The binary period and outburst behaviour of the SMC X-ray binary pulsar system SXP504.

W.R.T. Edge,¹ M.J. Coe,¹ J.L. Galache,¹ V.A. McBride,¹ R.H.D. Corbet,²,³ A.T. Okazaki,⁴ S. Laycock,⁵ C.B. Markwardt,²,⁶ F.E. Marshall,² A. Udalski,⁷

¹School of Physics and Astronomy, Southampton University, SO17 1BJ, UK  
²NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA  
³Universities Space Research Association  
⁴Faculty of Engineering, Hokkai-Gakuen University, Sapporo, Japan  
⁵Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA  
⁶Department of Astronomy, University of Maryland, College Park, MD 20742, USA  
⁷Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

Accepted 2005. Received 2005; in original form 2005

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 = AXJ0054.8-7244 = SXP504 in the Small Magellanic Cloud. This source was detected by Chandra on 04 Jul 2002 and subsequently observed by XMM-Newton on 18 Dec 2003. The source is coincident with an Optical Gravitational Lensing (OGLE) object in the lightcurves of which several optical outburst peaks are visible at ~268 day intervals. Timing analysis shows a period of 268.6±0.1 days at >99% significance. Archival Rossi X-ray Timing Explorer (RXTE) data for the 504s pulse-period has 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 504s is within the normal variance found in the Corbet diagram.

Key words: Be stars - X-rays: binaries: Magellanic Clouds.

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 R.A. 1hr Dec. -73°. It is therefore close enough to be observed with modest ground based telescopes whilst 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 (HMXBs). 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 High Mass X-ray Binaries (HMXBs) belong to the Be class, in which a neutron star orbits an OB star surrounded by a circumstellar disk of variable size and density. The optical companion stars are early-type O-B class stars of luminosity class III-V, typically of 10 to 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 disk-like configuration (Coe 2000, Okazaki & Negueruela 2001).

The mechanisms which give rise to the disk 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 disk 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 possi-
ble that the Be star undergoes a sudden ejection of matter (Negueruela 1998, Porter & Rivinius 2003).

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 disk and hence show relatively small outbursts. These are referred to as Type I (Stella et al., 1986) and usually coincide with the periastron passage, 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 4 July 2002 (MJD 52459) (Edge et al. 2004). Its position was determined as R.A. 00:54:55.8 Dec. -72:45:11 to an accuracy of ~1 arcsec. It was found to have a period of 503.5 ± 6.7 s at a > 99% level of confidence. The source was subsequently independently identified by Haberl et al. (2004) in an XMM-Newton observation of 18 Dec 2003 (MJD 52991). They computed the pulse period at 499 ± 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 504s pulse-period revealed a considerable number of detections. Those of > 99% significance are listed in Table 1 and are also plotted as histograms in Figures 2 and 3. Timing analysis was carried out on the consolidated RXTE detections. Those of > 99% significance are also shown, the height of the columns indicates the flux in counts pcu⁻¹ s⁻¹. The folded pulse profile of the RXTE X-ray lightcurve, is in the lower panel. \( T_0 \) was put at 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 9-12 May 1993, on 15 Apr 1994 and 3 Apr - 2 May 1997. It was not detected in several other ROSAT observations, however the detection threshold of these was not as low as the May 1993 level. It may also be the ASCA source AXJ0054.8-7244 which was detected in Nov 1998 (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 (Meyssonier & 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

| MJD  | Flux (cts pcu⁻¹ s⁻¹) | Sig (%) |
|------|---------------------|---------|
| 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 |

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

OGLE and MACHO databases. These databases provide an opportunity to investigate the variability of this object over a period of about 11 years.

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 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 lightcurves are shown in the top panel of figure 2. An inspection of the raw data showed that the partially calibrated Phase III data was offset from the Phase II data by a 6th 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% 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 day intervals, which are shown on the X axis of the diagram.

In order to examine the profile, the lightcurve was folded at 268 days using the MJD 50556 zeropoint. The result is
2.2.2 MACHO

In 1992 the MAssive Compact Halo Objects project (MACHO) 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 July 1992 to January 2000 and consist of lightcurves 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 halfway between R and I (Alcock et al. 1999).

