The Magellanic System: Stars, Gas, and Galaxies
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Optical properties of High-Mass X-ray Binaries (HMXBs) in the Small Magellanic Cloud

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Abstract. The SMC represents an exciting opportunity to observe the direct results of tidal interactions on star birth. One of the best indicators of recent star birth activity is the presence of significant numbers of High-Mass X-ray Binaries (HMXBs) — and the SMC has them in abundance! We present results from nearly 10 years of monitoring these systems plus a wealth of other ground-based optical data. Together they permit us to build a picture of a galaxy with a mass of only a few percent of the Milky Way but with a more extensive HMXB population. However, as often happens, new discoveries lead to some challenging puzzles — where are the other X-ray binaries (e.g., black hole systems) in the SMC? And why do virtually all the SMC HMXBs have Be star companions? The evidence arising from these extensive optical observations for this apparently unusual stellar evolution are discussed.

Keywords. stars: emission-line, Be, stars: evolution, pulsars: general, galaxies: individual (SMC), Magellanic Clouds, X-rays: binaries

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1. Introduction

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 detailed review of the X-ray properties of such systems may be found in Sasaki *et al.* (2003) and a review of the optical properties can be found in Coe *et al.* (2005).

Fig. 1 shows the current numbers for the different types of X-ray binary populations that are found in the Milky Way and the SMC. Since the number of LMXBs is thought to scale linearly with the mass of hydrogen in the galaxy, then the ratio of ~ 100 in masses between the two objects explains the lack of LMXBs known in the SMC. But where are the supergiant and Black Hole systems in the SMC?

We currently know of ~ 40 optically identified systems. This represents by far the largest homogeneous population of X-ray binaries in any galaxy including the Milky

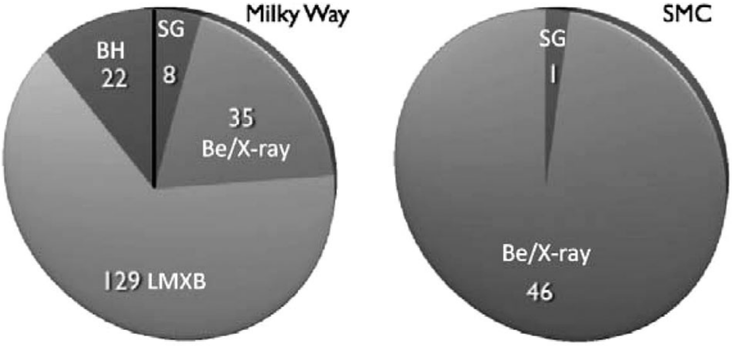

Figure 1. Relative X-ray binary populations in the SMC and the Milky Way.

Way. For all these systems OGLE & MACHO lightcurves exist for ⩾10 years enabling the confirmation of counterparts, the identification of binary periods, seeking correlated optical/X-ray flaring etc. These data are supported by follow-up spectroscopy (*SALT*, *AAT* & *ESO*) establishing spectral classes, circumstellar disk status and links into binary evolution.

2. Optical Binary modulation

Some 10–15 of the systems in the SMC have been observed to show a strong optical modulation at the binary period. Some of them also show evidence for quasi-periodic behaviour probably associated with Non Radial Pulsations (see, for example, Schmidtke & Cowley 2006). SXP 327 is an exceptional member of the SMC X-ray binary pulsar systems in that it shows a very strong optical modulation at the binary period (Coe *et al.* 2008, see Fig. 2). Another source, SXP 46.6, has also recently been shown by McGowan *et al.* (2008) to exhibit optical flaring at the same phase as X-ray outbursts, but not in the same strong and consistent manner as SXP 327. Those authors discuss the probable cause of this phenomenon as lying in the periodic disturbance of the Be stars circumstellar disk. At the time of periastron passage Okazaki & Negueruela (2001) have shown that the disk can be perturbed from its stable, resonant state with a resulting increase in surface area and, hence, optical brightness. What is very unusual about this system, SXP 327, is that there is not one, but at least two outbursts every binary cycle at phases 0.0 and 0.25 (i.e. separated by about 11 d). In addition, the average profile seems to also show a third peak at phase 0.55 — which could be close to apastron if the main peak represents periastron. Fig. 2 shows that the colours of the system reflect the optical brightness. It is obvious from this figure that the correlation between colour and flux occurs throughout the binary cycle even though it is most prominent at the time of the outbursts. The direction of the correlation is to make the system bluer when brighter — perhaps an indication of X-ray heating contributing to the colour changes.

