Optical properties of SMC X-ray binaries

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ABSTRACT

This work represents the first major study of the optical and IR characteristics of the mass donor companions to the X-ray pulsars in the Small Magellanic Cloud (SMC). In this work several new counterparts have been identified, and possible ones confirmed, as companions to X-ray pulsars in the SMC giving a total of 34 such objects now identified. In addition this work presents three new binary periods and confirms two X-ray periods using optical data for objects in this group. This homogeneous sample has been studied as a group to determine important general characteristics that may offer insight into the evolution of such systems. In particular, the spectral class distribution shows a much greater agreement with those of isolated Be stars, and appears to be in some disagreement with the galactic population of Be stars in Be/X-ray binaries. Studies of the long term optical modulation of the Be star companions reveal an extremely variable group of objects, a fact which will almost certainly make a major contribution to the pronounced X-ray variability. The spatial distribution of these systems within the SMC is investigated and strongly suggests a link between massive star formation and the HI density distribution. Finally, studies of the circumstellar disk characteristics reveal a strong link with optical variability offering important clues into the long-term stability of such disks.

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

1 INTRODUCTION AND BACKGROUND

The Be/X-ray systems represent the largest sub-class of massive X-ray binaries. A survey of the literature reveals that of the 115 identified massive X-ray binary pulsar systems (identified here 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 disk (Okazaki & Negueruela, 2001). A recent review of these systems may be found in Coe (2000).

A Be star is a non supergiant hot star, with a B spectral type, whose spectrum has, or had at some time, one or more Balmer lines in emission. The optical light from a Be/X-ray binary is dominated by the mass donor star at the blue end of the spectrum, but at the red end there is normally a significant contribution from the circumstellar disk. Long term optical observations provide valuable insights into the behaviour of the circumstellar disk, and hence into some of the details of the binary interactions within the system.

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 at a rate of about 2-3 per year, 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 LMC) 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.

The X-ray properties of many of the SMC Be/X-ray binaries were presented in the works of Majid, Lamb & Macomb (2004) and Haberl & Pietsch (2004). In those paper the authors summarised the known data on the high energy emission from the accreting pulsars. Haberl & Pietsch (2004) also proposed several optical counterparts based upon positional coincidences between the X-ray and optical catalogues. In this work several different/new counterparts are identified and the detailed optical properties of most of the sample of 48 objects are presented. Comparisons with the galactic sample of such objects are also made. Since the extinction and distance to the SMC is well documented, this provides an excellent opportunity to study an homogeneous population of objects in a different environment to that of the galaxy.
A list of all known X-ray pulsars may be found in Table 1. To minimise confusion arising from long, similar source names only the short SXP identities will be used in this paper. This identity is created simply from the acronym SXP (Small magellanic cloud X-ray Pulsar) followed by the pulse period in seconds to three significant figures.

2 PHOTOMETRY AND OPTICAL IDENTIFICATION

2.1 SAAO data
Optical photometric observations were taken from the SAAO 1.0m telescope on the nights of 14 & 15 December 2003. The data were collected using the Tek8 CCD giving a field of ∼6x6 arc minutes and a pixel scale of 0.6 arcsec/pixel. Observations were made through standard Johnson-Cousin filters plus an Hα filter.

2.2 Other photometric data
Standard B, V and I photometric data were obtained from the OGLE II survey of the SMC (Udalski et al., 1998). Driftscan observations were carried out on the 1.3m Warsaw telescope at the Las Campanas Observatory, Chile. Data of 11 fields covering the most dense parts of the SMC were collected with the SITe 2048×2048 CCD with a pixel size of 24µm.

In cases where data from the OGLE II project were not available, B, V and I magnitudes from the Magellanic Cloud Photometric Survey (Zaritsky et al., 2002) have been presented in Tables 2 & 3. Driftscan observations of the SMC were obtained using the Las Campanas Swope telescope and a 2K CCD, with U, B, V and I magnitudes converted to the standard Johnson-Kron-Cousins photometric system.

2.3 IR magnitudes
The infrared magnitudes are from the 2MASS All-Sky Catalog of Point Sources. 2MASS uses two automated 1.3 m telescopes, one at Mt. Hopkins, USA, and one at CTIO, Chile. The sky can be observed simultaneously in three near-infrared bands: J, H and K using a three-channel camera on each telescope with each channel consisting of a 256x256 array of HgCdTe detectors.

2.4 Summary of data
In order to indentify previously unknown optical counterparts to the SMX X-ray pulsars a star had to satisfy as many of the following conditions as possible:

(i) It should lie within, or very close to the X-ray error circle.
(ii) It should exhibit Hα in emission.
(iii) Its optical colours should match those expected for an O or B type star in the SMC.
(iv) If possible it should also exhibit significant optical variability in the OGLE or MACHO data.
(v) If possible it should be in the 2MASS catalogue.

3 Hα SPECTROSCOPY
Spectroscopic observations in Hα of possible optical counterparts were made using the SAAO 1.9m telescope. A 1200 lines mm⁻¹ reflection grating blazed at 6800Å was used with the SITe CCD which is effectively 266×1798 pixels in size, creating a wavelength coverage of 6160Å to 6980Å. The intrinsic resolution in this mode was 0.42Å/pixel.

