Spectral distribution of Be/X-ray binaries in the Small Magellanic Cloud

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ABSTRACT
The spectral distributions of Be/X-ray binaries in the Large Magellanic Cloud and Galaxy have been shown to differ significantly from the distribution of isolated Be stars in the Galaxy. Population synthesis models can explain this difference in spectral distributions through substantial angular momentum loss from the binary system. In this work we explore the spectral distribution of Be/X-ray binaries in the Small Magellanic Cloud (SMC) using high signal-to-noise spectroscopy of a sample of 37 optical counterparts to known X-ray pulsars. Our results show that the spectral distribution of Be/X-ray binaries in the SMC is consistent with that of the Galaxy, despite the lower metallicity environment of the SMC. This may indicate that, although the metallicity of the SMC is conducive to the formation of a large number of HMXBs, the spectral distribution of these systems is likely to be most strongly influenced by angular momentum losses during binary evolution, which are not particularly dependent on the local metallicity.

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

1 INTRODUCTION
Be/X-ray binaries are stellar systems in which a neutron star accretes material from a massive, early-type star with a circumstellar disc. Typically they have wide, eccentric orbits with X-ray outbursts occurring when the neutron star interacts with the circumstellar material of the Be star. Two predominant types of outburst behaviour are observed: Type I outbursts of luminosities in the range $10^{36}$–$10^{37}$ erg s$^{-1}$ last a few days and generally occur close to periastron, while Type II outbursts last much longer, reach higher luminosities ($\gtrsim 10^{37}$ erg s$^{-1}$) and show no correlation with orbital phase.

The Small Magellanic Cloud (SMC) is home to an unusually large population of high mass X-ray binaries (HMXBs). Based on the relative masses of the Milky Way and the SMC, there are a factor 50 more in the SMC than one would expect. (Although the sample of HMXBs in the Milky Way is by no means complete, as can be evidenced by the recent discoveries of numerous obscured X-ray binaries (Walter et al. 2006), we do not expect the population to increase by a factor of 50). Population synthesis simulations by Dray (2006) show that the reduced metallicity of the SMC (~one-fifth solar) can lead to an increase in the HMXB population by a factor of three. The metallicity is particularly relevant in influencing the evolution of massive stars, due to the impact it has on stellar winds. The line-driven stellar winds in massive stars become weakened in low metallicity environments (Kudritzki et al. 1989; Vink et al. 2001; Meynet et al. 2006; Mokiem et al. 2007), resulting in lower mass and angular momentum losses from the binary systems in which they are present. Such angular momentum losses may be reflected in both the final mass of the compact object and the evolutionary path of the binary, i.e. whether or not the binary is disrupted by the supernova kick. However, on its own, the reduced metallicity of the SMC cannot explain the large number of HMXB systems in this galaxy (Dray 2006). A recent increase in the star formation rate, such as required by Harris & Zaritsky (2004), possibly due to tidal interaction between the SMC and its nearest neighbour the Large Magellanic Cloud (LMC), is necessary to explain this excess of HMXBs. This is further substantiated by the results of Grimm et al. (2003), which have shown that the number of HMXB systems in a galaxy can be related to the galactic star formation rate. Using indicators such as the far infrared, Hα and ultraviolet to predict the number of HMXBs in the SMC (Shytkovsky & Gilfanov 2003), one finds that star formation rate alone cannot account for the number of HMXBs discovered so far in the SMC. Hence, it seems likely that the increased star formation rate in the
SMC combined with the reduced metallicity environment have given rise to the large observed population of HMXBs. With the advent of arcsecond resolution X-ray telescopes the number of optically identified Be/X-ray binaries (all but one of the HMXBs in the SMC are Be/X-ray binaries) in the SMC has risen dramatically over the last few years. As there are clear differences in the numbers of HMXBs between the Milky Way and SMC, which can be ascribed to metallicity and star formation, there may be other notable differences in the populations. Most fundamentally, how do the metallicity and star formation rate reflect on the spectral distribution of the optical counterparts to the Be/X-ray binary population of the SMC? Although their X-ray properties are well-studied, the spectral classifications of only five of the Be/X-ray binaries in the SMC are known (Covino et al. 2001; Coe et al. 2002; Schuch et al. 2007). An accurate spectral distribution of SMC sources can provide constraints on the evolutionary models put forward to explain the spectral distribution of Be/X-ray binaries. In addition, it may reflect the lower metallicity of the SMC and thus provide valuable insights into both binary evolution and star formation in a metal-poor environment.

