Dependence of the LMXB population on stellar age

Zhongli Zhang\(^1\), Marat Gilfanov\(^{1,2}\), and Ákos Bogdán\(^3\)

\(^1\) Max-Planck Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85741 Garching, Germany
\(^2\) Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia
\(^3\) Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA

Received ... / Accepted ...

ABSTRACT

Aims. We investigate the dependence of the low-mass X-ray binary (LMXB) population in early-type galaxies on stellar age.

Methods. We selected 20 massive nearby early-type galaxies from the \textit{Chandra} archive occupying a relatively narrow range of masses and spanning a broad range of ages, from 1.6 Gyr to more than 10 Gyr, with the median value of 6 Gyr. With the \approx 2000 X-ray point sources detected in total, we correlated the specific number of LMXBs in each galaxy with its stellar age and globular cluster (GC) content.

Results. We found a correlation between the LMXB population and stellar age: older galaxies tend to possess about \approx 50\% more LMXBs (per unit stellar mass) than the younger ones. The interpretation of this dependence is complicated by large scatter and a rather strong correlation between stellar age and GC content of galaxies in our sample. We present evidence suggesting that the more important factor may be the evolution of the LMXB population with time. Its effect is further amplified by the larger GC content of older galaxies and correspondingly, the larger numbers of dynamically formed binaries in them. We also found clear evolution of the X-ray luminosity function (XLF) with age, that younger galaxies have more bright sources and fewer faint sources per unit stellar mass. The XLF of LMXBs in younger galaxies appears to extend significantly beyond \approx 10\(^{39}\) erg/s. Such bright sources seem to be less frequent in older galaxies. We found that 6 out of \approx 12 (ultra-) luminous sources are located in GCs.

Key words. X-rays: binaries – (Galaxy:) globular clusters: general – Galaxy: stellar content

1. Introduction

LMXBs are accreting systems consisting of a low-mass star (\lesssim 1M\(_{\odot}\)) transferring mass onto a neutron star or black hole through Roche-lobe overflow. Extensive studies of nearby galaxies with \textit{Chandra} have confirmed the long-suspected fact that their contribution to X-ray emission in early-type galaxies is substantial (e.g., Irwin et al. 2003; Kim & Fabbiano 2004). Their collective luminosity was found to closely follow the near-infrared light as well as the scaling relation of the LMXB population with the stellar mass obtained (Gilfanov 2004). However, a moderate scatter exists in these relations, suggesting that the specific number (per unit stellar mass) of X-ray binaries is not universally constant among galaxies and that secondary correlations may play a role.

Obviously, one of the main candidates for the second-order correlation is the LMXBs with the age of the stellar population. Unlike high-mass X-ray binaries, LMXBs are found both in young and old galaxies. Given that the characteristic time scale for the stellar evolution of the donor star and for the orbital evolution of the binary are both in the Gyrs range, it is not surprising that younger and older galaxies differ in their LMXB content. For example, Kim & Fabbiano (2010) recently reported evidence that younger galaxies may have a higher fraction of bright sources than older ones. On the theoretical side, the population synthesis calculations by Fragos et al. (2008) predict that the formation rate of LMXBs steadily decreases with time after 1 Gyr from the star formation event. This conclusion seems to have been supported by observations: based on the analysis of galaxies detected in the extended \textit{Chandra} Deep Field South, Lehmer et al. (2007) found that for optically faint early-type galaxies (where LMXBs dominate the X-ray emission), \frac{L_X}{L_B} increases moderately with redshift over \approx 0.0 – 0.5 range. Furthermore, Fragos et al. (2012) calculated the evolution of the specific LMXB luminosity through cosmic time. Their results suggest that the specific luminosity density of LMXBs peaks at \approx 2.5 and declines towards redshift \approx 0. However, there are observational facts that appear to challenge these conclusions. In a S0 galaxy NGC 5102, whose stellar population is younger than 1 Gyr, Kraft et al. (2005) found only two sources brighter than \approx 10\(^{39}\) erg/s, which is three times less than the predicted number of six LMXBs. Bogdán & Gilfanov (2010) reported similar results for two young elliptical galaxies, NGC 3377 and NGC 3585. Admittedly, both studies suffered from relatively low statistical significance of the results and therefore cannot be considered as a final argument. Similarly, the result of Lehmer et al. (2007) was not based on a direct determination of the age of the stellar environment (which was rather inferred from the redshift) and could have been contaminated by other effects (e.g., the rate of galaxy mergers).

It is obvious that more observational effort is needed in order to clarify this issue. The progress in this direction is hampered by the difficulty in reliably determining the age of stellar populations. In addition, a significant fraction of LMXBs in elliptical galaxies reside in GCs that are dynamically formed in two-body stellar interactions, rather than having a primordial origin. In order to investigate the age effects on the primordial population of LMXBs, GC sources need to be identified and excluded completely from the analysis. To this end, clean and reliable lists of GCs are needed, which are not available for the large number of galaxies required for a statistically meaningful study.
Table 1. The galaxy sample