On a longer timescale, the average optical modulation varies from year to year (see Fig. 3), probably indicative of major changes in the disk structure on the same timescales as the well-known V/R ratio changes.

3. Population evolution

There is considerable interest in the evolutionary path of High-Mass X-ray binary systems (HMXBs), and, in particular, the proper motion of these systems arising from

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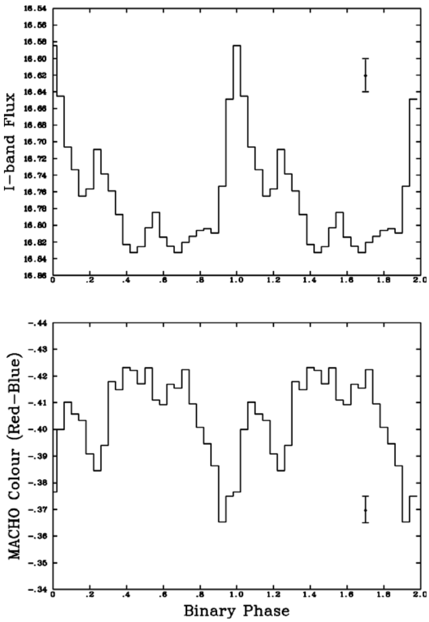

Figure 2. Strong correlated colour effects in SXP 327 when folded at binary period of 46 d. N.B. the double peaked structure.

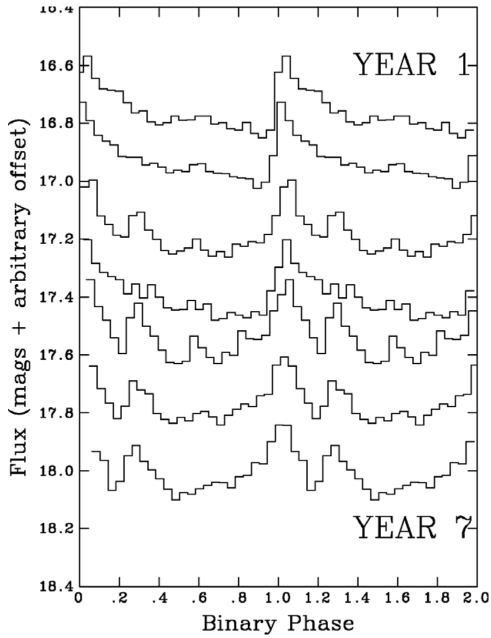

Figure 3. Annual variation in the binary profile of the optical photometry of SXP 327 obtained from folding the OGLE III data.

the kick velocity imparted when the neutron star was created. Portegies Zwart (1995) and van Bever & Vanbeveren (1997) investigate the evolutionary paths such systems might take and invoke kick velocities of the order 100–400 km s^{-1}. In an investigation into bow shocks around galactic HMXBs Huthoff & Kaper (2002) used *Hipparcos* proper motion data to derive associated space velocities for Be/X-ray and supergiant systems. From their results, an average value of 48 km s^{-1} is found for the 7 systems that they were able to fully determine the three dimensional motion. Since this is rather lower than the theoretical values it is important to seek other empirical determinations of this motion.

Coe (2005) used a sample of 17 SMC Be/X-ray binaries to address what may be learnt about kick velocities by looking at the possible association of HMXBs in the SMC with the nearby young star clusters from which they may have emerged as runaway systems (see Fig. 4). Here we extend this work to 37 systems.