All our measurements of the strength of the Hα emission lines from these systems are presented in Table 4. An approximate estimate of the shape of the line is given in this table (single or double profile), however the faintness of the objects for the telescope used means that some small splittings of the line profiles may have gone undetected. A
Table 1. List of known X-ray pulsars in the SMC. The [MA93] object numbers come from Meyssonnier & Azzopardi, 1993. Detailed lists of published references for many of the sources may be found in Haberl & Pietsch (2004).

| Short ID | RA (2000) | Dec (2000) | Full or alternative name |
|----------|-----------|------------|-------------------------|
| SXP0.09  | 00:42:35.0 | -73:40:30.0 | AX J0043-737            |
| SXP0.72  | 01:17:05.2 | -73:26:36.0 | SMC X-1                 |
| SXP0.92  | 00:45:35.0 | -73:19:02.0 | PSR J0045-7319          |
| SXP2.16  | 01:19:00.0 | -73:12:00.0 | XTE SMC2165             |
| SXP2.37  | 00:54:34.0 | -73:40:43.0 | SMC X-2                 |
| SXP2.76  | 00:59:12.8 | -71:38:44.0 | RX J0059.2-7138         |
| SXP3.34  | 01:05:02.0 | -72:11:00.0 | AX J0105-722, RX J0105.1-7211, [MA93]1506 |
| SXP4.78  | 01:00:42.8 | -72:11:32.0 | XTE J0052-723           |
| SXP6.85  | 01:01:00.0 | -72:43:00.0 | XTE J0103-728           |
| SXP7.78  | 00:52:07.7 | -72:25:43.7 | SMC X-3                 |
| SXP8.02  | 00:49:32.8 | -72:11:32.0 | CXOU J010042.8-721132   |
| SXP8.80  | 00:51:52.0 | -73:31:51.7 | RX J0051.8-7321,E0050.1-7247, [MA93]506 |
| SXP9.13  | 00:49:13.6 | -73:11:37.0 | AX J0049-732, RX J0049-7311 |
| SXP15.3  | 00:52:15.3 | -73:19:14.0 | RX J0052.1-7319, [MA93]552 |
| SXP16.1  | 00:50:00.0 | -73:16:00.0 | XTE J0050-732           |
| SXP18.3  | 00:55:00.0 | -72:42:00.0 | XTE SMC pulsar XTE J0055-727 |
| SXP22.1  | 01:17:40.5 | -73:30:52.0 | RX J0117-6-7330,X Nova92, [MA93]1845 |
| SXP31.0  | 01:11:00.0 | -73:16:00.0 | XTE J0111-2-7317        |
| SXP34.1  | 00:55:27.9 | -72:10:58.0 | CXOU J005527.9-721058, RXJ0055.4-72110 |
| SXP46.4  | 00:50:00.0 | -73:16:00.0 | XTE SMC pulsar           |
| SXP46.6  | 00:53:58.3 | -72:26:35.0 | 1WGA 0053.8-7226,XTE J0053-724 |
| SXP51.0  | 00:54:57.4 | -72:26:40.3 | RX J0054.9-7226,XTE J0055-724, [MA93]810 |
| SXP57.4  | 00:49:04.6 | -72:50:53.0 | RX J0049.1-7250, AX J0049-729 |
| SXP82.4  | 00:52:09.0 | -72:38:03.0 | XTE J0052-725, MACS J0052-726#004 |
| SXP89.0  | 00:50:55.8 | -72:13:38.0 | AX J0051-722 ,RX J0051.3-7216, [MA93]413 |
| SXP91.1  | 00:52:00.0 | -72:45:00.0 | XTE SMC95 pulsar         |
| SXP95.2  | 00:53:23.8 | -72:27:15.0 | CXOU J005323.3-7272175, [MA93]667 |
| SXP140   | 00:56:05.2 | -72:22:00.0 | XMMU J005605.2-722200,2E0054.4-7237, [MA93]904 |
| SXP144   | 00:57:50.3 | -72:07:50.0 | CXOU J005750.3-720756, [MA93]1038 |
| SXP152   | 00:57:50.3 | -72:07:50.0 | XTE SMC pulsar           |
| SXP165   | 00:57:50.3 | -72:07:50.0 | XTE SMC pulsar           |
| SXP169   | 00:52:54.0 | -71:58:08.0 | XTE J0054-720, AX J0054.9-7158, [MA93]623 |
| SXP172   | 00:52:50.0 | -73:10:40.0 | AX J0051.6-7311, RX J0051.9-7311, [MA93]504 |
| SXP200   | 00:52:20.8 | -72:23:16.0 | 1XMMU J005290.8-722316 |
| SXP286   | 00:47:23.7 | -73:12:27.0 | XMMU J004723.7-731226, RXJ0047.3-731226, [MA93]172 |
| SXP288   | 00:58:08.0 | -72:03:30.0 | AX J0058-72.0, [MA93]1036 |
| SXP293   | 00:50:00.0 | -73:06:00.0 | XTE J0051-727           |
| SXP304   | 01:01:02.7 | -72:06:58.0 | CXOU J010102.7-720658, [MA93]1240,RXJ0101.0-7206 |
| SXP323   | 00:50:44.8 | -73:16:06.0 | AX J0051-73.3,RXJ0050.7-7316, [MA93]387 |
| SXP348   | 00:51:30.0 | -72:09:18.0 | SXX J0103-7209, RX J0103-722, [MA93]1367 |
| SXP452   | 01:01:20.5 | -72:11:18.0 | RX J0101-7211, [MA93]1257 |
| SXP504   | 00:54:55.6 | -72:45:10.0 | CXOU J005455.6-724510,RXJ0054.9-7245,AXJ0054.8-7244, [MA93]809 |
| SXP565   | 00:57:36.2 | -72:19:34.0 | CXOU J005736.2-721934, [MA93]1020 |
| SXP701   | 00:55:17.9 | -72:38:53.0 | XMMU J005517.9-723853 |
| SXP756   | 00:49:40.0 | -73:23:17.0 | AX J0049.4-7323, RX J0049.7-7323, [MA93]315 |

Though Hα profiles of Be stars are known to vary between single and double peaks (see, for example, Reig et al., 1997), when in the double state the separation of the peaks provides information on the mean circumstellar disk velocities. A detailed analysis of the four Hα spectra that are resolved in these data revealed the following results on these objects.