| Galaxy     | Type | Distance | $N_H$ | $L_K$ | $M_*/L_K$ | $r_e$ | D25 | $M_V$ | $N_{GC}$ | $S_N$ |
|------------|------|----------|-------|-------|-----------|-------|-----|-------|----------|------|
| N720       | E5   | 27.7     | 1.54  | 21.50 | 0.86      | 1.20  | -   | 4.7, 2.4, 140 | -22.04  | 660 ± 190° | 1.01 ± 0.29 |
| N821       | E6   | 24.1     | 6.39  | 9.12  | 0.82      | 1.66  | -   | 2.6, 1.6, 25° | -21.12  | 320 ± 45° | 1.14 ± 0.16 |
| N1052      | E4   | 19.4     | 3.07  | 8.94  | 0.80      | 1.12  | -   | 3.0, 2.1, 120 | -21.00  | 400 ± 45° | 1.59 ± 0.18 |
| N1380      | SA0  | 17.6     | 1.31  | 12.57 | 0.81      | 1.32  | -   | 4.8, 2.3, 7°  | -21.23  | 560 ± 30° | 1.81 ± 0.10 |
| N1404      | E1   | 21.0     | 1.36  | 18.73 | 0.80      | 0.79  | -   | 3.3, 3.0, 162.5 | -21.58  | 725 ± 145° | 1.69 ± 0.34 |
| N3115      | S0   | 9.7      | 4.32  | 9.43  | 0.83      | 1.07  | -   | 7.2, 2.5, 40° | -21.13  | 630 ± 150° | 2.22 ± 0.53 |
| N3379      | E1   | 10.6     | 2.75  | 7.92  | 0.83      | 1.17  | -   | 5.4, 4.8, 67.5 | -20.88  | 270 ± 69° | 1.20 ± 0.31 |
| N3585      | E5   | 20.0     | 5.58  | 18.92 | 0.77      | 1.20  | -   | 4.7, 2.6, 107 | -21.76  | 50.0 ± 15° | -        |
| N3923      | E4-5 | 22.9     | 6.21  | 29.90 | 0.82      | 1.66  | -   | 5.9, 3.9, 50° | -22.11  | 2494 ± 286° | 3.57 ± 0.41 |
| N4125      | E6   | 23.9     | 1.84  | 23.49 | 0.80      | 1.95  | -   | 5.8, 3.2, 82.5 | -22.13  | -        | 1.30 ± 0.50 |
| N4278      | E1-2 | 16.1     | 1.77  | 7.87  | 0.78      | 1.15  | -   | 4.1, 3.8, 27.5 | -20.96  | 1300 ± 300° | 5.35 ± 1.23 |
| N4365      | E3   | 20.4     | 1.62  | 20.86 | 0.85      | 1.66  | -   | 6.9, 5.0, 40°  | -22.01  | 2511 ± 100° | 3.95 ± 1.57 |
| N4374      | E1   | 18.4     | 2.60  | 24.94 | 0.83      | 1.70  | -   | 6.5, 5.6, 135 | -22.25  | 4301 ± 120° | 5.39 ± 1.50 |
| N4382      | SA0  | 18.5     | 2.52  | 27.06 | 0.76      | 1.82  | -   | 7.1, 5.5, 12.5 | -22.23  | 1110 ± 181° | 1.43 ± 0.23 |
| N4472      | E2   | 16.3     | 1.66  | 41.88 | 0.85      | 3.47  | -   | 10.2, 8.3, 155 | -22.68  | 7813 ± 830° | 6.61 ± 0.70 |
| N4552      | E0-10| 15.3     | 1.67  | 10.82 | 0.83      | 0.98  | -   | 5.1, 4.7, 150 | -21.29  | 984 ± 198° | 2.99 ± 0.60 |
| N4636      | E0-1 | 14.7     | 1.81  | 13.24 | 0.85      | 2.95  | -   | 6.0, 4.7, 150 | -21.33  | 4200 ± 120° | 12.38 ± 0.35 |
| N4649      | E2   | 16.8     | 2.20  | 32.44 | 0.85      | 2.29  | -   | 7.4, 6.0, 105 | -22.38  | 4745 ± 109° | 5.32 ± 1.23 |
| N4697      | E6   | 11.7     | 2.12  | 8.82  | 0.77      | 2.40  | -   | 7.2, 4.7, 70° | -21.16  | 1100 ± 400° | 3.78 ± 1.37 |
| N5866      | SA0  | 15.3     | 1.46  | 9.47  | 0.72      | 1.35  | -   | 4.7, 1.9, 128 | -20.93  | 400 ± 10° | 1.69 ± 0.42 |

By now, Chandra has observed a large number of galaxies with different morphological types and ages. On the other hand, significant progress has been achieved in the accuracy of age-determination techniques and advanced spectroscopical methods have been applied to a large number of galaxies. This motivated us to undertake a systematic study of the dependence of properties of LMXB populations on stellar age. Among such properties, we consider the specific (per unit stellar mass) number and X-ray luminosity of LMXBs and their luminosity distributions. In our analysis, we will take into account possible contamination by the GC sources to the degree allowed by the available GC data.

The paper is structured as follows: In Sect. 2 we describe our selection criteria and the resulting sample. In Sect. 3 we describe the X-ray and infrared data preparation and analysis. In Sect. 4 we discuss average scaling relations for LMXBs and their average XLFs. Dependence of the LMXB numbers and luminosity distribution on stellar age is discussed in Sect. 5. In Sect. 6 we consider the origin of the luminous X-ray sources in early-type galaxies and their dependence on age. In Sect. 8 we discuss caveats and implications of our results. Finally, our results are summarized in Sect. 9.

2. The sample

Our goal was to build the largest possible sample covering the widest possible range of stellar ages. The size of the sample, however, was limited by the content of the Chandra archive and by the published age determinations. Our selection criteria were the following. Firstly we selected all early-type (E/S0) galaxies available in the Chandra archive. We cross-correlated this list with publications on stellar age determinations, leaving only galaxies for which reliable age determinations are available (see below). From the remaining galaxies, we selected only the ones located within the distance of ~ 25 Mpc, which ensures a source detection sensitivity of better than 5 · 10^{-17} erg/s in less than 150 ksec of Chandra observation. Then we chose massive systems with $L_K > 5 · 10^{10} L_{K,0}$ to guarantee the presence of a statistically meaningful number of LMXBs (≥ 20) above the Chandra sensitivity limit. Finally, we excluded galaxies with ongoing or very recent star formation since the stellar content in such galaxies is likely to be inhomogeneous.

In total, we selected 20 galaxies with the integrated $K_b$-band luminosity in the relatively narrow range from ~ 8 · 10^{10} to 4 · 10^{11} $L_{K,0}$. The main properties of these galaxies are listed in Table 1. Chandra detection sensitivity ($L_{lim}$), which is defined as 60% completeness level (Sect. 5.3), of LMXBs in the study field (Sect. 5.1), ranges from ~ 4 · 10^{16} to 10^{18} erg/s (Table 3). This ensures that there is a statistically meaningful number of compact sources in each galaxy.
Zhongli Zhang et al.: Stellar age dependence of LMXB population in early-type galaxies

2.1. The stellar age

The most accurate and widely used method of age determination of elliptical galaxies is the spectroscopic estimator, which compares observed strength of absorption lines of age-sensitive elements with predictions from the simple stellar population (SSP) synthesis models. A number of such measurements for different galaxy samples are published in the literature, e.g., Trager et al. (2000), Kuntschner et al. (2001), Terlevich & Forbes (2002), Caldwell et al. (2003), Thomas et al. (2005), Annibali et al. (2007), Gallagher et al. (2008). It is known that contamination by gas emission is one of the most important factors affecting the accuracy of age determination. Therefore, for galaxies with more than one measurement, we chose those correcting gas emission in a more rigorous way, and prioritized the age-determination studies in the following order: 1) Annibali et al. (2007), 2) Sánchez-Blázquez et al. (2006), and 3) Terlevich & Forbes (2002). These three papers contain ages for 18 galaxies in our sample. They are summarized in Table 2, where for each galaxy we also list the adopted age. Two galaxies (NGC 3923 and NGC 4125) are not covered by these measurements. We adopted their ages from Thomas et al. (2005) for NGC 3923 and from Schweizer & Seitzer (1992) for NGC 4125.

