STAR FORMATION HISTORY AND X-RAY BINARY POPULATIONS: THE CASE OF THE SMALL MAGELLANIC CLOUD

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ABSTRACT

Using Chandra, XMM-Newton, and optical photometric catalogs we study the young X-ray binary (XRB) populations of the Small Magellanic Cloud. We find that the Be/X-ray binaries (Be–XRBs) are observed in regions with star formation rate bursts ~25–60 Myr ago. The similarity of this age with the age of maximum occurrence of the Be phenomenon (~40 Myr) indicates that the presence of a circumstellar decretion disk plays a significant role in the number of observed XRBs in the 10–100 Myr age range. We also find that regions with strong but more recent star formation (e.g., the Wing) are deficient in Be–XRBs. By correlating the number of observed Be–XRBs with the formation rate of their parent populations, we measure a Be–XRB production rate of ~1 system per $3 \times 10^{-3} M_\odot$ yr$^{-1}$. Finally, we use the strong localization of the Be–XRB systems in order to set limits on the kicks imparted on the neutron star during the supernova explosion.

Key words: Magellanic Clouds – pulsars: general – stars: early-type – stars: emission-line, Be – stars: formation – X-rays: binaries

1. INTRODUCTION

Nearby star-forming galaxies offer a unique environment to study the young (~<100 Myr) X-ray binary (XRB) populations. One of the best cases is the Small Magellanic Cloud (SMC), which at ~60 kpc is our second nearest star-forming galaxy (Hilditch et al. 2005). Its proximity, well-mapped extinction ($N_H \approx 6 \times 10^{20} \text{cm}^{-2}$; Dickey & Lockman 1990), small line-of-sight depth of its young, central stellar populations (~<10 kpc; Crowl et al. 2001; Harries et al. 2003), and its well-determined recent star formation history (SFH; Harris & Zaritsky 2004, HZ04) make the SMC the ideal environment for directly studying the link between XRB populations and star formation (SF). Furthermore, the wealth of multi-wavelength data allows us to clarify the X-ray sources and obtain an even more precise picture of their population.

Several studies have compared the number of Be/X-ray binaries (Be–XRBs) in the Magellanic Clouds and the Galaxy (e.g., Majid et al. 2004; Haberl & Pietsch 2004; Coe et al. 2005), concluding that the SMC hosts an unusually large number of these systems. There is only one identified supergiant XRB located in the SMC Wing (SMC X-1; Webster et al. 1972) in a population of ~100 high-mass XRBs (HMXBs; e.g., Liu et al. 2005; Antoniou et al. 2009b, Paper II). However, only a few of these HMXBs have determined spectral types (e.g., out of the 92 listed in Liu et al. 2005, 53 are cited as Be–XRBs but only 19 have been confirmed spectroscopically). Later works by Antoniou et al. (2009a, Paper I), Haberl et al. (2008), McBride et al. (2008), Shklyoskovsky & Gilfanov (2005), Coe et al. (2005) and others have increased the number of known Be–XRBs to 67 to date. Nevertheless, this overabundance can be partly explained by the enhanced SMC SFH (~40 Myr ago (e.g., Majid et al. 2004; Shklyoskovsky & Gilfanov 2007, SG07). However, Antoniou et al. (2009b) show that even after accounting for the difference in the star formation rate (SFR) between the SMC and the Galaxy, the SMC hosts ~1.5 times more Be–XRBs than the Galaxy down to a limiting luminosity of $L_X \geq 10^{33}$ erg s$^{-1}$. This residual excess can be explained by the different metallicity of these galaxies, as justified by population synthesis models (Dray 2006) and recent observations of Be stars (e.g., Wisniewski & Bjorkman 2006; Martayan et al. 2007). The work of Antoniou et al. (2009b) also indicated spatial variations of the Be–XRB populations within the SMC Bar, which could be evidence for small supernova (SN) kicks.