SXP0.72 shows a clear double-peaked profile. Assuming a gaussian profile for the peaks, we find the FWHM of each peak to be 5.5 ± 0.4 Å, with a separation of 10.2 Å between the peaks. This separation implies a radial velocity of disk material of ~230 km/s. The V/R ratio is ~0.71.
| Short name | V   | δV  | B-V | δ(B-V) | V-I | δ(V-I) | J   | δJ  | J-K | δ(J-K) | V-K | δ(V-K) | Ref |
|------------|-----|-----|-----|--------|-----|--------|-----|-----|-----|--------|-----|--------|-----|
| SXP0.09    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP0.72    | 13.15 | 0.10 | -0.14 | 0.15 | -0.02 | 0.16 | 13.45 | 0.02 | -0.03 | 0.05 | -0.32 | 0.11 | Z    |
| SXP0.92    | 16.18 | 0.02 | -0.21 | 0.03 | 0.15 | 0.03 | 16.60 | 0.16 | < 0.31 |     | < −0.11 | O    |
| SXP2.16    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP2.37    | 16.64 | 0.04 | 0.06 | 0.06 | 0.15 | 0.07 |     |     |     |        |     |        | Z    |
| SXP2.76    | 14.01 | 0.08 | 0.06 | 0.09 | -0.02 | 0.09 | 14.04 | 0.04 | < 0.38 |     | < 0.36 | Z    |
| SXP3.34    | 15.63 | 0.03 | -0.01 | 0.05 | 0.03 | 0.05 | 15.76 | 0.07 | 0.32 | 0.19 | 0.19 | 0.18 | O    |
| SXP4.78    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP6.85    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP7.78    | 14.91 | 0.02 | 0.00 | 0.03 | 0.08 | 0.05 | 14.82 | 0.07 | 0.37 | 0.11 | 0.46 | 0.09 | Z    |
| SXP8.02    | 18.09 | 0.02 | -0.32 | 0.03 |     |     |     |     |     |        |     |        | V    |
| SXP8.80    | 14.87 | 0.12 | -0.27 | 0.13 | -0.04 | 0.18 | 14.47 | 0.03 | 0.21 | 0.07 | 0.61 | 0.14 | O    |
| SXP9.13    | 16.51 | 0.02 | 0.10 | 0.04 | 0.30 | 0.03 | 16.11 | 0.09 | < 0.22 |     | < 0.63 | O    |
| SXP15.3    | 14.67 | 0.04 | -0.01 | 0.05 | 0.15 | 0.06 | 14.40 | 0.03 | 0.29 | 0.07 | 0.56 | 0.08 | O    |
| SXP16.6    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP18.3    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP22.1    | 14.18 | 0.03 | -0.04 | 0.04 | 0.09 | 0.05 | 13.98 | 0.03 | 0.27 | 0.06 | 0.46 | 0.06 | Z    |
| SXP31.0    | 15.52 | 0.03 | -0.10 | 0.04 | 0.23 | 0.04 | 15.10 | 0.06 | 0.19 | 0.14 | 0.62 | 0.13 | Z    |
| SXP34.1    | 16.78 | 0.03 | -0.12 | 0.04 | -0.13 | 0.05 |     |     |     |        |     |        | Z    |
| SXP46.4    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP46.6    | 14.72 | 0.03 | -0.07 | 0.03 | 0.14 | 0.03 | 14.41 | 0.04 | 0.42 | 0.08 | 0.72 | 0.07 | Z    |
| SXP51.0    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP59.0    | 15.28 | 0.01 | -0.04 | 0.02 | 0.15 | 0.03 | 15.18 | 0.05 | 0.17 | 0.14 | 0.27 | 0.13 | O    |
| SXP74.7    | 16.92 | 0.06 | 0.09 | 0.10 | 0.24 | 0.07 | 16.35 | 0.12 | 0.76 | 0.26 | 1.33 | 0.24 | O    |
| SXP82.4    | 15.02 | 0.02 | 0.14 | 0.03 | 0.3 | 0.03 | 14.63 | 0.03 | 0.42 | 0.07 | 0.81 | 0.07 | O    |
| SXP89.0    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP91.1    | 15.06 | 0.06 | -0.08 | 0.06 | 0.20 | 0.07 | 14.84 | 0.04 | 0.47 | 0.08 | 0.69 | 0.09 | Z    |
| SXP95.2    |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP101     |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP138     | 16.19 | 0.12 | -0.09 | 0.12 | 0.05 | 0.26 | 16.27 | 0.11 | < −0.23 |     | < −0.31 | Z    |
| SXP140     | 15.88 | 0.03 | -0.04 | 0.03 | -0.11 | 0.05 | 15.85 | 0.09 | < 1.75 |     | < 1.78 | Z    |
| SXP144     | 16.51 | 0.02 | -0.25 | 0.03 | 0.65 | 0.03 |     |     |     |        |     |        | V    |
| SXP152     | 15.69 | 0.03 | -0.03 | 0.12 | 0.22 | 0.04 | 15.44 | 0.05 | 0.65 | 0.13 | 0.90 | 0.12 | Z    |
| SXP165     |     |     |     |        |     |        |     |     |     |        |     |        |     |
| SXP172     | 14.45 | 0.02 | -0.07 | 0.02 | 0.09 | 0.02 | 14.43 | 0.03 | 0.26 | 0.08 | 0.28 | 0.07 | O    |