The accuracy and limitations of age determination and its impact on our results are discussed in Sect. 7.1.

2.2. The GC content

To characterize the GC content of a galaxy, we use the GC specific frequency ($S_N$), which is conventionally defined by the relation $S_N = N_{GC}(10^3h_{75}d^{-1}+15)$ (Harris 1991). As this parameter is sensitive to the assumed distance to the galaxy, the sensitivity limit, and the completeness of the optical data, we collected the most accurate measurements of the total number of GCs ($N_{GC}$) in our galaxies and then computed $S_N$ with the distances used in this paper. For two galaxies, NGC 3585 and NGC 4125, $N_{GC}$ were not available, and we used the local $S_N$ from Humphrey (2009) as an approximation of its global value. All values of $S_N$ are listed in Table 1 and caveats are discussed in Sect. 7.2.

Table 2. Stellar age measurements.

| Galaxy  | Age1 (Gyr) | Age2 (Gyr) | Age3 (Gyr) | Adopted age (Gyr) |
|---------|------------|------------|------------|-------------------|
| YN720   | 3.4        | 3.4        |            |                   |
| YN821   | 5.2 ± 1.5  | 5.2 ± 1.5  |            |                   |
| N1052   | 14.5 ± 4.2 | 14.5 ± 4.2 |            |                   |
| YN1380  | 4.4 ± 0.7  | 4.4 ± 0.7  |            |                   |
| YN1404  | 5.9        | 5.9        |            |                   |
| N3115   | 8.4 ± 1.1  | 8.4 ± 1.1  |            |                   |
| N3379   | 8.2 ± 1.1  | 8.2 ± 1.1  |            |                   |
| YN3585  | 3.1        | 3.1        |            |                   |
| YN3923  | 3.3 ± 0.8  |            |            |                   |
| YN4125  | 5.0        |            |            |                   |
| N4278   | 12.5 ± 1.2 | 10.7       | 12.5 ± 1.2 |                   |
| N4365   | 7.9 ± 1.2  | 7.9 ± 1.2  |            |                   |
| N4374   | 9.8 ± 3.4  | 11.3 ± 1.3 | 11.8       | 9.8 ± 3.4         |
| YN4382  | 1.6        | 1.6        |            |                   |
| N4472   | 9.6 ± 1.2  | 8.5        | 9.6 ± 1.2  |                   |
| YN4550  | 6.0 ± 1.4  | 12.4 ± 1.2 | 9.6        | 6.0 ± 1.4         |
| N4636   | 13.5 ± 3.6 | 10.3 ± 1.3 | 13.5 ± 3.6 |                   |
| N4649   | 16.9 ± 2.3 | 11.0       | 16.9 ± 2.3 |                   |
| N4967   | 10.0 ± 1.4 | 5.9 ± 1.2  | 8.2        | 10.0 ± 1.4        |
| YN5660  | 1.8        | 1.8        |            |                   |

Ages for NGC 3923 and NGC 4125 are not covered by these measurements. We adopted their ages from Thomas et al. (2005) for two galaxies, NGC 3923 and from Schweizer & Seitzer (1992) respectively. Galaxies marked by “Y” are classified as young galaxies in the Sect. 5.2, the remaining galaxies are classified as old.

Table 3. Chandra observations.

| Galaxy   | Observation ID | Exposure (ks) | $L_{min}$ (erg/s) | $L_{min}$ (erg/s) |
|----------|---------------|---------------|-------------------|-------------------|
| YN720    | 492,7062,7372’ | 8448,8449     | 138.8             | 3.6              |
| YN821    | 4006,4408,5691,6310 | 212.9         | 1.3               | 2.8              |
| N1052    | 5910          | 59.2          | 3.1               | 6.3              |
| N1380    | 9526          | 416.1         | 3.9               | 6.1              |
| N1404    | 2942,4174’,9798,9799 | 114.5        | 2.4               | 11.7             |
| N3115    | 2040,11268,12095’ | 153.2        | 0.3               | 0.7              |
| N3379    | 1587,7073’–7076 | 337.0        | 0.06              | 0.42             |
| N3585    | 2078,9506’    | 94.7          | 2.3               | 4.1              |
| N4125    | 1563,9507’    | 102.1         | 2.6               | 6.3              |
| N4278    | 2071          | 64.2          | 3.0               | 8.9              |
| N4365    | 2003,5908’,6131 | 470.8        | 0.32              | 0.88             |
| N4382    | 2015’,5921–5924,7224 | 195.8       | 1.0               | 2.5              |
| N4374    | 803,5908’,6131 | 115.5         | 0.8               | 4.9              |
| N4472    | 321’,322,11274 | 89.6          | 0.58              | 5.6              |
| N4532    | 2072          | 54.4          | 1.3               | 4.5              |
| N4636    | 323,324,3926,4415’ | 209.8       | 0.13              | 3.9              |
| N4649    | 785,8182’,8507 | 108.0         | 2.1               | 6.8              |
| N4697    | 784,4727–4730’ | 193.0         | 0.41              | 0.83             |
| N5866    | 2879          | 33.7          | 2.1               | 4.7              |

(1) – Galaxy name. (2) – Chandra observation IDs. (3) – Total exposure time of Chandra observations. (4) – The 0.5-8 keV luminosity of the faintest source detected, and the luminosity corresponding to the 60% completeness in the study field (computed assuming that the spatial distribution of LMXBs follows the $K_s$-band light). The luminosities are in the units of $10^{37}$ erg/s.
angle following D25). We define the region outside the central 5″ inside D25 as the study field throughout this paper. The total number of point sources detected in the study field is listed in Table 4.

To estimate the source counts, we applied circular aperture centered on the central coordinates (output of wavdetect) of each source. We defined the source region as including 85% of the local point spread function (PSF) value. The PSF file was extracted by CIAO task mkpsf from each image, then combined together for multiple observations. The background region was defined as three times the radius of the source region. We excluded the source regions from background regions with overlapping neighboring sources. The source net counts (with the majority in the source region and minority in the background region), and errors were then computed by the equations (1) and (2) in Voss & Gilfanov (2007). To convert the absorbed source count rates into unabsorbed luminosities in 0.5-8 keV, we assumed a power-law spectrum ($\Gamma = 1.7$) with galactic absorption. We listed the faintest source detected in each galaxy in Table 4 and the total number of point sources above $L_{\text{lim}}$ in Table 4.