The SMC Bar hosts stellar populations with ages ~<100 Myr (HZ04) and the vast majority of the SMC pulsars (Galache et al. 2008). SG07 found that the age distribution of the HMXBs peaks at ~20–50 Myr after the SF event, while McSwain & Gies (2005) observed a strong evolution in the fraction of Be stars with age up to 100 Myr, with a maximum at ~25–80 Myr. These results motivated us to investigate the connection between the spatially resolved SFH and around the SMC Bar and the number and spatial distribution of the XRBs. In this study, we use the results from our Chandra survey of the central, most actively star-forming, SMC Bar (A. Zezas et al. 2010, in preparation; Papers I and II), and data from our XMM-Newton survey of the outer SMC regions which host young and intermediate age stellar populations (~10–500 Myr; HZ04).

2. X-RAY OBSERVATIONS AND DATA ANALYSIS

Using the ACIS-I detector on board Chandra we observed five fields in the central part of the SMC (the so-called SMC Bar), with typical exposure times of 8–12 ks. These observations yielded a total of 158 sources, down to a limiting luminosity of $\sim 4 \times 10^{33}$ erg s$^{-1}$ (0.5–7.0 keV band), reaching the luminosity range of quiescent HMXBs (typically $L_X \sim 10^{35}$–10$^{35}$ erg s$^{-1}$; van Paradijs & McClintock 1995). The analysis of the data, the source-list, and their X-ray luminosity functions are presented in A. Zezas et al. (2010, in preparation), while their optical counterparts and resulting classification are given in Papers I, II.
Table 1

| ID          | R.A.(J2000.0) (h m s) | Decl.(J2000.0) (° ′ ″) | Age (Myr) | Duration (Myr) | SFR (10^{-6} M_⊙ yr^{-1} arcmin^{-2}) | HMXBs (Be–XRBs) | OB Stars | Pulsars |
|-------------|-----------------------|------------------------|-----------|----------------|----------------------------------------|-----------------|----------|--------|
| Chandra 3   | 00 56 46.14           | -72 18 10.78           | 66.8      | 68             | 44.04\times10^{-07}                    | 10 (7)          | 2220     | 6      |
| Chandra 4   | 00 49 30.74           | -73 16 52.34           | 42.2      | 36             | 62.76\times10^{-07}                    | 17 (10)         | 4060     | 8      |
| Chandra 5   | 05 53 11.45           | -72 26 29.92           | 42.2      | 28             | 81.86\times10^{-07}                    | 20 (16)         | 2730     | 12     |
| Chandra 6   | 05 53 04.40           | -72 42 18.22           | 42.2      | 36             | 69.64\times10^{-07}                    | 20 (17)         | 3040     | 12     |
| Chandra 7   | 05 49 25.00           | -73 24 22.80           | 26.6      | 30             | 54.51\times10^{-07}                    | 7 (6)           | 1670     | 3      |
| XMM-Newton 1| 01 07 52.00           | -72 53 41.60           | 10.6      | 8              | 35.30\times10^{-07}                    | 4 (0)           | 3780     | 0      |
| XMM-Newton 2| 00 51 56.63           | -72 02 53.20           | 16.8      | 15             | 15.60\times10^{-07}                    | 3 (2)           | 3715     | 2      |
| XMM-Newton 3| 00 42 25.45           | -73 36 29.40           | 66.8      | 39             | 15.65\times10^{-07}                    | 4 (0)           | 1500     | 0      |
| XMM-Newton 6| 00 40 05.19           | -72 47 57.40           | 668.3     | >1200          | 4.35\times10^{-09}                     | 0 (0)           | 445      | 0      |

Notes. Columns 1–3: observed fields (ID, R.A., Decl.); Columns 4–6: age, duration—defined as the FWHM of its time evolution—and SFR; Columns 7–9: the number of HMXBs (Be–XRBs; see Section 2.1), OB stars (following Antoniou et al. 2009b), and pulsars (see Section 3).