In order to determine whether the SXP sources may have originated from a nearby stellar cluster, the coordinates of the 37 SXP objects were compared to those of the RZ clusters (Rafelski & Zaritsky (2005). For every SXP its position was compared to the location of all of the RZ clusters and the identification of the nearest cluster neighbour obtained. The average distance between the pairs of objects was found to be 3.54 arcminutes. The histogram of the distances between each SXP source and the nearest RZ cluster is shown in the upper panel of Fig. 5. Obviously it is important to ensure that the SXP-RZ cluster distances are significantly closer than a sample of randomly distributed points. One way to determine this is simply to just use the RZ cluster data and find the average cluster-cluster separation. This gives a value of 6.13 arcminutes. Alternatively, the minimum distance between 100,000 random points and, in each case, the nearest RZ cluster was found. The average value was found to be 5.30 arcminutes and the corresponding histogram is shown in the lower panel of Fig. 5. From comparing the two histograms it is clear that there does exist a much closer connection between

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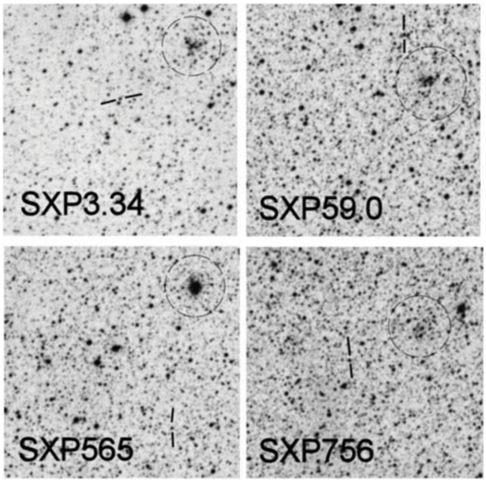

Figure 4. The fields around 4 Be/X-ray binary systems as a clue to HMXB evolution. In each case we note the presence of a nearby cluster catalogued by Rafelski & Zaritsky (2004).

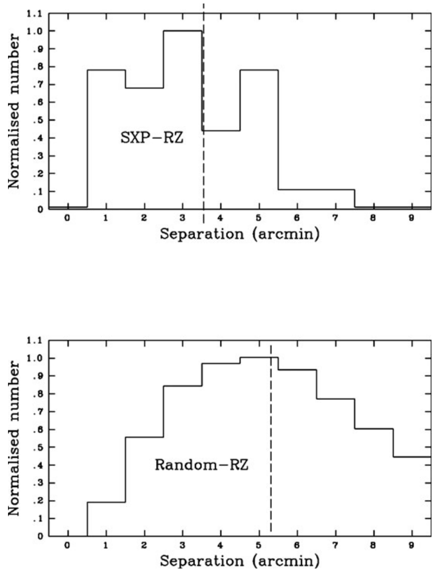

Figure 5. Upper panel: histogram of the distances between each SXP and its nearest neighbour RZ cluster. Lower panel: histogram of the minimum distance between 100,000 random points and RZ clusters. In each case the dotted vertical line shows the position of the mean of the distribution.

SXP sources and RZ clusters than expected randomly. A paired student t-test of the two distributions gives a probability of only 7% that the two distributions could have been drawn from the same parent population.

Using a value of 60 kpc for the distance to the SMC, then 3.54 arcminutes corresponds to 60 pc. Savonije & van den Heuvel (1977) estimate the maximum possible lifetime of the companion Be star after the creation of the neutron star to be $\sim$5 million years. So 60 pc indicates the minimum average transverse velocity of the SXP systems is 16 km s^{-1}. van den Heuvel *et al.* (2000) interpreted the Hipparcos results for galactic HMXBs in terms of models for kick velocities, and obtained values around 15 km s^{-1}.

