SXP 323 – an unusual X-ray binary system in the Small Magellanic Cloud

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ABSTRACT
We present spectroscopic observations, taken with the Very Large Telescope/Ultraviolet and Visual Echelle Spectrograph telescope/instrument, of the unusual Small Magellanic Cloud X-ray binary system SXP 323 = AX J0051−733. This system shows a clear modulation at 0.71 d in long-term optical photometry, which has been proposed as the binary period of this system. The high-resolution optical spectra, taken at a range of phases during the 0.71-d cycle, rule out this possibility. Instead it is suggested that this long-term effect is due to non-radial pulsations in the Be star companion to SXP 323. In addition, the spectra show clear evidence for major changes in the (V/R) ratio of the double peaks of the Balmer lines indicative of asymmetries in the circumstellar disc. The complex structure of the interstellar lines is also discussed in the context of the SMC structure.

Key words: stars: neutron – Magellanic Clouds – X-rays: binaries.

1 INTRODUCTION AND BACKGROUND
Be/X-ray systems represent the largest subclass of massive X-ray binaries. A survey of the literature reveals that of the 115 identified massive X-ray binary pulsar systems (here, identified means exhibiting a coherent X-ray pulse period), most of the systems fall within this Be counterpart class of binary. The orbit of the Be star and the compact object, presumably a neutron star, is generally wide and eccentric. X-ray outbursts are normally associated with the passage of the neutron star close to the circumstellar disc (Okazaki & Negueruela 2001).

X-ray satellite observations have revealed that the Small Magellanic Cloud (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 at a rate of about 2–3 yr−1, although only a small fraction of these are active at any one time because of their transient nature. Unusually (compared to the Milky Way and the Large Magellanic Cloud) all the X-ray binaries so far discovered in the SMC are HMXBs, and equally strangely, only one of the objects is a supergiant system; all the rest are Be/X-ray binaries. A recent review of these systems may be found in Coe et al. (2005).

The source that is the subject of this paper, SXP 323 = AX J0051−733, is one of these SMC systems. It was reported as a 323s pulsar by Yokogawa & Koyama (1998) and Imanishi et al. (1999). Subsequently, Cook (1998), using MACHO optical photometry, identified a 0.7-d optically variable object within the ASCA X-ray error circle. The system was discussed in the context of it being a HMXB by Coe & Orosz (2000), who presented some early OGLE data on the object identified by Cook (1998) and modelled the system parameters. Coe & Orosz identified several problems with understanding this system, primarily that if it was a binary, then its true period would be 1.4 d and it would be an extremely compact system. In addition, the combination of the pulse period and such a binary period violates the Corbet relationship for such systems (Corbet 1986). A discussion of the object as a possible triple system was presented in Coe et al. (2002).

In order to try and understand this unusual system better, high-resolution optical spectra were obtained at a variety of phases throughout the 1.4-d period.

2 OBSERVATIONAL DETAILS
Spectroscopy of the optical counterpart to SXP 323 was obtained with the Ultraviolet and Visual Echelle Spectrograph (UVES) mounted on the 8.2-m Very Large Telescope (VLT)/UT2 (Kueyen). UVES was used in the standard Diochroic #1 mode. The blue arm was equipped with a 2048 × 4096 15-μm pixel thinned EEV, providing coverage of the λλ 3821–4520 range. The red arm was equipped with a mosaic formed by a similar EEV CCD (covering λλ 4727–5804) and a MIT/LL CCID-20 chip (covering λλ 5818–6835). The spectral resolution of this configuration is 40 000.

Nine 2000-s exposures, each with a signal-to-noise (S/N) ratio of ∼35 pixel−1, were obtained in service mode at random times.
The nine sets are spread over the possible 1.4-d period and give a good coverage of different phases. The dates and phases of the observations are presented in Table 1.

### Table 1. Table of VLT observations. The phase given in the last column is that with respect to the precise OGLE period of 0.7081 d.

| Obs. date    | Obs. time (UT) | TJD   | Phase |
|--------------|----------------|-------|-------|
| 2003 June 9  | 09:12          | 2799.88 | 0.00  |
| 2003 June 12 | 08:48          | 2802.87 | 0.22  |
| 2003 June 13 | 09:35          | 2803.90 | 0.68  |
| 2003 June 23 | 08:13          | 2813.84 | 0.71  |
| 2003 July 4  | 06:21          | 2824.76 | 0.14  |
| 2003 July 6  | 05:43          | 2826.74 | 0.93  |
| 2003 July 11 | 05:12          | 2831.72 | 0.97  |
| 2003 July 28 | 08:45          | 2848.86 | 0.17  |
| 2003 July 31 | 03:56          | 2851.66 | 0.13  |

The high-quality, high-resolution spectra permit a detailed investigation of the interstellar line profiles in the direction of SXP 323. Specifically, two sets of interstellar lines were investigated: the Ca II H and K lines (3968.5 and 3933.7 Å, respectively) and the Na doublet (5890.0 and 5895.9 Å). Fig. 4 presents the region around the Ca II H line and shows the complex structure often associated with interstellar lines towards the SMC (see, for example, the extensive set of examples in Wayte 1990). The profiles of the Ca II H and K are almost identical to each other, and confirm the presence of at least three significant absorption features. These are indicated in Fig. 4 and listed in Table 2.