Our XMM-Newton survey consists of five observations in the outer SMC Bar, performed with the three EPIC (MOS1, MOS2, and PN) detectors in full frame mode. One of these fields was affected by high background flares and it is not included in this work. The data were analyzed with the XMM-Newton Science Analysis System (SAS) version v7.0.0. After processing the raw data with the echain and emchain tasks, we filtered any bad columns/pixels and high background flares (excluding times when the total count rate deviated more than 3σ from the mean), resulting in 5–18 ks net exposures. We only kept events of patterns 0–4 for the PN and 0–12 for the MOS detectors. Source detection was performed simultaneously in five energy bands (0.2−0.5, 0.5−1.0, 1.0−2.0, 2.0−4.5, and 4.5−12.0 keV) and the three EPIC detectors with the maximum likelihood method (threshold set to 7) of the edetect_chain task. The detected sources were visually inspected for spurious detections. We detected 186 sources down to a limiting luminosity of ~3.5 × 10^{-13} erg s^{-1} (0.2−12 keV), out of which 4–8 sources are expected to be spurious based on the calibration of Watson et al. (2009).

In Table 1, we give the ID and the coordinates of the X-ray fields, along with the properties of the dominant SF event in each field (see Section 3).

2.1. X-ray Source Classification

New HMXBs and candidate Be–XRBs are identified based on their X-ray and optical properties. Hardness ratios between the soft (0.5−1.0 keV), medium (1.0−2.0 keV), and hard (2.0−4.5 keV) bands were used as an initial measurement of their X-ray spectral properties. A hard X-ray spectrum or hardness ratio (equivalent to a photon index of Γ = 1) is indicative of a pulsar binary (e.g., Haberl et al. 2008). For the identification of the optical counterparts of the XMM-Newton sources we followed the analysis of Antoniou et al. (2009b). We cross-correlated their coordinates with the OGLE-II (Udalski et al. 1998) and MCPS (Zaritsky et al. 2002) catalogs and searched for optical matches in a 5″ radius around each X-ray source (which includes the boresight error of XMM-Newton; e.g., Brusa et al. 2007). Given the small number of X-ray sources with independently known optical counterparts, we cannot correct these observations for boresight errors. Based on the position of these counterparts on the V, B − V color–magnitude diagram, we identify sources with early OB-type counterparts, while from hardness ratio or spectral analysis we identified those hard X-ray sources (Γ ≈ 1), strongly suggesting they are XRB pulsars. Although Monte Carlo simulations indicate a significant number of spurious sources in these fields, the identification of a hard X-ray source with an early-type counterpart suggests that this is a true match.

We find that 15 XMM-Newton sources have O- or B-type counterparts, while only 8 of those are hard X-ray sources, suggesting they are HMXBs. Since all but one of the confirmed SMC HMXBs are Be–XRBs, they are also candidate Be–XRBs. Their properties are presented in Table 2. The X-ray luminosity is derived assuming a power-law spectrum of Γ = 1 and H column density equal to 4.81 × 10^{20}, 6.63 × 10^{20}, and 4.51 × 10^{20} cm^{-2} for fields 1, 2, and 3, respectively (based on Dickey & Lockman 1990). The X-ray spectra of two sources with >200 counts were fitted with an absorbed power law, resulting in a photon index of Γ = 0.65 ± 0.04 and 0.97 ± 0.25, and a column density of N_H = (3.31 ± 0.02) × 10^{20} cm^{-2} and (0.30 ± 0.15) × 10^{20} cm^{-2}, for sources 2-1 (by simultaneously fitting its MOS1 and MOS2 spectra) and 3-1 (from its PN spectrum), respectively. Source 2-1 in particular is a known Be–XRB pulsar with a period of 169.3 s (Lochner et al. 1998) associated with emission-line object [MA93]623 (Meyssonnier & Azzopardi 1993; 3′′3 away), source 3-1 remained unclassified in Sasaki et al. 2000 (ROSAT HRI src ID 11), while source 3-3 is the only one not included in the pipeline EPIC detection list.

If we include to the above sources the confirmed and candidate Be–XRBs that lie within the Chandra and XMM-Newton fields (from this work and those mentioned in Section 1), we have a total of 54 (39) and 11 (two) HMXBs (Be–XRBs), respectively. For Chandra fields this is the sum of unique Be–XRBs, i.e., sources detected in two overlapping fields are counted once.