### 3.2. Cosmic X-ray background sources

We estimated the cosmic X-ray background (CXB) sources (most of which are background active galactic nucleus (AGN)), using the full band (0.5-10 keV) log($N$)-log($S$) distribution of CXB sources from Georgakakis et al. (2008) and converted the flux to the 0.5-8 keV band, assuming a power-law spectrum with a photon index of 1.4. The total number of CXB sources among all detected point sources and point sources above $L_{\text{lim}}$ in the study field are listed in Table 4, the model was corrected by the incompleteness function of CXB sources derived in Sect. 3.3.

In most galaxies, CXB sources contribute less than 15% of the total X-ray population, except for NGC 3379 and NGC 4382, where the contribution is somewhat higher (25-30%), however, essential statistics sustain for the LMXB study. As well known, CXB source density is subject to field-to-field variations due to the cosmic variance. These variations limit the accuracy of the CXB level predictions based on the source counts in selected extragalactic fields to ~ 10 – 30% of the predicted CXB value, depending on the solid angle. As the CXB contribution to the total number of sources is rather small, these uncertainties are relatively unimportant in most of the luminosity range. The situation changes in the bright end of the XLF, where the cosmic variance becomes the major limiting factor in our analysis.

### 3.3. X-ray incompleteness correction

The detection sensitivity of point sources varies throughout the Chandra images. Reasons include the inhomogeneous level of the diffuse X-ray emission in the galaxy, the deterioration of the PSF at large off-axis angles, and the nonuniform exposure of an image in which observations with different pointings are combined. To calculate the point source detection sensitivity, we used the method and code from Voss & Gilfanov (2006), in which the detection method was inverted using the local PSF, background, and exposure. The incompleteness function $K(L)$ is computed as the fraction of pixels weighted by the assumed spatial distribution of sources, in which detection sensitivity is better (lower value) than the given luminosity. We calculated $K(L)$ separately for the CXB sources and LMXBs, while the CXB sources have a flat distribution, while the field LMXBs are expected to follow the $K_s$-band light (for which we used

| Galaxy | $N_{\text{tot, CXB}}$ | $N_{\text{lim, CXB}}$ | $N_{\text{lim, CXB}}$ | $N_{\text{lim, CXB}}$ | $N_{\text{lim, CXB}}$ | $L_K$ | $M_L$ |
|--------|----------------|----------------|----------------|----------------|----------------|--------|-------|
| N720   | 79             | 5.9            | 60             | 4.8            | 60.8           | 19.01  | 16.34 |
| N821   | 39             | 3.3            | 38             | 3.1            | 36.0           | 7.02   | 5.76  |
| N1052  | 41             | 2.5            | 35             | 2.2            | 35.4           | 7.42   | 5.93  |
| N1380  | 36             | 3.9            | 38             | 3.4            | 28.0           | 10.99  | 8.90  |
| N1404  | 33             | 3.6            | 18             | 2.5            | 17.9           | 15.14  | 12.87 |
| N3115  | 99             | 11.1           | 89             | 10.2           | 82.8           | 8.51   | 7.06  |
| N3379  | 95             | 23.4           | 87             | 22.9           | 65.8           | 6.89   | 5.72  |
| N3585  | 59             | 6.1            | 56             | 5.8            | 53.9           | 15.73  | 12.11 |
| N3923  | 105            | 10.8           | 83             | 9.8            | 89.6           | 26.36  | 21.61 |
| N4125  | 42             | 8.2            | 27             | 6.6            | 24.2           | 20.98  | 16.78 |
| N4278  | 177            | 16.3           | 160            | 14.9           | 154.2          | 6.71   | 5.24  |
| N4365  | 244            | 23.9           | 213            | 22.5           | 201.1          | 18.87  | 16.04 |
| N4374  | 133            | 18.1           | 88             | 13.9           | 91.5           | 22.33  | 18.53 |
| N4382  | 52             | 13.5           | 44             | 12.3           | 33.1           | 25.14  | 19.11 |
| N4472  | 238            | 26.3           | 171            | 24.0           | 171.6          | 39.71  | 33.76 |
| N4552  | 94             | 10.4           | 68             | 7.6            | 70.7           | 9.07   | 7.52  |
| N4636  | 123            | 12.2           | 82             | 9.1            | 83.6           | 11.39  | 9.22  |
| N4649  | 236            | 15.0           | 149            | 10.7           | 168.5          | 28.97  | 24.62 |
| N4697  | 120            | 22.4           | 107            | 21.4           | 85.9           | 7.96   | 6.13  |
| N5866  | 29             | 3.1            | 23             | 2.7            | 21.5           | 8.45   | 6.09  |

| Total  | 2074           | 240.0          | 1626           | 210.4          | 15761          | 316.6  | 259.4 |

(1) – Galaxy name. (2) and (4) – Number of all resolved X-ray point sources and sources brighter than $l_{\text{lim}}$. (3) – Predicted number of CXB sources among (2) and (4). (6) – Total number of LMXBs above $l_{\text{lim}}$ after incompleteness correction and CXB subtraction. (7) and (8) – Total $K_s$-band luminosity and stellar mass (in units of $10^{10} L_{\odot}$ and $10^{10} M_{\odot}$) in the study field.

To estimate the incompleteness-corrected number of LMXBs in the study field in each galaxy, we did incompleteness correction for the number of all resolved point sources, assuming $K(L)$ for the field LMXBs, and then subtracted the corresponding number of CXB sources. This procedure is described by the equation

$$N_{\text{LMXB}} = \frac{1}{K_{\text{LMXB}}(L)} \int_{L_{\text{lim}}}^{L_{\text{max}}} 4\pi D^2 \frac{dN_{\text{CXB}}}{dL} \frac{K_{\text{CXB}}(L)}{K_{\text{LMXB}}(L)} dL,$$

where $4\pi D^2 dN_{\text{CXB}}/dL$ equals $dN_{\text{CXB}}/dS$, which is the log($N$) – log($S$) distribution of the CXB sources. We listed the total number of LMXBs above $l_{\text{lim}}$, CXB subtracted and incompleteness corrected, in Table 4.

#### 3.4. Near-infrared data analysis

We calculated the stellar mass in the study field from near-infrared data, using the $K_s$ (2.16 μm) images from the 2MASS Large Galaxy Atlas (Jarrett et al. 2003) provided by the NASA/IPAC Infrared Science archive. Most images are background subtracted, except for NGC 821, for which we obtained the background from adjacent regions. We also removed the contamination of bright foreground point sources from images visually. The integrated, point source- and background-subtracted count rate ($\dot{S}$) was converted into calibrated magni-
Quantitatively, we detected 24 sources above 10
should be made. The more recent work of Georgakakis et al.
CXB log(\(S\)) found that they can fully account for the observed bright sources, as shown by the dotted line in Fig. 1. In computing this predic-
a low probability of
Its normalization, however, is somewhat higher than predicted
similar to the slope of the predicted distribution of CXB sources.
observed source counts in this luminosity range, whose slope is
38, where it accounts for approximately 10% of the observed
compact sources detected within the study fields of galaxies.