Table 2. Table of photometric values - Part I. In the final column the symbol indicates the source of the optical photometry: an O symbol refers to OGLE data (Udalski et al., 1998), the Z symbol refers to Zaritsky et al (2002), and the V symbol refers to data presented for the first time in this work from observations carried out using the SAAO 1.0m telescope. All δ values indicate the errors or limits on the value of that parameter. The IR data come from 2MASS.
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Table 3. Table of photometric values - Part II. In the final column the symbol indicates the source of the optical photometry: an O symbol refers to OGLE data (Udalski et al. 1998), the Z symbol refers to Zaritsky et al. (2002), and the V symbol refers to data presented for the first time in this work from observations carried out using the SAAO 1.0m telescope. All δ values indicate the errors or limits on the value of that parameter. The IR data come from 2MASS.

Table 4. Hα emission line measurements. In the second column the letter S refers to a single shaped profile and D to a double or split profile. The date of the observation is in the format YYM-MDD.

Figure 2. Histogram of the Hα equivalent widths for the systems presented in this paper (solid line) and a sample of isolated Be stars (dashed line - see text for references).
Using the same tools we find that SXP46.6 shows a close double-peaked profile with a FWHM of $5.8 \pm 0.3\AA$, a radial velocity of $\sim 100$ km/s and $V/R = \sim 0.92$.

SXP349 shows a highly disproportionate double profile which results in a $V/R = \sim 1.76$; the FWHM of the peaks is $4.1 \pm 0.2\AA$ and the radial velocity is also $\sim 100$ km/s.

SXP564 has a more complicated profile than the previous sources, showing 4 peaks (see Figure 3). In the top panel a double peak profile has been fitted with a FWHM of 3.3\AA and a separation of 4.7\AA between the peaks (providing a radial velocity of $\sim 105$ km/s and $V/R = \sim 1.16$). The resulting curve was then subtracted from the observed data (see bottom panel), resulting in clear evidence for two other peaks. A fit to this subtracted data results in a FWHM $= 4.1 \pm 0.4\AA$ for the peaks, with a radial velocity of $\sim 302$ km/s and $V/R = \sim 1.56$. The two innermost peaks from SXP564 would correspond to a high-density section in the outer edge of the circumstellar disk, while the two outermost peaks could be a sign that the star is undergoing a new period of mass ejection as the emmitting region must be very close to the stellar surface.

4 PERIODICITIES AND OTHER VARIABILITY

The optical brightness of the companion stars to many X-ray pulsars varies significantly over time and if these changes were related to the orbit of the compact object, a study of the optical lightcurves might yield information on the orbital period. Conversely, the detection of an optical period could identify a particular star as the optical counterpart from amongst a number of otherwise similar candidates.

To this end, the MACHO lightcurves of all stars identified as likely candidates were analyzed for periodicity. The selection of possible counterparts differed with each pulsar: In some cases a single star had been conclusively identified but in cases where there was no obvious candidate the following selection criteria were applied.

The first criterion, an optical (B-V) colour index, was obtained by assuming that the stars being searched for were in the spectral range B0V - B2V and that the extinction to the SMC was somewhere in the range $0.08 < E(B - V) < 0.25$. The lower value comes from the work of Schwering & Israel (1991) and the upper value from direct observations of similar Be systems (see, for example, Coe, Haigh and Reig 2000) and includes a local contribution from the circumstellar disk. The limits chosen were $-0.2 < (B - V) < 0.2$.

The second criterion was simply a cut-off in the V band magnitude at 17.0, again set by assuming the same spectral class range as above projected to the SMC through any reasonable amount of interstellar and circumstellar absorption.

The third criterion, an infrared (J-K) colour index was determined entirely from previous work. Since the circumstellar disk is the single major contributor to the IR flux, the state of the disk defines the size of the IR excess. Previously determined values for (J-K) range from -0.1 up to 0.6, so a limit of $(J - K) < 0.7$ was chosen from these observations.

Schmidtke et al. (2004) report a similar study of the photometric properties of SMC Be-neutron star systems but with the emphasis on the detection of orbital periods in well established counterparts.

An attempt was also made to measure the gross variation in the optical magnitudes by determining the standard deviation divided by the mean($\sigma/\mu$). This was done using the generally cleaner OGLE data. It is clear that some of these objects have a longer variability than the length of the data run.

Those objects showing particularly striking variability are shown in Figure 4 which also includes the MACHO lightcurves (covered in the following section). In order to avoid cluttering the diagram, only the blue data are shown. In the case of SXP140, where no OGLE data exists, both the blue and red curves are shown. The transformation equations, given by Alcock et al. (1999), which enable the instrumental magnitudes to be converted to approximate $V$ and $R$ spectral values have been used.

4.1 MACHO data

In 1992 the MA$\nu$se Compact Halo Objects project (MA$\nu$CHO) 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 Jan-

![Figure 3. The double Hå parameters of SXP565. The upper figure shows the raw data and the fit to the innermost pair of lines. The lower panel shows the result of subtracting the above fit from the raw data.](image-url)
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).

