It is also possible that the Be star undergoes a sudden ejection of matter (Negueruela 1998; Porter & Rivinius2003).

Be/X-ray binaries can present differing states of X-ray activity varying from persistent low or non-detectable luminosities to short outbursts. Systems with wide orbits will tend to accrete from less dense regions of the disc and hence show relatively small outbursts. These are referred to as Type I (Stella et al. 1986) and usually coincide with the periastron of the neutron star. Systems with smaller orbits are more likely to accrete from dense regions over a range

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of orbital phases and give rise to very high-luminosity outbursts, although these may be modulated by the presence of a density wave in the disc. Prolonged major outbursts, which are not confined to periastron passage, are normally called Type II (Negueruela 1998).

2 THE DATA

2.1 X-ray data

This X-ray object was discovered in archive data using an observation made by the *Chandra* X-ray Observatory on 2002 July 4 (MJD 52459) (Edge et al. 2004). Its position was determined as RA$00^h\,54^m\,55\overset{s}{.}8$, Dec. $-72^\circ\,45'\,11''$ to an accuracy of ~1 arcsec. It was found to have a period of 503.5 ± 6.7 s at a >99 per cent level of confidence. The source was subsequently independently identified by Haberl et al. (2004) in an *XMM–Newton* observation of 2003 December 18 (MJD 52991). They computed the pulse period at 499.2 ± 0.7 s. The object is very close to RX J0054.9–7245 = AX J0054.8–7244 which is listed by both Haberl & Pietsch (Haberl & Pietsch 2004) and Yokogawa et al. (Yokogawa et al. 2003) as a HMXB pulsar candidate.

The Rossi X-ray Timing Explorer (RXTE) has been regularly monitoring the SMC since 1997 on a weekly basis (Corbet et al. 2004; Laycock et al. 2004). A search of archival RXTE Proportional Counter Array (PCA) data for the 504-s pulse-period revealed a considerable number of detections. Those of >99 per cent significance are listed in Table 1 and are also plotted as histograms in Figs 2 and 3, below. Timing analysis was carried out on the consolidated RXTE observations and revealed a strong peak in the power spectrum at 268.1 ± 5 d at a significance of 56.5 per cent. This is shown in the upper panel of Fig. 1. The folded pulse profile of the RXTE X-ray light curve is in the lower panel. T_0 was put at MJD 50560.

Table 1. RXTE detections of >99 per cent significance, showing MJD, flux and significance.

MJD	Flux (count $pcu^{-1}\,s^{-1}$)	Sig (per cent)
51439.33	0.330	99.5
51624.15	0.741	99.9
51646.91	1.108	99.9
51898.86	0.899	99.9
51933.35	0.544	99.9
51941.38	0.495	99.5
52066.8	0.700	99.4
52171.31	0.639	99.7
52193.62	0.964	99.9
52438.72	1.336	99.9
52483.84	0.732	99.5
52515.41	0.915	99.9
52555.42	0.724	99.9
52606.21	0.583	99.9
52612.3	0.686	99.9
52660.25	0.930	99.9
52676.25	0.495	99.8
52683.09	0.715	99.9
52687.9	0.749	99.9
52717.96	0.720	99.9
52746	0.551	99.9
52778.87	0.678	99.7
52836.83	0.895	99.9
52954.72	0.474	99.8
52969.16	0.851	99.9
53044.37	0.451	99.9