Negueruela (1998) showed that the spectral distribution of Be stars occurring in Be/X-ray binary systems is significantly different from that of isolated Be stars in the Milky Way. Whereas isolated Galactic Be stars show a distribution beginning at the early B-types and continuing through until A0, the Be star companions of X-ray binaries show a clear cutoff near spectral type B2. Figure 1 shows the spectral distribution of Milky Way Be/X-ray binaries (dashed histogram) compared with the Milky Way Be/X-ray binaries (solid histogram). The Be/X-ray binary data used in the histogram are shown in Table 1, while the data used for the distribution of isolated Be stars are from Slettebak (1982) with a magnitude limit of $V \leq 6$. Such a magnitude cutoff basically preselects the early-type Be stars and thus we expect that the true distribution may peak towards later-types than shown in Fig 1.

| Name                  | Spectral Type     |
|-----------------------|-------------------|
| 4U 0115+634           | B0.2 V            |
| RX J0346.9+6121       | B1 V              |
| IGR J01363+6610       | B1                |
| LSI+61° 303           | B0 V              |
| V0332+53              | O8–9 V            |
| 4U 0352+30            | B0 V              |
| RX J0440.9+4431       | B0 V              |
| A 0535+262            | B0 III            |
| SAX J0653+0539        | B2 V – B1 III     |
| MXB 0656–072          | O9.7 V            |
| 4U 0726–26            | O8–9 V            |
| RX J0812.4–3114       | B0.5 V            |
| GS 0834–43            | B0–2 III–V        |
| RX J1037.5–5647       | B0 V–III          |
| A 1118–616            | O9.5 V            |
| 4U 1145–619           | B0.7 V            |
| GX 304-1              | B2 V              |
| 2S 1417–624           | B1 V              |
| RX J1744.7–2713       | B0.5              |
| Cep X-4               | B1–B2             |

<5") to allow the unambiguous identification of their optical counterparts. The objects are drawn from Coe et al. (2003), with the exception of those that have no known well-defined X-ray position. We also exclude SXP0.72(=SMC X-1), which we know to be a Roche-lobe overflowing supergiant system, and SXP8.02, which is now known to be an anomalous X-ray pulsar (McGarry et al. 2005). In addition to these objects, we include in our sample recently discovered X-ray pulsar systems with small positional errors, or previously known systems which have refined positions through detection with either Chandra or XMM-Newton or through previous optical follow up. Table 2 lists the sample, along with the method used to determine the optical counterparts and any comments relating to uncertainties in the identification of the correct optical counterpart.

The resulting sample comprises 37 stars with V-magnitudes in the range 14–17.

## 3 OBSERVATIONS AND DATA ANALYSIS

With a view to characterising the spectral population of Be star counterparts of X-ray binaries in the SMC, we acquired spectra of 32 of the objects listed in Table 2 which do not yet have spectroscopically determined spectral types.

The data were acquired on the nights of 2006 September 13–15 and 2007 September 18 and 19 using the EFOSC2
Table 2. Sample of SMC Be/X-ray binary systems with well-defined optical counterparts. The source name in column 1 is based on the pulse period. The column labeled T indicates the telescope used to determine the best position of the source: C – *Chandra*, X – *XMM*, A – *ASCA*, R – *ROSAT*, and O – refers to optical identification by photometry or spectroscopy of objects within the error circle. Column 4 gives a literature reference for X-ray error circle or optical identification.

