First results from a *Chandra* survey of the 'Bar' region of the SMC

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We present the first results from a *Chandra* survey of the central region of the Small Magellanic Cloud. We detect a total of 122 sources down to a limiting luminosity of $\sim 4.3 \times 10^{33}$erg s^{-1}(corrected for Galactic N_H), which is ~ 10 times lower than in any previous survey of the SMC. We identify 20 candidate transient sources: eighteen previously known sources in this area which are not detected in our observations, and two new bright sources. The spectral parameters of the brightest sources indicate that they are X-ray binary pulsars. The high spatial resolution of *Chandra* allows us to initially identify optical counterparts for 35 sources, 13 of which are new identifications.

1. Introduction

The Small Magellanic Cloud (SMC) is one of the prime objects to study the extragalactic X-ray binary populations because its small distance and low Galactic extinction allows the detection of very faint sources and the identification of their optical counterparts. For the same reasons it is possible to determine its star-formation history much more accurately than in more distant galaxies. This gives us the possibility to investigate the connection between star-formation and the X-ray binary populations.

Studies of the stellar populations of the SMC show that its central region is dominated by a young stellar population from a recent burst of star-formation which occurred between 50 and 10 Myr ago (e.g. Harris 2000; Maragoudaki *et al.*, 2001). Together with this population coexists a population of older stars forming a uniform spheroidal distribution (e.g. Gardiner & Hadzidimitriou, 1992; Harris 2000).

The SMC has been observed with all major X-ray observatories. *Einstein* detected over 70 sources down to a detection limit of $\sim 5\times10^{34}$ erg s^{-1}† over an area of 32°, 24 of which have been identified as physically associated with the SMC (Wang & Wu, 1992). ROSAT performed two major surveys of the SMC, one with the PSPC (e.g. Haberl *et al.*, 2000; Kahabka & Pietsch, 1996) and one with HRI (Sasaki *et al.*, 2000) detecting a total of 517 and 121 X-ray sources respectively. The detection limits of these surveys vary across the observed area, with the flux of the faintest sources being $\sim 5 \times 10^{34}$ erg s^{-1} and $\sim 3 \times 10^{35}$ erg s^{-1} for the PSPC and the HRI surveys respectively.

The first hard X-ray survey of the SMC (0.5-7.0 keV) was performed with ASCA (Yokogawa *et al.*, 2000, 2003). This survey identified 106 individual sources, 5 of which were newly discovered pulsar binaries (based on the detection of coherent pulsations), while 8 sources were classified as pulsar candidates based on their hard spectra. Recently

† Throughout this paper the luminosities are in the 0.1-10.0 keV band, assuming an absorbed ($N_H = 5.9 \times 10^{20}$ cm^{-2}) power-law model ($\Gamma = 1.7$) and are not corrected for absorption, unless otherwise stated. The assumed distance is 60 kpc (van den Bergh 2000).

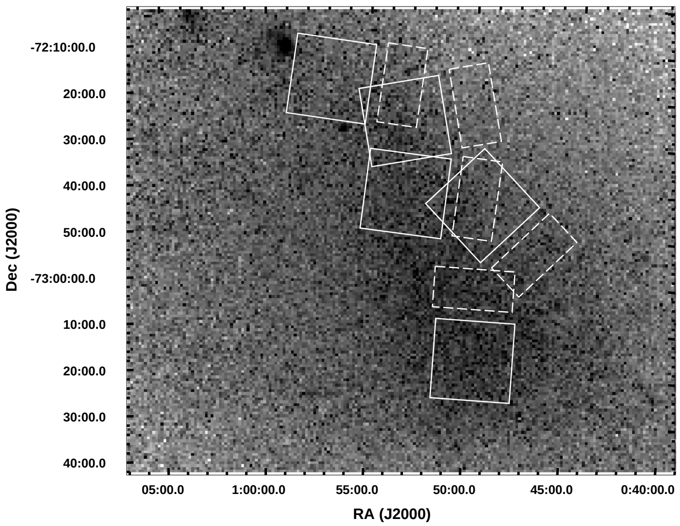

FIGURE 1. A DSS image of the central part of the SMC with the outline of the 5 observed fields (solid lines show the ACIS-I array which was at the aimpoint and dashed lines show the two ACIS-S CCDs. Each ACIS-I field is $16.9' \times 16.9'$ wide.

four fields in the outer parts of the SMC were observed with XMM-Newton (Sasaki *et al.*, 2003) which identified two new pulsars and two additional new X-ray sources.