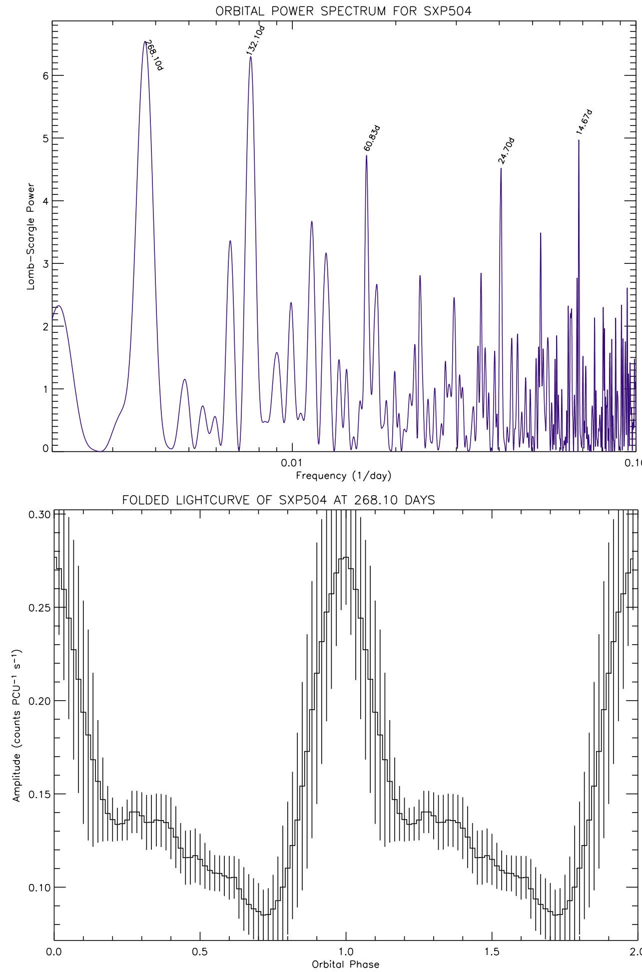

Figure 1. Upper panel: power spectrum from timing analysis of consolidated RXTE observations of SXP 504. This shows a strong peak at 268.1 ± 5 d. Lower panel: light curve folded at 268.1 d. T_0 is MJD 50560.

This object is likely to be the same as the *ROSAT* source RX J0054.9–7245 which was detected in three observations: on 1993 May 9–12, on 1994 April 15 and 1997 April 3 to 1997 May 2. It was not detected in several other *ROSAT* observations; however the detection threshold of these was not as low as the 1993 May level. It may also be the *ASCA* source AX J0054.8–7244 which was detected in 1998 November (Haberl et al. 2004).

2.2 Optical data

The position of the source given in Section 2.1 coincides with the emission-line object [MA93] 809 (Meyssonnier & Azzopardi 1993) which is taken to be the optical counterpart. The star has a V magnitude of 14.99 and a $B - V$ colour index of −0.02 (Coe et al. 2005) and appears in both the OGLE and MACHO data bases. These data bases provide an opportunity to investigate the variability of this object over a period of about 11 yr.

2.2.1 OGLE

The Optical Gravitational Lensing Experiment (OGLE) is a long-term project, started in 1992, with the main goal of searching for

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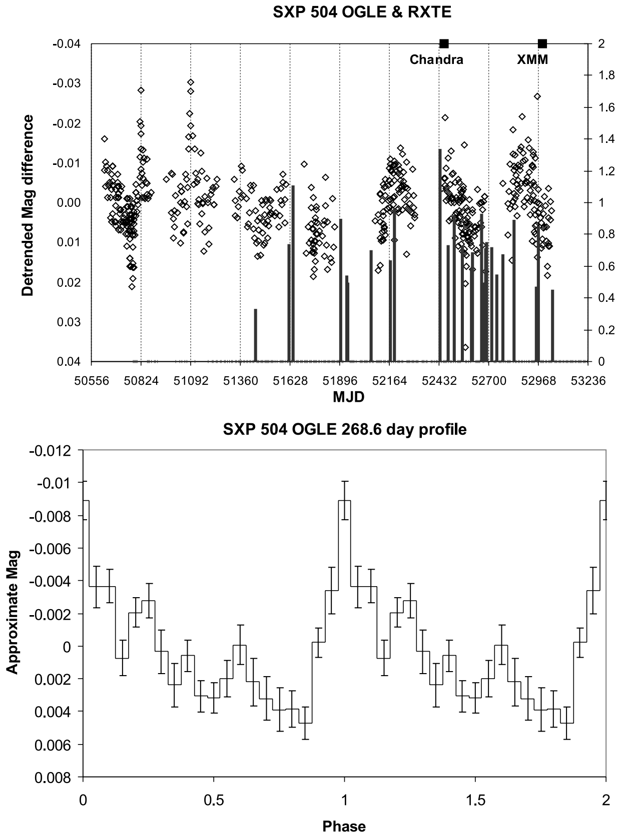

Figure 2. SXP 504 OGLE light curve (top panel). The epochs of the *Chandra* and *XMM–Newton* observations are marked on the upper *X*-axis of the diagram. All RXTE detections of >99 per cent significance are shown against the right-hand *Y*-axis scale. Optical outburst peaks are visible at MJD 50829, 51098 and 52965. These observations indicate an orbital period of ~268 d, marked on the *X*-axis. The bottom panel shows the OGLE light curve folded at 268 d using the MJD 50556 zero-point. The modulation amplitude is 0.015 mag.

dark matter with microlensing phenomena (Udalski et al. 1998). Two sets of OGLE data, designated II and III, are available for this object. Both show *I*-band magnitudes using the standard system; however the more recent OGLE III data have not yet been fully calibrated to photometric accuracy. The source is coincident with the OGLE object numbered 47103, in Phase II, and 36877, in Phase III.