Figure 1 presents the combined luminosity distribution of all X-
4.1. XLF of compact sources and the CXB contribution
Figure 1 presents the combined luminosity distribution of all X-
Due to quick declining of the LMXB XLF in the log(\(L_X\)) ~
38.5 – 39 range, an accurate account of the CXB contribution
becomes crucial at log(\(L_X\)) ~ 39. There is an apparent tail of the
observed source counts in this luminosity range, whose slope is
similar to the slope of the predicted distribution of CXB sources.
Its normalization, however, is somewhat higher than predicted
by the CXB log(N) – log(S) from Georgakakis et al. (2008).
Quantitatively, we detected 24 sources above 10^{39} erg/s, while
11.8 background AGN in these fields is predicted, based on Georgakakis et al. (2008). The Poissonian distribution predicts
a low probability of ~ 1.2 · 10^{-3} for such a deviation solely due
to random fluctuations. We also checked the predictions of the
CXB log(N) – log(S) determined by Moretti et al. (2003) and
found that they can fully account for the observed bright sources,
as shown by the dotted line in Fig. 1. In computing this predic-
tion, we used the soft band (0.5–2 keV) counts and converted
them to the 0.5–8 keV band, as described in Zhang et al. (2011).

Comparing the two predictions, the following remarks
should be made. The more recent work of Georgakakis et al.

4. Average XLF and scaling relations for LMXBs

4.1. XLF of compact sources and the CXB contribution

The CXB-subtracted and incompleteness-corrected cumulative
XLFs of compact X-ray sources in each galaxy are plotted in Fig. 2. As LMXBs are almost the only type of compact X-
ray source in early-type galaxies capable of emitting at the
log(\(L_X\)) ~ 36 luminosity level, the distributions shown in Fig. 2
can be regarded as luminosity functions of LMXBs in these
galaxies. The XLFs have been normalized to unit stellar mass in
the study field. It is clear that all the XLFs have a similar shape,
which is broadly consistent with the average XLF of LMXBs in
nearby galaxies obtained by Gilfanov (2004) (plotted with the
thick line in the figure). On the other hand, a notable scatter of
more than a factor of two exists for the normalization, which is
a manifestation of the scatter in the LMXB-stellar mass relation,
as discussed below.

To construct combined XLF of all galaxies with differ-
ent detection sensitivity, we followed the method described in
Zhang et al. (2011). The cumulative and differential forms of our
XLF are plotted in Fig. 3. We fitted the combined XLF with the
template introduced in Gilfanov (2004):

\[
\frac{dN}{dL_{36}} = \left\{ \begin{array}{ll}
K_1 \left( \frac{L_{36}}{L_{b_1}} \right)^{-\alpha_1}, & L_{36} < L_{b_1} \\
K_2 \left( \frac{L_{36}}{L_{b_2}} \right)^{-\alpha_2}, & L_{b_1} < L_{36} < L_{b_2} \\
K_3 \left( \frac{L_{36}}{L_{cut}} \right)^{-\alpha_3}, & L_{b_2} < L_{36} < L_{cut} \\
0, & L_{36} > L_{cut}
\end{array} \right.
\]

(2)
where \( L_3 = L_X/10^{36} \) erg/s and normalizations \( K_{1,2,3} \) are related by:

\[
K_3 = K_1 (L_{b,1}/L_{b,2})^{\alpha_1}, \\
K_3 = K_2 (L_{b,2}/L_{cut})^{\alpha_2}.
\]

The value of the high-luminosity cut-off was fixed at \( L_{cut} = 5 \cdot 10^7 \) erg/s. We performed maximum-likelihood fitting to the unbinned data. Our best-fit parameters with 1\( \sigma \) errors are: \( \alpha_1 = 1.02^{+0.07}_{-0.08} \), \( \alpha_2 = 2.06^{+0.06}_{-0.05} \), \( \alpha_3 = 3.63^{+0.67}_{-0.49} \), \( L_{b,1} = 54.6^{+4.4}_{-3.2} \), and \( L_{b,2} = 599^{+95}_{-67} \). The normalization is \( K_3 = 1.01 \pm 0.28 \) per \( 10^{11} M_\odot \).

The combined XLF obtained in this study is broadly consistent with the average LMXB XLF obtained by Gifanov (2004) (cf. dotted line in Fig. 3). The XLF of the sources in our sample appears to be somewhat flatter in the bright end of \( \log(L_X) \gtrsim 38.5 \), having more luminous sources. As evident in Sect. 5.2, this is related to the large fraction of younger galaxies in our sample. Additionally, there is a rather peculiar tail of luminous sources above \( \log(L_X) \gtrsim 39 \), which will be discussed in Sect. 6.

4.3. Scaling relations for LMXBs

By definition, the present sample is not designed for detailed analysis of scaling relations of LMXBs with stellar mass, since selected galaxies occupy a rather narrow range of masses (less than a factor of \( \lesssim 7 \)). The XLF analysis presented above suggests that our data is generally consistent with the \( N_X - M \) and \( L_X - M \) dependence obtained previously. This is analyzed below.

5. Dependence on stellar age and GC content

5.1. Correlation of LMXBs with age and GC content of the host galaxy

To characterize the number of LMXBs per unit stellar mass in each galaxy, we used the following quantity

\[
f_{XLF} = \frac{N_X(L > L_{lim}) - N_{CXB}(L > L_{lim})}{M_* \times \int_{L_{lim}}^{L_X} F(L) K_{LMXB}(L) dL},
\]

where \( N_X(L > L_{lim}) \) and \( N_{CXB}(L > L_{lim}) \) are the numbers of detected X-ray sources and predicted CXB sources (Table 3), \( F(L) \) is the best-fit differential XLF normalized to \( 10^{11} M_\odot \), \( M_* \) is the stellar mass in units of \( 10^{11} M_\odot \), and \( K_{LMXB}(L) \) is the incompleteness function of LMXBs in the given galaxy. The so-defined \( f_{XLF} \) is the specific (per \( 10^{11} M_\odot \)) XLF normalization.
computed from the number of resolved LMXBs above $L_{\text{lim}}$, assuming the average XLF shape of the resolved sources, modified by the point-source detection incompleteness. For the average XLF, we used the best-fit model from Sect. 4. With this definition, the $f_{\text{XLF}}$ equals 1 corresponds to 5.4 LMXBs with luminosity $L_X > 5 \times 10^{37}$ erg/s per $10^{10} M_\odot$.