4. Spectral classification

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?

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

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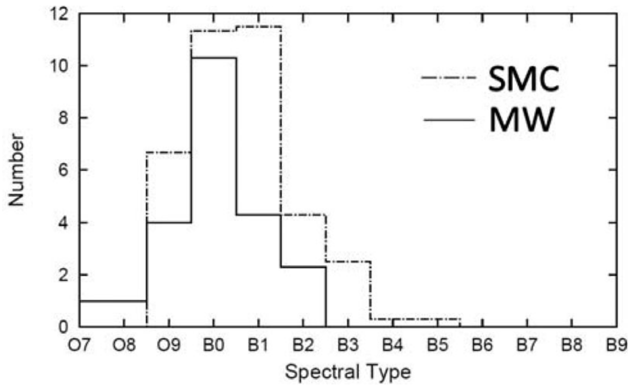

Figure 6. Spectral distribution, determined from blue spectra of ∼ 40 Be/X-ray binaries in the SMC, as compared the distribution of Be/X-ray binaries in the Galaxy (McBride *et al* 2008).

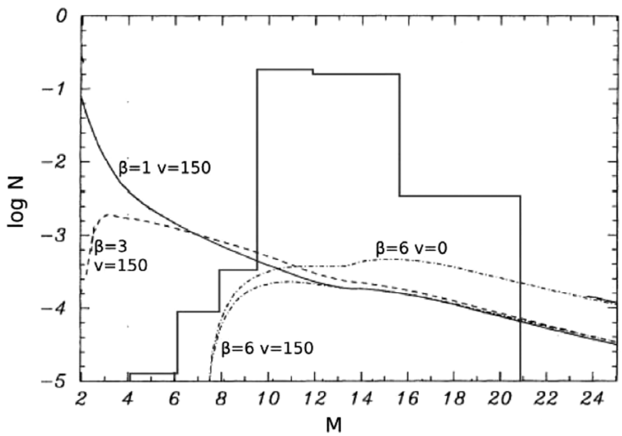

Figure 7. The absolute normalised number distribution of Be stars with a neutron star companion for four evolutionary scenarios. The solid histogram represents the spectral distribution of SMC Be/X-ray binaries from McBride *et al* (2008). v represents the supernova kick velocities (in km s^{-1}), while β represents the amount of angular momentum lost per unit mass loss from the system during evolution. Original figure from Portegies Zwart (1995).

B-types and continuing through until A0, the Be star companions of X-ray binaries show a clear cutoff near spectral type B2.

McBride *et al.* (2008) carried out detailed blue spectral observations and used these data to classify each counterpart. The spectral distribution of SMC Be/X-ray binaries is shown in Fig. 6. The distribution shows a similarity to the spectral distributions of the Galactic (Negueruela 1998) and LMC (Negueruela & Coe 2002) 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 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.

Fig. 7 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 (~ 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.

5. Future work and conclusions

This next year should provide us with a wealth of new high-energy and optical data of the XRB population in the SMC:

• Weekly X-ray (*RXTE*) monitoring campaign of the SMC Bar will continue for as long as possible.

• For the period July–Sep 2008 we will obtain *VLT* high resolution spectral data on 21 systems every week. We will use the detailed line profiles to study circumstellar disk structures, correlating with X-ray outbursts, as well as RV measurements to identify/confirm binary periods.

• From November 2008 till July 2009 *ESA*'s *INTEGRAL* observatory will carry out a detailed study of the whole of the SMC to a total depth of 2 Msec (equivalent to ~ 70 nights of telescope time).

So, in summary, we have an excellent homogeneous population of High-Mass X-ray Binaries. The combined optical & X-ray data are proving to be a superb laboratory for exploring X-ray binary evolutionary and accretion processes. In addition, the population as a whole has crucial differences with their partners in the Milky Way that need explaining. Finally, the High-Mass X-ray Binaries are providing us with invaluable insights into the recent history of star formation in the SMC.

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