The region around the Na doublet is presented in Fig. 5 and the values also given in Table 2. From the Na group, we can immediately see similarities and differences with the Ca II line profiles. The main similarity is the presence of at least three major absorption features at essentially the same velocities to those in the Ca II lines. The other two features seen in the Ca II lines are weaker and cannot be ruled out as also being present in the Na D lines.

The main difference is the striking reversal in the relative strengths of the line sets between the Ca II and Na features. In the Ca II lines, the strongest feature is that at the highest velocity (204 km s$^{-1}$) while the weakest is that at the lowest velocity (0 km s$^{-1}$). The complete opposite is true for the Na lines.

### 7 POSSIBLE NON-RADIAL PULSATIONS

If the possibility of binary motion is excluded as an explanation for the 0.71-d modulation, then other explanations must be found. One possible alternative would be non-radial pulsations (NRPs) from the Be star. Such effects are well documented in B-type stars (see, for example, Uytterhoeven et al. 2004). In addition, Fabrycky (2005) has suggested an NRP explanation for two periods of 0.28 and 0.65 d seen in the OGLE data for SXP 702 (=XMMU J005517.9–723853).

The presence of strong emission components in most of the lines renders the search for profile variability extremely difficult.
Figure 2. Average Balmer line profiles for the first four of the series. The discontinuity to the left of Hβ is due to a slight mismatch in adjacent echelle orders.

Figure 3. Variations in the V/R ratio as a function of time for the Hβ line.

Figure 4. Interstellar line features associated with the Ca II H line.

Table 2. Table of measured interstellar line features. The error on each measurement is approximately ±5 km s⁻¹.

| Line Feature | Feature 1 (km s⁻¹) | Feature 2 (km s⁻¹) | Feature 3 (km s⁻¹) |
|--------------|--------------------|--------------------|--------------------|
| Ca II H      | 0                  | 128                | 204                |
| Ca II K      | 0                  | 130                | 198                |
| Na D         | 5                  | 132                | 200                |
| Na D         | 10                 | 137                | 200                |
| Average      | 4                  | 132                | 201                |

Figure 5. Interstellar line features associated with the Na D lines.

He I λ4026 was selected as showing particularly little emission contamination and its profile was studied closely to search for any evidence of features moving in phase with the 0.71-d period. The result of this is shown in Fig. 6 in which the top line is the average profile for the He I λ4026 line. This profile was then subtracted from each of the individual nine spectra and the spectra were then stacked in order of their occurrence in the 0.71-d phase (see Table 1). It is
The upper limit results presented for the amplitude of any radial velocity is presented for the amplitude of any radial velocity for a Keplerian orbit of a 15-M_☉ star and a 1.4-M_☉ companion are of the order 480 km s⁻¹ for such an orbit. Implicit in this calculation is the assumption that the system is not being viewed pole-on. To check this assumption, the stellar v sin i was determined using the He I λ4026 line and the conversion formula presented in equation (4) from Steele, Negueruela & Clark (1999). This method gives v sin i = 371 ± 5 km s⁻¹ for SXP 323, a higher value than any those authors obtained for a long list of Be stars in their work. It is therefore exceedingly unlikely that this star is being viewed pole-on. Furthermore, the clearly split Balmer lines indicate that the circumstellar disc is also far from being viewed pole-on. It is therefore possible to rule out binary motion with a period of 0.71 d as the explanation for the sinusoidal modulation of the photometric light curve.

Laycock et al. (2005) suggest that, based on X-ray activity cycles, the correct binary period for this system is 108 ± 18 d. This period is much closer to the expected binary period of ~180 d based upon a rigorous interpretation of the Corbet diagram (Corbet 1986). Of course, the actual Corbet diagram exhibits quite a spread of values and it is quite feasible that the correct binary period is the X-ray one. Such a period, assuming a circular orbit, implies speeds of ~120 km s⁻¹, which again exceeds the observational upper limits presented here. A period of ~180 d and a circular orbit would give radial velocity amplitudes of ~100 km s⁻¹.

However, most Be/X-ray binaries present very eccentric orbits and the presence of regular outbursts in a wide orbit (such as a 108-d or 180-d period would imply) is generally associated with high eccentricity (cf. Okazaki & Negueruela 2001). In such a situation, we should have observed the source close to periastron in order to see significant velocity changes; however, the data presented here cover only 51 d, which is less than half the X-ray period. Therefore, the

8 DISCUSSION

8.1 Binary motion

The upper limit results presented for the amplitude of any radial velocity behaviour in SXP 323 (30–50 km s⁻¹) may be compared to the expected radial velocity values for the 1.4-d orbit suggested by Coe & Orosz (2000). Assuming no eccentricity, the expected velocities for a Keplerian orbit of a 15-M_☉ star and a 1.4-M_☉ companion are of the order 480 km s⁻¹ for such an orbit. Implicit in this calculation is the assumption that the system is not being viewed pole-on. To check this assumption, the stellar v sin i was determined using the He I λ4026 line and the conversion formula presented in equation (4) from Steele, Negueruela & Clark (1999). This method gives v sin i = 371 ± 5 km s⁻¹ for SXP 323, a higher value than any those authors obtained for a long list of Be stars in their work. It is therefore exceedingly unlikely that this star is being viewed pole-on. Furthermore, the clearly split Balmer lines indicate that the circumstellar disc is also far from being viewed pole-on. It is therefore possible to rule out binary motion with a period of 0.71 d as the explanation for the sinusoidal modulation of the photometric light curve.