These light curves are shown in the top panel of Fig. 2. An inspection of the raw data showed that the partially calibrated Phase III data were offset from the Phase II data by 0.05 mag. An adjustment of this amount was therefore applied after which the light curves were joined and detrended with a sixth-order polynomial. The epochs of the *Chandra* and *XMM–Newton* observations are marked on the upper *X*-axis of the diagram. All RXTE detections of >99 per cent significance are also shown; the height of the columns indicates the flux in counts pcu^{-1} s^{-1} against the right-hand *Y*-axis scale. Several optical outburst peaks are visible at ~268-d intervals, which are shown on the *X*-axis of the diagram.

In order to examine the profile, the light curve was folded at 268 d using the MJD 50556 zero-point. The result is shown in the bottom panel of Fig. 2 which reveals a sharp profile with a peak-to-peak modulation of 0.015 ± 0.002 mag.

2.2.2 *MACHO*

In 1992 the MAssive Compact Halo Objects (MACHO) project began a survey of regular photometric measurements of several million Magellanic Cloud and Galactic bulge stars (Alcock et al. 1993). The MACHO data cover the period 1992 July to 2000 January and consist of light curves in two colour bands described as *blue* and *red*. *Blue* is close to the standard *V* passband and *red* occupies a position in the spectrum about half-way between *R* and *I* (Alcock et al. 1999).

This source is coincident with MACHO object 207.16245.16. The light curve from the *red* data is shown in the top panel of Fig. 3. A single rogue observation at MJD 50359, which was 2 mag brighter that all the others, was removed after which it was detrended using a fifth-order polynomial. The figure shows clear evidence for optical outbursts at the ~268-d intervals marked on the *X*-axis. RXTE detections of >99 per cent significance are shown against the right-hand *Y*-axis scale. The epochs of the *ROSAT* (solid squares) and *ASCA* (solid circle) detections are also shown on the upper *X*-axis.

To examine the pulse profile, the light curve was also folded at 268 d (Fig. 3, bottom panel) using the same zero-point as Fig. 2 (MJD 50556). The amplitude of the peak-to-peak modulation is 0.018 ± 0.0006 mag.

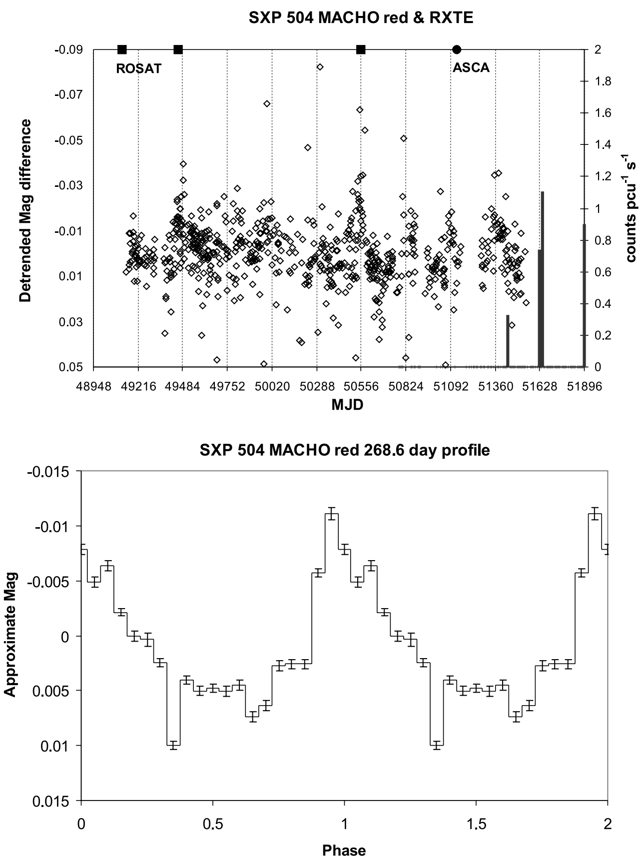

Figure 3. SXP 504 MACHO *red* light curve (top panel). RXTE detections of >99 per cent significance are shown against the right-hand *Y*-axis scale. The epochs of the *ROSAT* detections are shown as solid squares and that of the *ASCA* detection as a solid circle, on the upper *X*-axis. there is clear evidence for optical outbursts at the ~268-d intervals marked on the *X*-axis. The bottom panel shows the MACHO *red* light curve folded at 268 d using the MJD 50556 zero-point. The modulation amplitude is 0.018 mag.