| Source   | Name       | T  | Ref  |
|----------|------------|----|------|
| SXP0.92  | PSR J0045−7319 | O  | (1)  |
| SXP2.37  | SMC X-2     | O  | (2)  |
| SXP2.76  | RX J0059.2−7138 | O  | (3)  |
| SXP3.34  | RX J0105.1−7211 | A  | (4)  |
| SXP6.85  | XTE J0103−728  | X  | (5)  |
| SXP7.78  | SMC X-3     | C  | (6)  |
| SXP8.80  | RX J0051.8−7231 | R² | (7)  |
| SXP9.13  | RX J0049.5−7310 | R  | (8)  |
| SXP15.3  | RX J0052.1−7319 | O  | (9)  |
| SXP22.1  | RX J0117.6−7330 | O  | (10)|
| SXP31.0  | XTE J0117−7317 | O  | (11)|
| SXP34.1  | RX J0055.4−7210 | C,0| (12)|
| SXP46.6  | I WGA J0053.8−7226 | C,0| (13)|
| SXP59.0  | RX J0054.9−7226 | X  | (14)|
| SXP65.8  | CXOU J010712.6−72353 | C  | (15)|
| SXP74.7  | RX J0049.0−7250 | O  | (16)|
| SXP82.4  | XTE J0052−725  | C  | (17)|
| SXP91.1  | RX J0051.3−7216 | R  | (18)|
| SXP101   | RX J0057.3−7235 | C  | (19)|
| SXP138   | CXOU J005323.8−722715 | C  | (20)|
| SXP140   | 2E 0054.7−7217 | X  | (21)|
| SXP152   | CXOU J005750.3−720756 | C  | (22)|
| SXP169   | 2E 0051.1−7214 | R  | (23)|
| SXP172   | AX J0051.6−7311 | X  | (24)|
| SXP204   | RXM X J005920.8−722316 | X  | (25)|
| SXP264   | AX J0047.3−7312 | X  | (26)|
| SXP280   | RX J0058.8−7272 | X  | (27)|
| SXP304   | RX J0101.0−7206 | C  | (28)|
| SXP323   | RX J0051−735  | X  | (29)|
| SXP348   | 2E 0100.5−7225 | C  | (30)|
| SXP455   | RX J0101.3−7211 | X  | (31)|
| SXP504   | RX J0054.9−7245 | C  | (32)|
| SXP565   | CXOU J005736.2−721934 | C  | (33)|
| SXP700   | CXOU J010206.6−714115 | C  | (34)|
| SXP701   | XMM X J005517.9−723853 | X  | (35)|
| SXP756   | RX J0049.7−7323 | X  | (36)|
| SXP1323  | RX J0103.6−7201 | X  | (37)|

(1) Bell (1994); (2) Murdin et al. (1979); (3) Haberl & Pietsch (2008); (4) Edge et al. (2004); (5) Haberl & Pietsch (2000); (6) Covino et al. (2003); (7) Coe et al. (2002); (8) Buckle et al. (2001); (9) Sasaki et al. (2003); (10) McGowan et al. (2007); (11) Yokogawa et al. (2002); (12) Cowley et al. (1997); (13) Haberl & Pietsch (2004); (14) Maud et al. (2004); (15) Haberl & Pietsch (2001); (16) Haberl & Pietsch (2004); (17) Coe et al. (2005); (18) Coe 2007 priv. comm. 1–Be ctp to radio & X-ray pulsar, 2–2° error circle - no ambiguity in opt ctp.

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4 CLASSIFICATION

Although many attempts have been made to apply the Morgan-Keenan (MK) system of stellar classification to stars observed in the SMC (Humphreys 1983; Azzopardi & Vigneau 1975), one typically comes up against two problems. Firstly, the low metallicity of the SMC means that the metal absorption lines are very weak, making the classification of B-type stars, which rely on metal-helium against two problems. Firstly, the low metallicity of the SMC means that the metal absorption lines are very weak, making the classification of B-type stars, which rely on metal-helium against two problems. Secondly, the low order polynomial was employed to trace the spectrum across the CCD. All spectra were extracted using the optical extraction algorithm presented by Horne (1986). Comparison spectra were extracted along the same trace as the individual science spectra they were used to calibrate.

Although flux calibration was not desired for this project (spectral classification was to be performed by identifying lines rather than fitting atmospheric models), a single spectrophotometric standard star (LTT 7987) was observed to get an idea of the rough response of the telescope, grism and CCD as a function of wavelength.