This source is coincident with MACHO object 207.16245.16. The lightcurve from the red data is shown in the top panel of figure 2. A single rogue observation at MJD 50359, which was 2 magnitudes brighter that all the others, was removed after which it was detrended using a 5th order polynomial. The figure shows clear evidence for optical outbursts at the ~ 268 day intervals marked on the X axis.

RXTE detections of > 99% 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 lightcurve was also folded at 268 days (figure 3 bottom panel) using the same zeropoint as figure 2 (MJD 50556). The amplitude of the peak to peak modulation is 0.018 ± 0.0006 mag.

The MACHO blue lightcurve is not strongly modulated and did not produce either a significant period or a coherent pulse profile.
Figure 3. SXP 504 MACHO red lightcurve (Top panel). RXTE detections of > 99% 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 day intervals marked on the X axis. The bottom panel shows the MACHO red lightcurve folded at 268 days using the MJD 50556 zeropoint. The modulation amplitude is 0.018 mag.

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 lightcurves at the binary period. The most comparable system in the SMC is SXP756 which also has a long orbital period at 394 days 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 Be star disk at periastron. The tidal torque, which is strongest at this point, removes angular momentum from the outermost part of the disk, causing it to shrink and its density to increase. In addition, the two-armed spiral wave, which is excited at periastron, also enhances the disk density. If the disk 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 2005, in preparation). The subsequent decay of the optical outburst results from expansion of the disk by viscous diffusion and is necessarily slower.

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

The 268 day period detected in this system is visible as outburst peaks in both the OGLE and MACHO lightcurves. 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 days, which agrees closely with the observed period of the outburst intervals.

All these observations can be described by an ephemeris of:

$$T = (\text{MJD } 50556 \pm 3) + n (268 \pm 0.6)$$  \hspace{1cm} (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 days. Furthermore the stronger X-ray detections of > 99% 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 504s is within the normal variance found in the Corbet diagram (Corbet 1984).

These results, taken together, confirm that 268 days 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.

© 2005 RAS, MNRAS 000, 1–
ACKNOWLEDGMENTS

This paper utilizes public domain data obtained by the MA-CHO Project, jointly funded by the US Department of Energy through the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48, by the National Science Foundation through the Center for Particle Astrophysics of the University of California under cooperative agreement AST-8809616, and by the Mount Stromlo and Siding Spring Observatory, part of the Australian National University.

Partial support to the OGLE project was provided with the following grants: Polish MNII grant 2P03D02124, NSF grant AST-0204908 and NASA grant NAG5-12212.

REFERENCES

Alcock, C. et al. 1993, ASP Conf. Ser. 43: Sky Surveys. Protostars to Protogalaxies, 291
Coe, M. J., Edge, W. R. T., Galache, J. L., & McBride, V. A. 2005, MNRAS, 356, 502
Corbet, R. H. D., Laycock, S., Coe, M. J., Marshall, F. E., & Markwardt, C. B. 2004, AIP Conf. Proc. 714: X-ray Timing 2003: Rossi and Beyond, 714, 337
Edge, W. R. T., Coe, M. J., Galache, J. L., McBride, V. A., Corbet, R. H. D., Markwardt, C. B., & Laycock, S. 2004, MNRAS, 353, 1286
Haberl, F., Pietsch, W., Schartel, N., Rodriguez, P., & Corbet, R. H. D. 2004, A&A, 420, L19
Haberl, F., & Pietsch, W. 2004, A&A, 414, 667
Laycock, S., Corbet, R. H. D., Coe, M. J., Marshall, F. E., Markwardt, C, Lochner, J 2005, astro-ph 0406420
Meissner, N., & Azzopardi, M. 1993, A&AS, 102, 451
Okazaki, A. T., Bate, M. R., Ogilvie, G. I., & Pringle, J. E. 2002, MNRAS, 337, 967
Okazaki, A. T. 2005, Private communication
Stella, L., White, N. E., & Rosner, R. 1986, APJ, 308, 669
Udalski, A., Szymanski, M., Kubia, M., Pietrzynski, G., Wozniak, P., & Zebrun, K. 1998, Acta Astronomica, 48, 147
Yokogawa, J., Imanishi, K., Tsujimoto, M., Koyama, K., & Nishiuchi, M. 2003, PASJ, 55, 161