These data were extensively analysed for periodicity using a variety of period search algorithms. Initially all potential optical counterparts were analyzed using the Nthalias binary period detection program (T R Marsh, private communication). They were then further examined using the Starlink PERIOD and the Grup d’Estudis Astronòmics Analisis de Variabilidad Estelar (AVE) programs. Finally all counterparts were examined with the Analysis of Variance (AoV) periodogram devised by Aleksander Schwarzenberg-Czerny (Schwarzenberg-Czerny. 1989). Apart from the removal of non-physical observations (e.g those having magnitudes of -99.99), the lightcurves have been used in their original form, without being detrended or cleaned, so as to avoid the risk of arbitrarily removing or introducing periodicity. The results are shown in Table 5. A number of likely orbital periods were detected although in the majority of cases significant optical periods were either not found at all or else only appeared in one or two of the four data sets examined.

A period of around 29.6 days was found in a number of objects, and for this reason it is likely to be an artefact. We have not therefore included any mention of it in the following subsections.

4.2 OGLE data

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

Two sets of OGLE data, designated II and III, are available for most of the objects discussed in this paper. 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. OGLE II data points are earlier than MJD 52000, OGLE III are later.

5 DISCUSSION ON INDIVIDUAL SOURCES

5.1 SXP3.34

This X-ray pulsar is identified here with [MA93] 1506. This object lies within the ASCA error circle (Yokogawa & Koyama 1998) and shows strong Hα emission. In addition, this object was found to have an unusually strong optical period of 11.09 days in both types of data. This would be consistent with the Corbet diagram (Corbet, 1986) if it was the orbital period. On the other hand, the fact that it has an Hα equivalent width of -54 Å, is at variance with the relationship between orbital period and EW established by Reig, Fabregat, & Coe (1997) which would imply a longer period. It is possible therefore that the true binary period is considerably longer and that the one seen here represents the the rotation period of part of the circumstellar disk. The MACHO red power spectrum and pulse profile are shown in Figure 5. A curious triple structure is visible in the peak. Similar effects are also visible at periods of 1/2 and 1/3.

SXP323 (Coe et al., 2002), this may well be the shortest known binary period for a Be/X-ray system.

5.2 SXP4.78

The possible counterparts to the XTE pulsar were discussed in Laycock et al., (2003). Those authors suggested that the probable optical counterpart was [MA93] 537, however the determination of the X-ray position remains poor. It is therefore not possible to state with any confidence exactly which object is the counterpart. However, we note that MACHO object 207.16146.9 at RA 00 52 05.5 Dec -72 26 04.0 detected a period of 23.9 ± 0.1 days in both colours. This object is identified with AzV129 which lies within the XTE error box. An orbital period of ~22 days would be anticipated from the Corbet spin/orbit relationship.

5.3 SXP7.78

Corbet et al. (2004) give a probable binary period of 45.1 ± 0.4 days. An analysis of MACHO counterpart 208.16088.4 at RA: 00 52 05.5 Dec -72 26 04.0 detected a period of 44.6 ± 0.2 days in the red lightcurve which contains large annual gaps in the data.
Figure 4. MACHO (top) and OGLE (bottom) Lightcurves. MACHO data show approximate V-band magnitudes while OGLE data are in the standard I-band. OGLE II data points are earlier than MJD 52000, OGLE III are later and have not yet been fully calibrated to precise photometric accuracy. In the case of SXP140, where only MACHO data exists, Red and Blue data are shown. MJD=Julian date -2450000.5.
5.4 SXP8.80 (= SXP16.6?)

Though previously identified with two different emission line objects ([MA93] 506 by Haberl & Pietsch (2004) and “Star 1” by Israel et al., 1997) it is far from clear whether either of these identifications are secure. In addition, there is a third star (AzV111) lying about 15” to the south of [MA93] 506 which also shows Hα emission and is inside both the ROSAT and Einstein error circles. For the purpose of this paper we have used the star identified by Haberl & Pietsch since it lies in the centre of all three independent X-ray positional determinations. A more precise X-ray position is required to resolve this object. Corbet et al., (2004) have calculated a period of 28.0 ± 0.3 from RXTE X-ray data. Laycock et al. (2004) have conjectured that this is the same object as SXP16.6 for which they find an orbital period of 189 ± 18 days based on X-ray data. Assuming object 208.16087.9 at RA: 00 51 53.0 Dec: -72 31 48.1 to be the MACHO counterpart, we find a period of 185 ± 4 days in the red data. Significant periods were not found in the OGLE data.

5.5 SXP9.13

This source is identified with an Hα bright object lying in the revised ASCA error circle (Ueno et al., 2001). A finding chart is shown in Figure 1. In addition the position of this optical object coincides with the ROSAT source RX J0049.2-7311. However, other authors have proposed a second ROSAT source, RX J0049.5-7310, as the correct identification for the X-ray pulsar (Filipovic et al (2000) and Schmidtke et
al (2004)). Furthermore, Schmidtke et al (2004) find an orbital period of 91.5 days for this second ROSAT source in the MACHO data. However, this object lies well outside the revised X-ray error circle presented in Ueno et al (2001) and consequently RX J0049.2-7311 is presented here as a more likely counterpart to the ASCA pulsar.

5.6 SXP15.3
The large peak in the MACHO data visible in Figure 4 coincides with a ROSAT HRI X-ray detection on 19 Oct 1996 (MJD 50375) (Kahabka, 1999).