Finally, spectra were shifted by −150 km s$^{-1}$ (Allen 1973) to account roughly for the recession velocity of the SMC and hence to place spectral features at approximately the correct wavelengths.
As the Si lines are weakened by the lower metallicity environment of the SMC, we use the strengthening He II λ4686 alongside the C III/O II blend to estimate a luminosity class of V (Walborn & Fitzpatrick 1990). The apparent magnitude of \( V = 15.87 \) confirms this luminosity class, as a star of higher luminosity class would need to be of later spectral type, and this can certainly be discounted on the basis of the He II lines.

For fainter stars which were observed with the lower dispersion grism, we employed two methods that would give us an idea of the general spectral type of the star, rather than attempting to use very broad and shallow spectral lines to pinpoint the exact spectral type. The dereddened spectra (using an extinction of \( E(B-V) = 0.16 \)) were compared to template spectra of different spectral types, using the general continuum and line features to constrain the spectral type. In addition, the He I λ4009, 4026/He line ratio, which decreases rapidly through the B main sequence and is hardly influenced by emission from the circumstellar disc, was used to gauge the rough spectral class. Once again, the apparent magnitude of the star was used to confirm the spectral and luminosity class. Figure 3 demonstrates the value of this approach for SXP138. It is clear just from the slope of the spectrum that the star is earlier than B3, but probably later than B0 due to the lack of He II absorption features in the spectrum.

\(^1\) This is the average extinction for optical counterparts of Be/X-ray systems in the SMC as measured by Zuritsky et al. (2002) at http://ngala.as.arizona.edu/dennis/smcext.html
Table 4. Properties of SMC Be/X-ray binaries. Source names are related their X-ray pulse periods. In the Ref column, O refers to colours from Udalski et al. (1998), M refers to colours from Massey (2002), while Z refers to colours from Zaritsky et al. (2002). The Grism column refers to the ruling, in l/mm of the grism used in each case. The Spec column lists the classifications determined from blue spectra in this work unless otherwise noted. The luminosity class, as determined from the spectrum in the case of 600 l/mm data, and as determined from the absolute magnitude in the case of 400 l/mm data, of each source is given in the Lum column.