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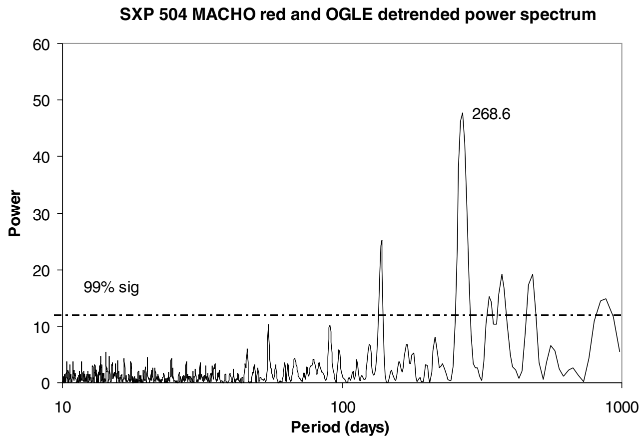

Figure 4. SXP 504 combined MACHO *red* and OGLE optical power spectrum generated using the Lomb–Scargle algorithm. There is a strong period at 268.6 ± 0.1 d which corresponds closely with the observed outburst intervals. The smaller peak is the half-period harmonic.

The MACHO *blue* light curve is not strongly modulated and did not produce either a significant period or a coherent pulse profile.

2.2.3 *Optical timing analysis*

For the purpose of timing analysis the OGLE and MACHO *red* data were normalized and combined into a single data set. This was then subjected to Lomb–Scargle analysis which revealed a strong period of 268.6 ± 0.1 d corresponding closely with the observed outburst intervals. The power spectrum is in Fig. 4. The smaller peak is the half-period harmonic.

3 DISCUSSION AND CONCLUSION

SXP504 has been identified as an X-ray binary pulsar system in the SMC (Edge et al. 2004). It appears to be typical of such systems insofar as the optical counterpart is a Be star, but it is unusual because it is one of a minority of such objects that show visible peaks in the optical light curves at the binary period. The most comparable system in the SMC is SXP756 which also has a long orbital period at 394 d as well as highly visible, but narrow and short-lived, optical outbursts.

The optical modulation is thought to arise when the neutron star in a highly eccentric orbit briefly interacts with the Be star disc at periastron. The tidal torque, which is strongest at this point, removes angular momentum from the outermost part of the disc, causing it to shrink and its density to increase. In addition, the two-armed spiral wave, which is excited at periastron, also enhances the disc density. If the disc is optically thin, the luminosity will also increase because the local emissivity is proportional to the square of the density. This occurs just after the periastron passage of the neutron star (Okazaki et al. 2002). The higher the orbital eccentricity, the more rapid and significant the luminosity increase is expected to be (Okazaki, in preparation). The subsequent decay of the optical outburst results from expansion of the disc by viscous diffusion and is necessarily slower.

It follows that where the binary orbit is long and highly eccentric, the disc is almost unaffected for much of the orbital phase and the optical outbursts are likely to be more clearly marked.

The 268-d period detected in this system is visible as outburst peaks in both the OGLE and MACHO light curves. The existence of these peaks has been confirmed by folding the data and revealing the pulse profiles. Lomb–Scargle analysis of the MACHO and OGLE data has detected a period of 268.6 ± 0.1 d, which agrees closely with the observed period of the outburst intervals.

All these observations can be described by an ephemeris of:

$$T = (\mathrm{MJD}\ 50556 \pm 3) + n(268 \pm 0.6) \quad (1)$$

where T is the epoch of the outburst and n is the outburst cycle number.

Lomb–Scargle analysis of the consolidated RXTE observations has detected a period of 268.1 ± 5 d. Furthermore the stronger X-ray detections of >99 per cent are nearly all very close to the peaks predicted by the optical ephemeris, but because of non-continuous X-ray coverage, others may well have been missed. The relationship between this orbital period and the pulse period of 504 s is within the normal variance found in the Corbet diagram (Corbet 1984).

These results, taken together, confirm that 268 d is the binary period of the system. They also provide an instructive example of the use of parallel and complementary long-term X-ray and optical data in determining the orbital characteristics of an X-ray binary system.

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