Obviously, $f_{\text{XLF}}$ has the advantage that all detected X-ray sources above 0.6 incompleteness level are involved in the calculation. The disadvantage is that it relies on the assumption that the XLF shape does not change from galaxy to galaxy. However, it is known that the XLFs of GC and field LMXBs are different (Zhang et al. 2011), as well as the LMXBs in young and old galaxies (Kim & Fabbiano 2010). The systematic bias can be further amplified by the fact that different galaxies have different values of $L_{\text{lim}}$. To investigate the importance of these effects, we computed $f_{\text{XLF}}$ for several galaxies using the average XLFs for young and old galaxies (see the next section) and found that they differ by no more than ~ 30%. This is insignificant given the scatter of the points and the amplitude of the correlations found below. As a further check, we recomputed $f_{\text{XLF}}$ in the luminosity range of $5 \times 10^{37}$ to $5 \times 10^{38}$ erg/s where both effects are minimal. We did not find any systematic changes in our results.

We plot $f_{\text{XLF}}$ versus stellar age and $S_N$ in Fig. 5. Both plots show moderate trends that the $f_{\text{XLF}}$ increases with the stellar age of the host galaxy and its GC content. Despite rather large scatter of the points, the Spearman rank-order correlation test gives the null hypothesis probability of $p = 0.003$ for the age- and much larger value of $p = 0.017$ for the $S_N$-dependence. These numbers indicate a moderately significant correlation of ~ 2.5 – $3\sigma$.

The correlation of $f_{\text{XLF}}$ with $S_N$ is similar to the one found in previous studies (e.g. Humphrey & Buote 2008; Boroson et al. 2011). The presence of such correlation was interpreted as evidence suggesting that a significant part (if not all) of the LMXB population, including the field sources, was formed in GCs and subsequently expelled into the field. The existence of the equally strong correlation of the specific LMXB frequency with the age of the stellar population suggests that this interpretation is not unique and the more important correlation may be with the stellar age.

In order to investigate this further, we fit the data with a two-parameter linear model in the form $f_{\text{XLF}} = a \times t + b \times S_N + c$. Using $\chi^2$ minimization, we found the following values of best-fit parameters: $a = 0.044 \pm 0.008$, $b = 0.049 \pm 0.012$, $c = 0.385 \pm 0.047$, with a very large value of $\chi^2 = 129.7$ for 17 d.o.f. With these best-fit values the contribution of the age term is about two times larger than the contribution of the $S_N$ term, suggesting that the more important parameter is the age, rather than the GC content of the host galaxy. However, because of the rather large dispersion of the points and correspondingly large value of $\chi^2$, any firm conclusion is premature.

The average values of $f_{\text{XLF}}$ for galaxies younger and older than 6 Gyr are 0.75 ± 0.08 and 1.08 ± 0.06, respectively. The statistical significance of the difference between these two values is $\approx 3.3 \sigma$, in agreement with the Spearman test results. The total number of LMXBs per unit stellar mass above $5 \times 10^{37}$ erg/s in the young galaxy sample is 4.17 ± 0.27, which is $\sim 2/3$ of that in the old (6.27 ± 0.26). The prediction from the average XLF is 5.4.

### 5.2. XLFs of young and old galaxies

In order to investigate the age dependence of the LMXB XLFs, we divided galaxies into young and old groups using their median age (6 Gyr) as a boundary. Each group contains ten galaxies, which are marked correspondingly in Table 2. The study regions in young and old galaxies cover a total solid angle of 125.9 and 251.6 arcmin$^2$ respectively, with a total stellar mass of 1.28 and $1.32 \times 10^{12}$ $M_\odot$.

We constructed combined XLF of each group and plotted them in Fig. 6. In general, older galaxies have deeper Chandra observations that have reached a sensitivity of $\sim 5 \times 10^{36}$ erg/s, while the young group has a sensitivity of $\sim 3 \times 10^{37}$ erg/s. The overall shape of the XLF for young galaxies is flatter than that of the old ones. This behavior is in agreement with findings of Kim & Fabbiano (2010).

Similarly, we use the median value of the $S_N$ distribution ($S_N = 2.0$) to divide galaxies into GC-rich and GC-poor subgroups. The resulting XLFs are shown in Fig. 7. As expected from the age dependence of the XLF and the general correlation between age and $S_N$, the combined XLF of GC-rich galaxies is steeper than that of the GC-poor ones. However, unlike XLFs of young and old galaxies, they appear to be similar in the bright end $\log(L_X) \approx 38.5 - 39$.

### 6. Nature of (ultra-) luminous X-ray sources

After subtracting the contribution of background sources, a rather peculiar tail of luminous sources with $\log(L_X) \gtrsim 39$ remains (Fig. 3). Although the CXB contribution is insignificant throughout most of the luminosity range, its correct subtraction is critical for establishing the nature of bright sources. In total, we detected 24 compact sources with luminosity exceeding $10^{39}$ erg/s. Subtracting from this number the 11.8 back-
Fig. 5. Correlation of the XLF normalization, \( f_{XLF} \) (Eq. 3), with stellar age (left) and \( S_N \) (right). Circles mark galaxies with \( S_N > 2.0 \) (left panel), and squares mark galaxies with the stellar age >6 Gyr (right panel).

Table 5. Sources brighter than 10\(^{39}\) erg/s.