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absence of obvious radial velocity variations within the 30 km s$^{-1}$ limit reported here does not rule out such a wide orbit. However, it makes it exceedingly unlikely that the true binary period could be as short as 0.71 d.

8.2 $V/R$ variability

From the measured $V/R$ variability presented in Fig. 3 it is possible to estimate the time for a complete cycle of $V/R$ changes to be at least $\sim$0.3 yr. Such a time-scale does not differ significantly from those seen in other Be/X-ray binaries (e.g. Negueruela et al. 1998). SXP 323 is thought to be a B1 star (Coe et al. 2002) and, although there is not a strong variation in $V/R$ time-scales with spectral class (Mennickent & Vogt 1991), such a value would be consistent with other measurements of stars of a similar type. The presence of obvious $V/R$ variability in the profiles of emission lines also argues strongly against a close binary. The existence of $V/R$ variability in Be stars is explained by the theory of global one-armed oscillations in circumstellar discs (Okazaki 2000).

The presence of global one-armed oscillations requires the existence of a large disc around the Be star, extending to several $R_*$ (Okazaki 2000). Such a disc would not have the space to form in a close binary with a period of 0.7–1.4 d.

8.3 Non-radial pulsations

Previous authors have shown that Be stars exhibiting cyclic photometric variations show a weak colour variation with phase. Spear, Mills & Snedden (1981) studied the Be star 28 Cygni (spectral type B3Ve) and determined a (U−B) variation of $\sim$0.01 mag in phase with the 0.7-d cycle. As in the observations presented here, the star became slightly bluer when it became brighter, but the magnitude of the change in 28 Cyg seems somewhat larger than that seen in SXP 323 (red–blue $\sim$0.001 mag). However, Spear et al. (1981) concluded that they were not seeing NRP behaviour but a phenomenon related to the rotation of the photosphere.

The case for NRP behaviour is, unfortunately, not supported by evidence of line profile changes in these VLT data. However, this effect may well be masked by the changes in the circumstellar disc as indicated by the evolution of the $V/R$ ratio in H$\beta$ (Fig. 3). A data set taken over a much shorter period of time ($\sim$ a few days) could be much more successful in exploring this possibility.

8.4 Interstellar lines

The multiple structure seen in the interstellar lines is indicative of the complex spatial structure of the SMC.

Wayte (1990) obtained Ca II absorption spectra of 17 stars in the SMC and presented their profiles. It is clear from studying their results that there is a huge range of variations in these profiles across the SMC, reflecting its complex structure. The nearest object to SXP 323 in the data of Wayte is Sk 35, which reveals features at a heliocentric velocity of $\sim$50, $\sim$115, $\sim$160 and $\sim$190 km s$^{-1}$. Although some of these are close to our observed features, there are significant differences as well (for example, our data show nothing at 115 km s$^{-1}$). However, this may not be too surprising given the large spread of velocity features seen by Wayte across the SMC.

Danforth et al. (2002) used FUSE data on 37 objects to identify two major features: one at 125 km s$^{-1}$ and another at 156 km s$^{-1}$. Both of these features are probably present in our data, but at slightly different velocities (132 and $\sim$167 km s$^{-1}$). The same authors also report a feature at $\sim$180 km s$^{-1}$ often seen in the Bar – where SXP 323 lies. This velocity lies between two of the main components reported here at 167 and 201 km s$^{-1}$.

Most authors agree that there are major separate structures throughout the SMC and our data reflect this level of detail. Studies of many of the other 40–50 SXP sources will add vital information to this complex question.

9 CONCLUSIONS

The VLT observations reported here conclusively rule out the possibility of any binary motion as an explanation for the 0.71-d period seen in the optical counterpart to SXP 323. This fact, combined with the slight colour change seen in the photometric data, suggests instead that this is a phenomenon associated with the Be star – either NRPs or the rotational modulation of photospheric structures. However, the probable stability and lack of any phase change in the entire MACHO and OGLE data sets of many years (Coe et al. 2002) strongly support the NRP case. Future observations over a much shorter time base should be able to confirm this directly.

In addition, the spectra show clear evidence for major changes in the ($V/R$) ratio of the double peaks of the Balmer lines indicative of asymmetries in the circumstellar disc. Finally, the complex structure of the interstellar lines presents clear evidence for multiple structures within the SMC.

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