5.7 SXP34.1
This X-ray object was discovered from Chandra observations by Edge et al. (2004). Its position was determined to ~1 arcsec. The nearest optical counterpart lies ~2 arcsec away from the X-ray position and is shown in Figure 4. Its optical colours are consistent with a B type star.

5.8 SXP46.6
Laycock et al. (2004) derive a period of 139 ± 6 days from the X-ray data. Although we consider that the following is unlikely to be the correct counterpart, we place on record that MACHO object 207.16202.30 at RA: 00 53 55.13 Dec: -72 26 31.8, which is 28 arcsec from the presumed star, was found to have a period of 152.4 ± 2.4 days with a secondary period of 98 ± 1 days. This object has approximate V and R magnitudes of 16.59 and 15.15 respectively, derived from the transformation equations given by Alcock et al. (1999). The optical variability is clearly visible in the lightcurves.

5.9 SXP59.0
Laycock et al. (2004) find a possible orbital period of 123 ± 1 days. We did not find any significant period in the optical data.

5.10 SXP74.7
Laycock et al. (2004) indicate a candidate orbital period of 642 ± 59 days. No such period was found in any of the MACHO candidates.

5.11 SXP91.1
The optical counterpart to this object was identified by Stevens, Coe and Buckley (1999) with an Hα emitting object designated [MA 93]413 (Schmidtke et al., 2004). Laycock et al. (2004) report a period of 115 days. Schmidtke et al. (2004) find an optical period of 115 days. The optical variability is clearly visible in the lightcurves.

5.12 SXP140
This is a difficult field - see Figure 4 with several sources blended together. Zaritsky et al. (2002) identify 3 objects, as does 2MASS, but there is probably at least one more object in the blend. The object indicated in Figure 4 is [MA93]904 - identified by Haberl & Pietsch (2004) as the correct counterpart based upon an XMM position. The SAAO data were carefully deblended and the resulting magnitudes are presented in Table 4 for [MA93]904 along with the Zaritsky et al. numbers. The discrepancies between the two sets of data are noted but, until much higher quality images of the field are obtained, they cannot be resolved.

5.13 SXP172
A significant proportion of the observations in the presumed MACHO counterpart 212.16077.13 blue data fall below the mean curve in what appears to be an annual cycle. This is assumed to be an artefact of the system. Laycock et al. (2004) derive a period of 67 ± 5 days. No such period was found in the optical data.

5.14 SXP202
The presumed MACHO counterpart 207.16545.12 RA: 00 59 20.9 Dec: -72 23 17.4 shows very high optical variability which is similar to other optical counterparts but no significant optical period was found.

5.15 SXP323
All four data sets consistently exhibited a period of 0.708 ± 0.001 days and a slightly weaker period of 1.695 ± 0.003 days. The former period has been reported and discussed by Coe et al., (2002).

5.16 SXP452
Schmidtke et al. (2004) report the discovery of an orbital period at 74.7 days. We confirm a similar orbital period in MACHO object 205.16662.14 at RA: 01 01 20.6 Dec: -72 11 18.3 and conclude that this is the same object as the one they report.

5.17 SXP564
Schmidtke et al. (2004) report an orbital period of 95.3 days. We find the same period in MACHO object 207.16432.1575 RA: 00 57 35.9 Dec: -72 19 34.4. and conclude that this is the same object.
5.18 SXP756

This object is unusual in that there are clearly visible peaks in all the optical data, which coincide with X-ray detections, confirming an orbital period of 394 days (Cowley & Schmidtke, 2003, Coe & Edge, 2004). The data points forming the short peaks were excluded from the long-term variability calculation.

6 DISCUSSION OF GENERAL PROPERTIES

6.1 Long term optical variability

Extensive analysis of up to four separate data sets for each object, using a variety of period search algorithms, has not generally been successful in determining the orbital periods of these X-ray binary stars. This finding is consistent with previous observations of Galactic Be/X-ray binaries where no modulation of the optical lightcurve at the known binary period was detected, e.g.: A0535+26 (Clark et al. 1998 & 1999). Although a variety of periods could be detected, in most cases they were ambiguous and did not occur in all the data sets. In some cases it is possible that the wrong star has been identified as the optical counterpart but there is good reason to believe that the majority are correct. It is also possible, but unlikely, that the orbital period may be marked by short disturbances which are not apparent in the lightcurves and which are not detectable by period search algorithms.

On the other hand, as can be seen in Figure 4, many of these systems undergo significant long-term aperiodic fluctuations in luminosity. Roche et al. (1997) have shown that, in the case of X Persei, a long term variation in the V band photometry over 10 years represents a phase change in the companion star from Be to OB and back. The authors further demonstrate that the only source of variability in the system is the circumstellar envelope and that during the OB phase the star displays almost no variation. Negueruela et al. (2001) use a similar interpretation to postulate a ~3 year cycle of disk loss and reformation in 4U0115+63/V635 Casiopeiae.

The objects studied in this paper, however, do not generally show strong evidence of cyclic behavior of the sort seen in X Persei, although SXP8.80 has a rather similar profile. SXP140, for example, declines unevenly in brightness, by 0.53 mag over a duration of ~1050 days, then increases by 0.43 mag in 230 days and declines again in 220 days. If there is an underlying cycle, it may be longer that the data set used in this study.