2. Description of the Survey

In order to study in detail the low-luminosity end of the X-ray binary population in an actively star-forming galaxy and its connection to the stellar populations of the galaxy, we initiated a *Chandra* survey of the "Bar" region of the SMC. This region hosted the most recent starburst event in the SMC, between 50 and 10 Myr ago (Harris *et al.*, 2000).

We observed 5 individual fields, between May and October 2002, with the *Chandra* ACIS-I camera which provides a $16.9' \times 16.9'$ field of view. Figure 1 shows the observed fields overlaid on a DSS image of the SMC. The exposure times (7.6 ksec and 11.6 ksec) were chosen, based on an HI map of the SMC (Staveley-smith *et al.*, 1997), in order to achieve a uniform detection limit of $\sim 7 \times 10^{34}$erg s^{-1}(0.1-10.0 keV, corrected for absorption) across the surveyed area, even for sources located in the far edge of the SMC (i.e. are seen through the maximum HI column density).

3. First results

The data were analyzed following the standard procedures for the analysis of *Chandra* data. Fig. 2 shows a full band (0.5-7.0 keV), adaptively smoothed, exposure corrected, mosaic of the 5 observations. Images in soft (0.5-2.0 keV), medium (2.0-4.0 keV) and hard (4.0-7.0 keV) bands were searched for sources using the wavelets based *wavdetect* source detection algorithm. This search yielded between 21 and 32 sources per field at the 3σ level above the local background. The observed flux of the faintest sources is $\sim 1.5 \times 10^{-14}$ erg s^{-1} cm^{-2} (0.1-10.0 keV) which corresponds to a luminosity of $\sim 6.5 \times 10^{33}$ erg s^{-1} for the adopted distance of 60 kpc (van den Bergh 2000). This limit is ~ 10 times lower than the limit of the ROSAT and the ASCA surveys.

Based on the LogN-LogS distribution of the sources in the ChaMP survey (Kim *et al.*, 2003) we expect to detect 31 and 24 interlopers per field in the (0.5-2.0) keV and (2.0-4.0) keV bands respectively. This is larger than the observed number of sources by a factor of ~ 2 and a factor of ~ 3 for the soft and the hard band respectively (we detect 13-16 and 7-15 sources in soft and medium bands respectively). Even if all of the detected hard X-ray sources are not physically associated with the SMC, this discrepancy indicates that the SMC resides in a local minimum of the cosmic X-ray source distribution (the fact that the excess of observed sources is visible in both the medium and the soft band indicates that is not due to shadowing of the background sources by the ISM of the SMC). The association of at least 33% of the detected X-ray sources with stars in the SMC as well as their X-ray properties which are consistent with pulsar X-ray binaries, suggest that a significant fraction of them belongs to the SMC.

The first results from the comparison of the *Chandra* data with the ROSAT and ASCA surveys indicate that at least two of the detected sources are transient sources. Moreover, 18 sources previously detected by ROSAT or ASCA were not detected in our surveys despite the 10-fold higher sensitivity, indicating that they may also be X-ray transients.

Based on their extent and soft colour we identify at least 5 candidate supernova remnants, 3 of which were previously known. In one of them (previously detected by ROSAT and *Einstein*) we find a central, weak ($L_X = 1.6 \times 10^{34}$ erg s^{-1}, assuming isotropic emission), source with a hard spectrum possibly associated with a pulsar in the center of this SNR.

All 14 point-like sources for which it is possible to perform spectral fitting have hard X-ray spectra ($\Gamma < 2.0$) indicative of pulsar X-ray binaries. Five of them were not detected in the ASCA survey and two were not detected in the ROSAT surveys either. For the sources with previously published ASCA spectra we find consistent results within the errors. However, the fluxes we derive are systematically lower than the ASCA fluxes; in some cases this might be due to the fact that the ASCA sources are resolved in several *Chandra* sources.

Comparison with the MOA catalogue of eclipsing binaries (Bayne *et al.*, 2002) did not yield any coincidences. On the other hand comparison with the optical source catalogue from the photometric survey of Massey *et al.* (2002) gave 43 associations with 37 *Chandra* sources (the chance coincidence rate is 50%). One of these sources is of B2 spectral type while the other one is classified as B-extreme type star (Massey 2002). For thirteen previously detected X-ray sources we identify for the first time candidate optical counterparts.

In a nutshell the *Chandra* survey of the central part of the SMC provides a view of the X-ray source populations in the youngest regions of this galaxy with a ten-fold improvement in sensitivity over the previous X-ray surveys. The first results show that the majority of the bright sources (most of which were previously known) are High Mass X-ray binaries. Key for the association of the detected sources with the SMC is the identification of their optical counterparts. For 1/3 of the sources we have identified optical counterparts (13 of which are new) while with future optical follow-up observations will pursue the identification of counterparts for the remaining sources, which will allow us to determine their nature and construct the most complete (in terms of luminosity limit) sample of X-ray binary in an external galaxy so far.