3. SFH AND XRB POPULATIONS

The recent SFH in our Chandra and XMM-Newton fields is derived by averaging the spatially resolved SFH of the MCPS regions (~12′ × 12′; HZ04) encompassed by them. We find the following.

1. For the Chandra fields, the most recent major burst peaked ~42 Myr ago, and it had a duration of ~40 Myr. Moreover, there were older SF episodes (~0.4 Gyr ago) with lower...
intensity but longer duration, besides a more recent episode (∼7 Myr) observed only in Chandra field 4.

2. For XMM-Newton field 3, the most recent major burst occurred ∼67 Myr ago. We also observed two fields with very young populations (most recent major burst at ∼11 and 17 Myr ago for fields 1 and 2, respectively). XMM-Newton field 2 had an additional intense burst ∼67 Myr ago (Table 1).

In order to investigate the link between stellar and XRB populations, we calculate the average SFH for the MCPS regions (∼12′ × 12′; HZ04) that host one or more Be–XRBs (candidate and confirmed) detected in our Chandra and XMM-Newton surveys (39 and two, respectively; see Section 2.1). The SFH in each region is weighted by the encompassed number of Be–XRBs, and the error bars are derived based on the upper and lower limits of HZ04. We repeat this exercise for the 15 MCPS regions without any known Be–XRBs. The two SFHs are presented in Figure 1. The SFH of the Be–XRBs (black points) is strongly peaked at ∼42 Myr, while fields without any Be–XRB (gray points) have minimal SFR at this age. This underscores the difference between the fields with and without Be–XRBs and suggests a clear connection between an SF event and the observed Be–XRBs.

Following the above comparison, we also construct the SFH of the MCPS regions hosting one or more known X-ray pulsars within any of our fields7 (Figure 1; black points), and for those that do not host such sources (gray points). A large fraction of these pulsars (∼60%; Liu et al. 2005) also appears in the Be–XRB sample, since the vast majority of their companions are Be stars. This link is reinforced by the fact that all the counterparts of these X-ray sources lie on the region of the color–magnitude diagram consistent with main-sequence stars of age ∼40 Myr (Paper II). For completeness we present both, since the pulsar and the Be–XRB samples are selected on the basis of their timing and optical properties, respectively. In total, in the MCPS regions that overlap with the Chandra fields lie 30 X-ray pulsars, while in the XMM-Newton fields only two (sum of unique sources as in Section 2.1). As expected, the pattern in their SFH is very similar to that of Be–XRBs. For regions rich in X-ray pulsars the SF peaks at ∼42 Myr, while for regions without pulsars there is no peak at this age.

The average SFH of the MCPS regions with and without any Be–XRBs detected in the Chandra Wing survey (P.I. M. Coe; McGowan et al. 2008) is presented in Figure 1, top right (black and gray points, respectively). This survey covered 20 fields (three of which are not used in this study because they do not overlap with any MCPS region) and discovered four Be–XRB pulsars (Schurch et al. 2007). Repeating the same analysis, we find an SF peak at ∼42 Myr for fields with one or more known Be–XRBs. For regions in the Wing without Be–XRBs there is no SF burst at this age; however, we see an intense burst at ∼11 Myr. For completeness, we also present (Figure 1) the average SFH of the MCPS regions with candidate (i.e., non-spectroscopically confirmed) Be–XRBs from the census of Liu et al. (2005), which also shows that they are produced from the same SF burst as the pulsars and confirmed Be–XRBs. The above comparisons are summarized in Table 3.