The most significant exception to the lack of evidence for orbital period in the lightcurves is SXP755, which has several unusual features. In the first place the orbital period had already been established from the pattern of X-ray observations. Secondly, the X-ray outbursts coincide with abrupt, spiky peaks which are clearly visible in the optical data. These peaks are not-sinusoidal and are not detectable by some types of periodic analysis. The fact that this object has a long orbital period as well as low variability suggests that the disk is in a relatively stable configuration which is less prone to tidal disturbance by the neutron star except at periastron passage.

The possible relationship between the size and stability of the circumstellar disk has been explored by comparing the disk size with the star’s variability. Figure 6 plots the equivalent width data from Table 4 against the optical variability from Table 5. The fitted curve shows an inverse powerlaw relationship.

![Figure 6](image)

Clearly the notion that low EW might be an indicator of high variability is inconsistent with the principle that the photometric state is correlated with disk size. Moreover the equivalent widths in Table 4 are given for only a single point in time and it has previously been stated that many Be stars are known to oscillate between a Be and a B phase (Negueruela et al., 2001). It has also been demonstrated that Hα emissions can vary over very short timescales (Clark et al. 1998). To test the validity of the apparent relationship shown in Figure 6 it would therefore be necessary to take spectroscopic measurements over a period of time, in parallel with photometric ones. Long term Hα spectroscopic data is not available for the objects studied here, if, however, a low photometric state were to be interpreted as a disk-loss event then the low equivalent widths seen in Table 4 might be expected to coincide with low points on the lightcurves. We do not find such a correlation although the curves generally show reddening in the brighter phases suggesting a relative enlargement of the disk. For example, where the OGLE II (I) and macho blue (V) overlap in SXP8.80, the I band changes by 0.85 mag as compared with 0.5 for the V band.

If the Figure 6 relationship is genuine then the fact that the variability appears to be greatest where the disk size is least might be taken to suggest that it is intrinsic to the companion star and not the disk. Although this seems partly to be born out by the fact that it also appears strongly in the blue (V) part of the spectrum, such a conclusion is at variance with strong evidence that optical variability in Be stars results from changes in the disk, moreover Negueruela et al. have shown that even when the disk is almost totally absent, the presence of some circumstellar material contributes significantly to the total brightness and hence variability.

Reig, Fabregat, & Coe (1997) have shown that there is also a relationship between HαEW and orbital period which is attributed to increased truncation of the circumstellar disk...
with shortened period. It might therefore be concluded from the evidence of Figure 6 that long term variability can be related to short orbital period. Unfortunately there are not enough orbital periods in this sample which are known with sufficient confidence to test such a relationship directly, nor is it immediately obvious what physical process would serve to connect a binary period of a few tens of days with largely aperiodic variations spanning years. A plot of pulse period against variability (Figure 7), however, appears to show an inverse relationship of the kind seen in Figure 6. This would be expected if both the Corbet spin/orbit and the indicated variability/orbital period relationships were valid and is indirect confirmation of the latter.

6.2 Spectral Class of counterparts

In order to determine the approximate spectral class of the counterparts listed in this work, the colour (B-V) of each object was used. To do this, the (B-V) colour was first corrected for the extinction to the SMC of $E(B-V) = 0.08$ (Schwering & Israel, 1991) and then the resulting (B-V) used to identify the spectral class using the data of Johnson (1966). However, the resulting spectral class distribution peaked a long way from the distribution of such objects in our galaxy (see, for example, Negueruela 1998). In order to adjust the (B-V) colour scale for possible extra reddening (arising primarily from the presence of the circumstellar disk), it was decided to use the class determinations derived from independent blue spectra to normalise the data presented here. Fortunately, three of the objects studied have had previously determined spectral classes based upon such accurate blue band spectroscopy - see Table 6. Using these three objects, an average extra (B-V) shift was calculated of $(B-V)=-0.13$ to bring them to their correct spectral class. This shift was then applied globally to all the objects.

In each of the three reference objects listed in Table 6, extra reddening had been reported as an individual effect attributed to either the circumstellar disk, or maybe due to column enhancements at the objects locality. However, it is now very likely that this is a general characteristic of all SMC Be/X-ray systems.

To allow for the uncertainty in the spectral class derived by this method, each object was fractionally divided amongst the range of classes consistent with its (B-V). For example, the source SXP59.0 has a B-V value of $-0.04\pm0.02$. According to Johnson (1966) the counterpart has a spectral type in the range from B0 to B2. Consequently SXP59.0 has had one-third of its contribution allocated to spectral type B0, another third to B1 and the final third to B2. The resulting distribution is then the sum of all these fractional contributions and is shown in Figure 8 as the shaded histogram.

For comparison, a histogram of galactic systems was also produced (dashed line in Figure 8). This distribution was determined from the catalogue of Liu, van Paradijs & van den Heuvel (2000) in a similar manner to the SMC distribution. Namely, the objects selected from the catalogue all have X-ray pulse periods and O/B type companions, luminosity classes III or V. Again, where there was some uncertainty in the spectral class the contribution of that source was fractionally allocated. A total of 16 objects contribute to this distribution.

| Source   | Spectral Class | Predicted (B-V) | Observed (B-V) | Reference |
|----------|----------------|-----------------|----------------|-----------|
| SXP31.0  | B0.5-B1 V      | -0.19           | -0.10          | 1         |
| SXP323   | B0 III-V       | -0.22           | -0.04          | 2         |
| SXP22.1  | B1-B2 III-V    | -0.17           | -0.04          | 3         |

Table 6. Spectral class previously determined from blue spectroscopy measurements (references are 1 - Covino et al., 2001, 2 - Coe et al., 2002, 3 - Coe et al., 1998). In each case the predicted (B-V) is derived assuming the spectral class in column 2 and that $E(B-V)=0.08$ is the extinction to the SMC (Schwering & Israel, 1991).
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Figure 9. Location of known X-ray pulsars superimposed on an HI map of the SMC (Stanimirovic et al., 1999). Grey-scale intensity range is 0 to 143×10^{20} atom cm^{-2}. Contour lines are at 19.9×10^{20} and 39.4×10^{20} atom cm^{-2}.