| Source | V | $\Delta V$ | $B - V$ | $\Delta (B - V)$ | Ref | Grism | Spec | Lum |
|--------|---|------------|--------|-----------------|-----|-------|------|-----|
| SXP0.92 | 16.18 | 0.02 | -0.21 | 0.03 | O | 600 | B0.5–B2 | IV–V |
| SXP2.37 | 16.38 | 0.02 | 0.02 | 0.04 | Z | 600 | O9.5 | III–V |
| SXP2.76 | 14.01 | 0.08 | 0.06 | 0.09 | Z | 600 | B1–B1.5 | II–III |
| SXP3.34 | 15.63 | 0.03 | -0.01 | 0.05 | O | 600 | B1–B2 | III–V |
| SXP6.85 | 14.59 | 0.02 | -0.08 | 0.02 | M | 600 | O9.5–B0 | IV–V |
| SXP7.78 | 14.91 | 0.02 | 0.00 | 0.03 | Z | 600 | B1–B1.5 | IV–V |
| SXP8.80 | 14.87 | 0.12 | -0.27 | 0.13 | O | 600 | O9.5–B0 | IV–V |
| SXP9.13 | 16.51 | 0.02 | 0.01 | 0.04 | O | 400 | B1–B3 | IV–V |
| SXP15.3 | 14.67 | 0.04 | -0.01 | 0.05 | O | 600 | O9.5–B0 | III–V |
| SXP22.1 | 14.18 | 0.03 | -0.04 | 0.04 | Z | 600 | O9.5–B0 | IV–V |
| SXP31.0 | 15.52 | 0.03 | -0.10 | 0.04 | Z | 600 | O9.5–B1 | V |
| SXP34.1 | 16.78 | 0.03 | -0.12 | 0.04 | Z | 600 | B2–B3 | IV–V |
| SXP46.6 | 14.72 | 0.03 | -0.07 | 0.03 | Z | 600 | O9.5–B1 | IV–V |
| SXP59.0 | 15.28 | 0.01 | -0.04 | 0.02 | O | 600 | O9 | V |
| SXP65.8 | 15.64 | 0.03 | -0.12 | 0.03 | M | 600 | B1–B1.5 | II–III |
| SXP74.7 | 16.92 | 0.02 | 0.09 | 0.01 | O | 400 | ~B3 | V |
| SXP82.4 | 15.02 | 0.02 | 0.14 | 0.03 | O | 600 | B1–B3 | III–V |
| SXP91.1 | 15.05 | 0.06 | -0.08 | 0.06 | Z | 600 | B0.5 | III–V |
| SXP101 | 15.67 | 0.15 | -0.05 | 0.15 | M | 600 | B3–B5 | Ib–II? |
| SXP138 | 16.19 | 0.12 | -0.09 | 0.12 | Z | 600 | B1–B2 | IV–V |
| SXP140 | 15.88 | 0.03 | -0.04 | 0.03 | Z | 600 | B1 | V |
| SXP152 | 15.69 | 0.03 | -0.05 | 0.12 | Z | 600 | B1–B2 | III–V |
| SXP169 | 15.53 | 0.02 | -0.05 | 0.04 | Z | 600 | B0–B1 | III–V |
| SXP172 | 14.45 | 0.02 | -0.07 | 0.02 | O | 600 | O9.5–B0 | V |
| SXP202 | 14.82 | 0.02 | -0.07 | 0.01 | O | 600 | B0–B1 | V |
| SXP264 | 15.85 | 0.01 | 0.00 | 0.01 | Z | 600 | B1–B1.5 | V |
| SXP280 | 15.64 | 0.03 | -0.12 | 0.04 | Z | 600 | B0–B2 | III–V |
| SXP304 | 15.72 | 0.01 | -0.04 | 0.02 | O | 600 | B0–B2 | III–V |
| SXP323 | 15.44 | 0.04 | -0.04 | 0.05 | O | 600 | B0–B0.5 | V |
| SXP348 | 14.79 | 0.01 | -0.09 | 0.01 | O | 600 | B0.5 | IV–V |
| SXP455 | 15.49 | 0.02 | -0.07 | 0.05 | O | 600 | B0.5–B2 | IV–V |
| SXP504 | 14.99 | 0.01 | -0.02 | 0.01 | O | 600 | B1 | III–V |
| SXP565 | 15.97 | 0.02 | -0.02 | 0.04 | O | 600 | B0–B2 | IV–V |
| SXP700 | 14.60 | 0.02 | -0.08 | 0.02 | M | 600 | B0–B0.5 | III–V |
| SXP701 | 15.87 | 0.05 | 0.15 | 0.05 | M | 600 | O9.5 | V |
| SXP756 | 14.98 | 0.02 | 0.05 | 0.03 | O | 600 | O9.5–B0.5 | III–V |
| SXP1383 | 14.65 | 0.02 | -0.11 | 0.03 | Z | 600 | B0 | III–V |

(1) Covino et al. (2001) (2) Schurch et al. (2007) (3) Coe et al. (2002)

5 RESULTS

The spectral distribution of SMC Be/X-ray binaries is shown in Fig. 4 with individual spectral types given in Table 4. Our procedure for the binning of stars where we were unable to constrain the spectral type to one subtype involved allocating the object fractionally to the spectral classes within the estimated spectral range of the source. For example, SXP82.4 which can be constrained to the B1–B3 range translates into the histogram as $\frac{1}{3}$ B1, $\frac{1}{3}$ B2 and $\frac{1}{3}$ B3.

The distribution shows a similarity to the spectral distributions of the Galactic and LMC Be/X-ray binaries. The spectral distribution of Be/X-ray binary counterparts in the SMC peaks at spectral type B1, compared to the LMC and Galaxy distributions, which peak at B0. The Galactic and LMC distributions show a sharp cutoff at B2, whereas there are 5 SMC objects with possible spectral types beyond B2, but as one can see from Table 4 the exact spectral type cannot be determined with certainty in these cases. A Kolmogorov-Smirnov test of the difference between the SMC and Galactic distributions gives a K-S statistic $D = 0.22$, indicating that the null hypothesis (which is that the two distributions are the same) cannot be rejected even at significances as low as 90%. Hence, it is likely that both Galactic and SMC Be/X-ray binary counterparts are drawn from the same population.