The strong correlation between the number of XRBs and the age of the stellar populations at their location allows us to measure for the first time the XRB formation rate per unit SFR of their parent populations. The number of Be–XRBs (or HMXBs)

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7 Based on the online census of Malcolm Coe (http://www.astro.soton.ac.uk/~mjcs/mc as of 2009 June 18).
per unit area detected in our Chandra and XMM-Newton surveys versus the SFR at ~42 Myr for the different fields is plotted in Figure 2. In order to have a homogenous sample we used Be–XRBs detected only in these surveys. The best fit bisector line was calculated using the “Linear Regression Software” (Akritas & Bershady 1996), which takes into account heteroscedastic errors. We find a slope of 0.35 ± 0.03 Be–XRBs/SFR (or 0.40 ± 0.04 HMXBs/SFR), where SFR is in units of 10^{-3} M\odot yr^{-1}. This is the first direct calibration of the XRB formation rate, and the fact that it is based on the source population in a single galaxy minimizes systematic effects related to metallicity. For the same reason, this reflects the Be–XRB formation rate for a low metallicity (∼1/5 Z\odot; Luck et al. 1998).

### 4. DISCUSSION

From the above analysis we find that the number of SMC XRBs peaks for stellar populations of ages ~25–60 Myr. In Figure 1, we also see two additional peaks at ~11 and ~422 Myr. The one at ~11 Myr is too early to produce any pulsar XRBs, but could result in a population of black hole binaries (Belczynski et al. 2008) with O or early B-type donors which due to their massive companion evolve fast. The second SFR peak (at ~422 Myr) cannot result in HMXB formation, since by that time all OB stars have ended their lives.

The large number of Be–XRBs observed at ages ~25–60 Myr is consistent with the work of McSwain & Gies (2005), who find that Be stars develop their decretion disks at ages of

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**Table 3**

| Region     | Populations    | Age       | Duration (Myr) | SFR of Most Intense Peak at 42.2 Myr (10^{-6} M\odot yr^{-1} (arcmin)^{-2}) |
|------------|----------------|-----------|----------------|--------------------------------------------------------------------------------|
| SMC Bar    | Be–XRBs        | 42.2      | 33             | 54.50^{+3.16}_{-3.94}                                                            |
|            | Non-Be–XRBs    | 10.6      | 7              | 6.22^{+2.41}_{-1.44}                                                            |
| SMC Bar    | Pulsars        | 42.2      | 33             | 60.09^{+4.43}_{-4.14}                                                            |
|            | Non-Pulsars    | 10.6      | 5              | 12.40^{+5.7}_{-5.90}                                                            |
| SMC Wing   | Be–XRBs        | 4.6       | 8              | 58.47^{+3.48}_{-3.72}                                                            |
|            | Non-Be–XRBs    | 10.6      | 25             | 32.73^{+4.66}_{-4.91}                                                            |
| SMC Bar    | Candidate Be–XRBs | 42.2    | 31             | 128.69^{+26.73}_{-17.69}                                                        |

Notes. Column 1: SMC region; Column 2: source populations; Column 3: age of the most intense SF burst; Column 4: FWHM of burst’s time evolution; Column 5: SFR of the most intense peak; Column 6: SFR at 42 Myr.

*a* Additional burst at ages <100 Myr.
of the binary system, and (3) the luminosity cutoff (which however does not account for the Be phenomenon. They maximum number at ages of 20–50 Myr after the SF event, decretion disk formation at the current epoch. ∼

Number of observed Be–XRBs and HMXBs (shown in black and gray, respectively) in the Chandra and XMM-Newton fields vs. the SFR ∼42 Myr ago. Chandra (circles) and XMM-Newton (asterisks) fields are marked with their IDs. The point marked as WING includes observations from XMM-Newton field 1 and fields 5487, 5490, 5494, and 5495 from the Chandra Wing survey (P.I. M. Coe).

∼25–80 Myr, with a peak at ∼40 Myr. OB stars formed ∼40 Myr ago are expected to reach the maximum rate of decretion disk formation at the current epoch.

A study of the evolution of XRBs by SG07 also found their maximum number at ages of 20–50 Myr after the SF event, which however does not account for the Be phenomenon. They interpret this peak in the HMXB numbers as the result of (1) the pulsar spin-period evolution, (2) the nuclear evolution of the binary system, and (3) the luminosity cutoff (L_X ~ 10^{44} erg s^{-1}) due to the sensitivity of the observations. However, the luminosity cutoff (e.g., Linden et al. 2009) and evolution of the binary system may well result in variations of the observed number of binaries at different ages.