This SMC distribution indicates that “missing” B3-B9 spectral class counterparts to galactic Be/X-ray systems (Negueruela, 1998) may not be similarly absent in the SMC systems. The distribution in the SMC may well be intrinsically different to that in our own galaxy reflecting a somewhat different evolutionary development. The much lower metallicity and the tidal interactions between the clouds are two major factors that may well have played an important role in promoting such a difference - though the models of van Bever & Vanbeveren 1997 question the importance of the metallicity factor.

6.3 Locations of pulsars in the SMC

The HI distribution of the SMC (from Stanimirovic et al., 1999) is shown as a greyscale contour map in Figure 9 superimposed on it are the 41 pulsars with well established positions. It is therefore possible to extract the column density of HI towards each of these pulsars and plot the resulting distribution as a histogram. This can be seen in Figure 10 together with the overall histogram of HI density in the SMC; 25 bins were used for the pulsar data, 2000 for the SMC HI. In each case, the peak of the distribution was normalised to 1.0. The figures indicate that the pulsars favour low/medium HI densities. Over half the SMC population is found in the range of HI density \( \sim (15-45) \times 10^{20} \) cm\(^{-2}\). In this same region of HI densities, the SMC histogram curve appears to deviate from an exponential decay shape showing a clear dip. If these accurately reflect the volume densities, there would be a strong suggestion that high-mass star formation is particularly well suited to these densities.

It must be noted that the X-ray coverage by RXTE, Chandra and XMM of the Wing of the SMC has been particularly sparse compared to that of the Bar. Consequently the general distribution across different components of the

Figure 10. Histogram of SMC HI intensity distributions (continuous line) and the corresponding histogram of HI columns at the location of the X-ray pulsars (step curve).

Figure 11. Comparison of the properties of the SXP systems (square symbols) with those of a sample of isolated galactic Be stars (triangles) - see text for references.
SMC is yet to be accurately determined. Since the Wing and Bar are thought to be separated by up to 20kpc (Laney & Stobie, 1986) it wouldn't be surprising to find differing population densities in the two components.

6.4 Circumstellar disks in Be/X-ray binaries

Figure 11 shows two measures of the size of the circumstellar disk in these systems plotted against each other - the Hα EW and the "intrinsic" IR colour \((J - K)_{\alpha}\). The data on isolated Be stars are taken from the Be star surveys of Dachs & Wamsteker (1982) and Ashok et al (1984). The \((J-K)\) colour for each SXP object was corrected for all reddening effects by using the same colour shift described in Section 6.2 to determine the spectral class. This produced the "intrinsic" \((J - K)_{\alpha}\) colours plotted in this figure. This figure reinforces the result presented earlier in Figure 2 which suggests a similar range in disk sizes for the isolated systems and the Be/X-ray binaries. Possibly the Be/X-ray systems do not extend down to the lowest values, but this is probably a selection effect since we only detect the more active systems. At the high value end the sample is too sparse to draw any conclusions. In making plots like this one must always be aware that the data are not taken contemporaneously, and unusually high values in Hα will not match the average IR colours taken at some other time. Hence the Be/X-ray binaries with the two highest Hα EWs should almost certainly lie further to the right on this diagram.

As pointed out by Dachs et al. (1986) the disk inclination of these systems is also likely to have an effect on the measured EWs. This will have the result of spreading out the distribution in Figure 2. However, from our Hα profile work we found very few systems with an obviously low inclination angle (i.e. showing a strongly split profile) - though this is not something to which the data were very sensitive.

7 CONCLUSIONS

The X-ray pulsar population of the SMC is providing an excellent homogeneous sample of such objects at the same distance and reddening. Consequently it is possible to investigate the physical characteristics of such high mass X-ray binaries and put the conclusions in the context of a different environment to the galactic population. From this work the following conclusions have been drawn:

- The spectral class distribution shows a much greater agreement with those of isolated Be stars, and appears to be in some disagreement with the galactic population of Be stars in Be/X-ray binaries. Future accurate spectral measurements will provide better determinations of the spectral class than the photometry presented in this work.
- Studies of the long term optical modulation of the Be star companions reveal an extremely variable group of objects, a fact which is almost certainly linked to the observed large X-ray variability. The common underlying link is the rate of mass outflow from the Be star and its contribution to the circumstellar disk.
- The spatial distribution of these systems within the SMC strongly suggests a link between massive star formation and the HI density. Though the line of sight density needs to be interpreted in three dimensional terms, the results do point to a clear preference for massive star formation under specific conditions.
- Finally, studies of the circumstellar disk characteristics (equivalent width, optical variability, infra-red colours) reveal a strong link with the degree of optical variability offering potential clues into the long-term stability of such disks.

As further observations increase the population of these objects in the SMC these initial conclusions can be further examined. Given the current growth rate of discoveries, the final population numbers may well exceed the galactic population by a factor of ten, and hence they will become increasingly important as reference population for understanding the evolution of such massive/neutron star binaries.

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