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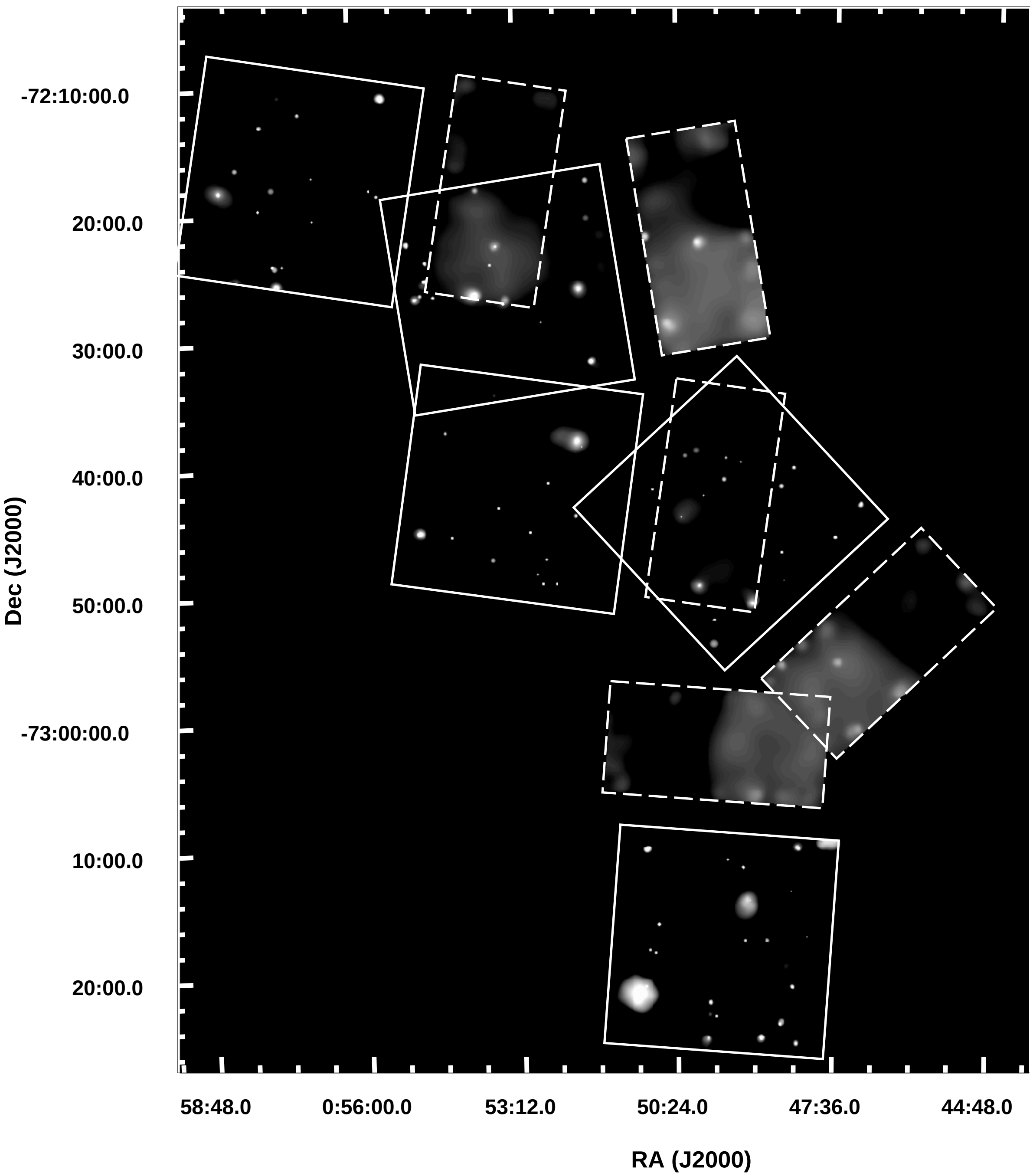

FIGURE 2. An adaptively smoothed, exposure corrected full band (0.5-7.0 keV) mosaic of the *Chandra* observations. As in Fig. 1 solid lines show the ACIS-I array and dashed lines show the two ACIS-S CCDs. The enhanced diffuse emission on one of the ACIS-S CCDs is due to the higher background of the S3 CCD.