| Galaxy  | RA(J2000)   | DEC(J2000)   | Luminosity | D25 opt. |
|---------|-------------|--------------|------------|----------|
|         |             |              |            |          |
| Young Galaxies (< 6 Gyrs) |
| N720    | +01:52:56.50 | -13:43:47.77 | 1.04 ± 0.08 | 0.55 GC  |
|         | +01:53:06.43 | -13:45:40.58 | 1.08 ± 0.08 | 0.86 –   |
|         | +01:52:55.82 | -13:43:50.90 | 1.14 ± 0.08 | 0.67 –   |
|         | +01:52:59.39 | -13:43:57.28 | 1.17 ± 0.08 | 0.19 GC  |
|         | +01:53:01.12 | -13:44:19.53 | 1.52 ± 0.08 | 0.10 –   |
| N1380   | +03:36:26.56 | -34:56:58.96 | 1.09 ± 0.09 | 0.73 –   |
|         | +03:36:25.25 | -34:59:18.09 | 3.51 ± 0.04 | 0.47 –   |
| N1404   | +03:38:51.99 | -35:35:93.93 | 1.14 ± 0.07 | 0.20 –   |
|         | +03:38:54.78 | -35:35:00.96 | 1.21 ± 0.07 | 0.57 –   |
| N3923   | +11:50:58.65 | -28:49:13.16 | 1.31 ± 0.08 | 0.38 –   |
|         | +11:51:09.54 | -28:48:00.67 | 2.98 ± 0.12 | 0.68 –   |
|         | +11:51:06.22 | -28:46:49.91 | 3.50 ± 0.13 | 0.65 Q   |
| N4125   | +12:08:07.46 | +65:10:28.61 | 7.41 ± 0.23 | 0.05 –   |
| N4382   | +12:25:20.32 | +18:13:01.41 | 1.12 ± 0.09 | 0.58 –   |
|         | +12:25:17.17 | +18:13:46.52 | 3.76 ± 0.18 | 0.93 Q   |
| N4552   | +12:35:45.77 | +12:33:02.46 | 1.14 ± 0.06 | 0.61 GC  |
|         | +12:35:41.22 | +12:34:51.43 | 1.18 ± 0.06 | 0.62 GC  |
| Old Galaxies (> 6 Gyrs) |
| N3379   | +10:47:50.01 | +12:34:56.77 | 2.14 ± 0.03 | 0.04 –   |
| N4365   | +12:24:26.36 | +10:16:53.55 | 1.53 ± 0.05 | 0.71 –   |
| N4374   | +12:25:11.92 | +12:51:53.81 | 10.38 ± 0.16 | 0.74 Q |
| N4472   | +12:29:41.00 | +07:57:44.46 | 1.96 ± 0.08 | 0.62 GC  |
|         | +12:29:34.46 | +07:58:51.63 | 1.33 ± 0.06 | 0.79 G   |
|         | +12:29:42.33 | +08:00:07.96 | 1.02 ± 0.05 | 0.25 GC  |
| N4649   | +12:43:46.90 | +11:32:34.19 | 1.54 ± 0.06 | 0.48 –   |

Columns are the host galaxy name, coordinates, luminosity in units of 10\(^{39}\) erg/s, offset from the center in units of the D25 radius, optical counterpart from NED (Q: Quasi-stellar object, GC: globular cluster, G: galaxy).

On the other hand, it is well known that the CXB source counts produce somewhat different results in different sky fields due to cosmic variance. Moreover, the slope of the bright tail of the luminosity distribution of all compact sources in Fig. 3 is similar to the slope of the CXB \( \log(N) - \log(S) \). It is therefore possible that the tail of bright sources in Fig. 3 is due to background AGN, which is unaccounted for due to cosmic variance. The amplitude of CXB source density variations depends primarily on the considered angular scales and decreases as the solid angle increases. Because we combined data from 20 galaxies distributed over the extragalactic sky, we do not expect cos-

ground AGN predicted from the Georgakakis et al. (2008) CXB \( \log(N) - \log(S) \), we obtain that \( \sim 12 \) – 13 sources should be associated with galaxies from our sample. Similarly, among sources with \( L_X > 2 \cdot 10^{39} \) erg/s (7 sources observed, 4.3 background AGN predicted), \( \sim 2 \) – 3 sources are expected to be associated with galaxies. Assuming Poissonian distribution, these numbers correspond to moderately low probabilities of being a result of pure statistical fluctuations: \( \sim 1.2 \cdot 10^{-3} \) and 0.14 for the two luminosity ranges, suggesting that the luminous sources may indeed be X-ray binaries.
mic variance to be particularly strong in the combined LMXB XLFs shown in Figs. 4 and 5. In order to investigate this further, we checked the source numbers outside the D25 but within ∼ 10′ × 10′ around the aim point of the Chandra observation. In total 41 sources with log($L_x$) > 39 were detected, while the CXB log($N/\sigma$) of Georgakis et al. (2008) predicts 49.8 background AGN. These two numbers are consistent within ∼ 1.4σ, which suggests that the effect of cosmic variance is not very strong. Moreover, the observed local CXB source density is ∼ 20% lower than predicted, i.e., in computing the LMXB XLF observed at lower luminosities. The luminosities of these sources, up to ∼ 3 · 7 · 10^39 erg/s, are compatible with, or exceed only slightly, the Eddington limit for a ∼ 10 M_\odot black hole. We therefore believe that most likely these sources are stellar mass black holes accreting from a low or intermediate mass companion. In the case of an evolved companion, such systems may be transient sources (King et al. 1997; Pro & Bildsten 2002). In order to check this possibility, we investigated the variability of those luminous sources for which multiple observations were available. Although bright sources show significant variability, we did not find any evidence for transient behavior up to a factor of ∼ 5.

7. Caveats and uncertainties

The accuracy of our conclusions obviously depends on the accuracy of the quantities used to characterize stellar ages and GC content of galaxies. However, both quantities are subject to several, currently unavoidable, uncertainties. In the following subsections, we discuss these uncertainties in detail.

7.1. Stellar age determinations

Stellar age determinations are based on the comparison of the strengths of the absorption lines of age-sensitive elements with predictions from the stellar synthesis models. In the core of their algorithms lies the assumption of SSP. The SSP assumption is obviously oversimplified picture of the stellar populations in early-type galaxies. This is especially true when the entire galaxy is characterized by a single value of the stellar age. In this case, the problem can be addressed considering the spatially resolved stellar age maps, as discussed below. It is more complicated when a small fraction of the young population is mixed with the older underlying population, thus biasing the SSP-equivalent age towards younger ages (e.g., Salim &Rich 2010; Marino et al. 2011). In this case, more sophisticated assumptions regarding the stellar population content have to be made. At present, such analysis is not available for a sufficiently large number of galaxies for statistically meaningful study. Also, the complexity of the answer obtained in this case would not allow an analysis in terms of simple age–$\phi_{\text{XLF}}$ plots.

More “technical” issues also affect the outcome of age determination in each particular galaxy. These include, for example, differences in the correction for the ionized gas emission, in the
selection of absorption lines used for fitting the spectral population models, and in the choice of libraries of stellar population synthesis models (see, e.g., Annibali et al. 2007). As a result, there is a spread of values obtained by different authors that is sometimes rather large. We tried to minimize the effect of these issues by assigning priorities to different age determinations, as described in the Sect. 2.1.