Another factor which may result in the excess of SMC HMXBs stems from the similarity between the epoch of the maximum occurrence of Be stars and the ages of the stellar populations hosting XRBs, and the fact their majority have Be-star donors. This indicates that the development of a decretion disk plays a major role in the overall statistics of the X-ray source populations by (1) increasing the number of active objects and (2) by increasing their observed luminosities due to the higher density and lower velocity of the outflow (Waters et al. 1988).

This is also supported by the deficit of Be–XRBs in the SMC Wing. Figure 1 shows that the Wing has a weaker SF burst at the age of enhanced formation of Be stars (i.e., at ∼42 Myr) than the Bar, while its most recent SF burst occurred only ∼11 Myr ago. Thus, based on the above scenario, we do not expect a significant number of SMC Wing Be–XRBs. Indeed, the number of observed sources is lower than that in the SMC Bar, but consistent if we account for the SFR difference at 42 Myr (Figure 2). On the other hand, an SF burst at these early ages (∼11 Myr ago) suggests that supergiant HMXBs should dominate over Be–XRBs in the Wing. We also note that by comparing the number of binaries against the SFR (or the number of stars) in the same region any projection effects cancel out.

The strong correlation between the number of XRBs and the localized SF event can be used to constrain the kick velocity (v_kick) imparted on the compact object during the SN explosion.

In the case of large kicks the XRBs would be scattered over larger scales, diluting the correlation with their parent stellar populations and resulting in lower contrast between the SFR of regions with and without XRBs. Given an SF burst at ∼42 Myr and assuming a minimum pulsar birth timescale of ∼10 Myr after the burst (e.g., Belczynski et al. 2008), the elapsed time since the kick is ∼30 Myr. In order to contain the XRBs within the spatial scale of the star-forming regions (∼40°; HZ04), we require a maximum velocity of ∼15–20 km s^{-1}. This is in agreement with measured velocities of Be–XRBs in the Galaxy (15 ± 6 km s^{-1}; van den Heuvel et al. 2000) and estimations derived from the mean distance between a few pulsars and their nearest clusters in the SMC (∼30 km s^{-1}; Coe 2005). Although these center of mass velocities are consistent with typical SN kicks of ∼100 km s^{-1} (Cordes & Chernoff 1998), they could be much smaller given that the XRBs show indication of local concentrations within the Bar associated with SFR enhancements in much smaller scales (∼10–15°; Paper II). This suggests at least a factor of 2 lower v_kick which would be consistent with enhanced fraction of electron-capture SNe, which impart very low v_kick, as predicted by Linden et al. (2009) for the SMC metallicity.

In this Letter, we discuss the importance of Be–XRBs as a dominant component of young XRBs, based on a study of the connection between X-ray source populations and their parent stellar populations. We find that a significant number of Be–XRBs and/or pulsars are connected with a burst of SF ∼25–60 Myr ago, while regions with weak SFR at ∼42 Myr, such as the SMC Wing, are deficient in Be–XRBs. We argue that the very strong similarity between the age of maximum occurrence of Be stars and the age of the parent populations of XRBs in the SMC indicates that the Be phenomenon plays a significant role in the number of XRBs in this age range. Finally, based on the spatial correlation between the SF activity and the XRBs, we set a limit on their v_kick of ∼15–20 km s^{-1} while there is strong indication for velocities of even a factor of 2 lower, and we estimate a Be–XRB production rate of ∼1 system per 3 × 10^{-3} M_☉ yr^{-1}.

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Figure 2. Number of observed Be–XRBs and HMXBs (shown in black and gray, respectively) in the Chandra and XMM-Newton fields vs. the SFR ∼42 Myr ago. Chandra (circles) and XMM-Newton (asterisks) fields are marked with their IDs. The point marked as WING includes observations from XMM-Newton field 1 and fields 5487, 5490, 5494, and 5495 from the Chandra Wing survey (P.I. M. Coe).
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