The most noteworthy selection effect, which may mask the real distribution of spectral types in the SMC, is magnitude related: fainter stars, which are most likely to be those...
its outer layers, may be spun up (Packet 1981). As it is well-known that the Be phenomenon is closely associated with high stellar rotational velocities (Porter & Rivinius 2003) it is not far-fetched to suppose that such binary mass transfer may rejuvenate the secondary star and, somehow, give rise to the Be phenomenon. Studies of Be stars in clusters (McSwain & Gies 2007) indicate that most cases of the Be phenomenon may be brought about by spin-up processes in close binaries, rather than Be stars being born as fast rotators or being spun-up in the final stages of their main sequence lives.

Such a model of rejuvenation may also account for the narrow spectral distribution of Be/X-ray binaries. In population synthesis models (Portegies Zwart 1995) includes the effects of both supernova kick velocities and angular momentum loss through the $L_2$ point. He finds that this angular momentum leakage is just as influential in restricting the final number of Be binary pulsars as the effect of a supernova kick and, in addition, that angular momentum loss restricts the spectral distribution of the Be star companions. (Portegies Zwart 1995) shows clearly that a higher loss of angular momentum restricts the mass of the Be star counterparts to $> 8 M_\odot$, i.e. to spectral types earlier than B2 V (Allen 1973). This is caused by the fact that binary systems holding late-type stars, which have smaller mass ratios, tend to undergo a spiralling-in effect when mass is lost through the $L_2$ point (Pols et al. 1991). In these cases the components may merge or form a common envelope. Whatever the eventuality in such a case, it is clear that a Be neutron star system will not be the outcome.

Negueruela & Cod (2002) have shown that Be/X-ray binaries in the LMC follow the same distribution as those in the Milky Way, and this work (see Fig. 1) shows that the spectral distribution of Be/X-ray binaries in the SMC is also consistent with that of the Milky Way systems.

Although no major spectral survey of Be stars in the SMC has been performed, preliminary results (Martayan et al. 2006) obtained from photometric colours of $\sim 7700$ emission line stars indicate that the spectral distribution of isolated Be stars in the SMC is similar to that in the Galaxy. Hence, at this time we cannot exclude the possibility that isolated Be stars in the SMC may have a different spectral distribution from those in the Milky Way.

Figure 5 shows the arbitrarily scaled spectral distribution of SMC Be/X-ray binaries superimposed on the predicted spectral distribution of Be/X-ray binaries (from Portegies Zwart 1995). As with the Milky Way and LMC distributions, the SMC distribution cuts off around spectral type B2 ($\sim 8 M_\odot$), indicating that there may be significant angular momentum losses in the binary system prior to the Be/X-ray binary evolutionary phase. A possible interpretation of the fact that there is no significant metallicity dependence of the spectral distributions of Be/X-ray binaries is that the angular momentum is lost through mechanisms other than the stellar winds of early-type components of these systems. For example, as (Portegies Zwart 1995) infers, the mass may be lost through the $L_2$ point during the initial phase of mass transfer which serves to spin up the star to Be star status. It is also worth noting that there are no SMC Be/X-ray binaries with masses greater than $\sim 22 M_\odot$. This may be due to the fact that heavier systems go on to become supergiant X-ray binaries, which have lifetimes sig-
Figure 5. The absolute normalised number distribution of Be stars with a neutron star companion for four evolutionary scenarios. $v$ represents the supernova kick velocities (in km s$^{-1}$) while $\beta$ represents the angular momentum lost from the binary system. The solid histogram represents the spectral distribution of SMC Be/X-ray binaries from this work (spectral type/mass calibration from Zombeck (2007), arbitrarily scaled along vertical axis) superimposed. Original figure from Portegies Zwart (1995).

significantly shorter than the Be/X-ray systems and are consequently less abundant (there is only one in the SMC – SMC X-1).

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