Many of the age measurements analyze the spectrum of the very small central region of the galaxy, usually corresponding to $r_e/8$, where $r_e$ is the effective radius of the galaxy with a typical size of 30″. As LMXBs are rare objects, their numbers inside $r_e/8$ detected in a typical Chandra observation of a typical galaxy are by far too insufficient for any statistically meaningful analysis. On the contrary, to increase their numbers, LMXBs are collected from a region whose size is comparable with the D25 diameter. Moreover, the central region of the size of ~ few arcsec is usually excluded from the X-ray point source analysis in order to exclude from the analysis the central (weak) AGN, peaked diffuse emission, and source confusion. Thus, the LMXBs and age measurements are inevitably performed in geometrically different, sometimes barely overlapping regions of the galaxy. Obviously, such analysis requires an assumption of the homogeneity of the stellar population, which may not be fulfilled in all cases. The statistical study of Tortora et al. (2010) investigated a sample of ~50000 nearby galaxies with the Sloan Digital Sky Survey data. Their results show no age gradient for massive early-type galaxies ($> 10^8 M_\odot$) with a central age older than 6 Gyr, while for the ones with a central age younger than 6 Gyr, age gradients can be as big as $\nabla_{\text{age}} \sim 0.4$ (2.5 times difference). Based on the spatially resolved age maps delivered by the SAURON project (Kuntschner et al. 2010) came to a similar conclusion. This result suggests that the ages of old galaxies in our sample should be on average sufficiently reliable, whereas an additional scatter of a factor of ~ 2 along the age axis may be possible for younger galaxies. Evidence for such behavior can possibly be seen in Fig.6.

To investigate this further, we searched for individual studies of the age gradients galaxy by galaxy. The six galaxies included in the SAURON sample (NGC 821, NGC 3379, NGC 4278, NGC 4374, NGC 4382, and NGC 4552) do not have significant age gradients. Based on the long-slit spectroscopy results, we found evidence for complicated age structure in the following galaxies. NGC 720 was suggested to have been formed by a merger of an old (5-13 Gyr) small-scale spheroid and a younger (2.5-5 Gyr) large-scale disk component (Rembold et al. 2005), meaning that the average stellar age of NGC 720 should be older than 3 Gyr value adopted in this paper. NGC 4125 was found to have experienced a recent merger event: thus young stellar components likely exist in this galaxy (Pu et al. 2010). NGC 4365 is likely to be older than 7.9 Gyr, as the results of Davies et al. (2001) suggest that the decoupled core and the main body of the galaxy have the same age of ~14 Gyr. With these numbers, the data points for NGC 720 and NGC 4365 should shift to the right in the left-hand panel of Fig.5, while NGC 4125 may shift to the left. Such a correction will reduce the scatter on this plot. No such detailed studies could be found for other galaxies from our sample. This analysis confirms that at least a part of the scatter on the age – f_{XLF} plot is due to complexities of the age structure of the early-type galaxies.

The above discussion suggests a promising venue for future studies, based on the comparison of the spatial distribution of compact sources with spatially resolved stellar age maps. This is similar to the analysis conducted by Shykovskiy & Gilfanov (2007) for high-mass X-ray binaries, based on the comparison of their spatial distribution with spatially resolved star-formation history in the Small Magellanic Cloud. The outcome of such an analysis would be the full-time dependence of the LMXB population passed from the star-formation event.

7.2. Specific frequency of GCs ($S_N$)

The main complication in determining the GC content is the lack of uniform optical data suitable for this purpose, in particular individual GC lists for all galaxies. For this reason, we had to rely on the published total numbers of GC candidates detected in each galaxy to calculate the $S_N$. Since LMXBs are collected from the D25 region of each galaxy, GCs in the same region should be counted. However, published numbers often referred to different regions. For example, the HST data typically covered regions smaller than D25, while the data from ground-based telescopes often had a larger field of view. Because we compute V-band luminosity for the same region where GCs are counted, this would not matter if the spatial distribution of GCs followed that of stellar light. However, GCs are known to have a broader distribution than stars (Bassino et al. 2006), so the value of $S_N$ depends on the spatial region over which it was computed. For example, the $S_N$ values measured from the HST data (e.g., Humphreys 2009, Peng et al. 2008) is on average smaller than the ones determined by the ground-based telescopes (see references in Table 1).

The picture is further complicated by the fact that red (metal-rich) GCs are more concentrated toward the galaxy centers, more accurately tracing the stellar population, while the blue (metal-poor) GCs are often more extended (e.g., Bassino et al. 2006). Since there are approximately three times as many LMXBs in red GCs as in blue GCs (e.g., Bellazzini et al. 1995), an accurate selection of the spatial regions and, ideally, a separation of the red and blue GCs are important.

Our ability to take these complications into account is limited due to the lack of uniform optical data for the GC systems in the galaxies in our sample. These complications introduce scatter in our data, which currently cannot be eliminated.

7.3. Correlation between stellar age and $S_N$

In our sample, there is a strong correlation between stellar age and $S_N$, as illustrated by Fig.8. Although we did not find any report about such a correlation in the literature, its existence is not surprising because more GCs are expected to be found in older galaxies as a result of more massive GCs being formed in larger star bursts at larger redshifts (Bastian 2008). A significant fraction of these GCs will survive through the following evolution of the galaxy (Fall & Zhang 2001). A detailed investigation of the behavior of $S_N$ and its dependence on the environment and formation history of the host galaxy is beyond the scope of this paper. However, presence of the $S_N$-age correlation (at least in our sample) significantly complicates the separation of the effects of these two factors on the LMXB population.

7.4. Conclusion

There are a number of uncertainties associated with measurements of stellar age and $S_N$. Many of these, for example, age gradients, can be alleviated in principle with more sophisticated analysis of the optical data, e.g., with spatially resolved stellar age maps. On the other hand, proper use of the improved optical data would require better statistics in the X-ray data. Indeed, as
The uncertainties do not completely wash out the tribute to their dispersion. However, the fact that we detect stationary galaxies. This is further supported by the correlation between the data points in the age–

Obviously, the age and XLFs of GC sources in the log(L_X) ≥ 37 luminosity range is flatter than that of the field sources (see, e.g., their Fig.7). Therefore, as older galaxies have larger GC content, i.e., a larger fraction of dynamically formed binaries, their XLF should be expected to be flatter than the XLF of the young galaxy sample, if the main increase is due to the dynamically formed sources. This prediction is at odds with our observations: the XLF of old galaxies is steeper than that of the young galaxies (see also Kim & Fabbiano 2010). This suggests that the effects of the evolution of the LMXB population are at least comparable to the effect of the increased GC content, if not stronger.

8.2. Comparison with Fragos et al. calculations

Our results appear to be at odds with the population synthesis calculations of Fragos et al. (2008), who predicted a significant decrease of the LMXB population with time. In particular, they predict more than an order of magnitude decrease of the number of LMXBs in the age interval from 5.5 Gyrs to 9.5 Gyrs. Their predictions include the log(L_X) ≥ 37.5 luminosity range, well covered by the Chandra data used here, so that such a significant change in the specific number of sources would clearly reveal itself in our analysis. This is illustrated, for example, by the comparison of our Fig.5 with the Fig.3 in Fragos et al. (2008). Along the same lines, in more recent calculations Fragos et al. (2012) considered the overall evolution of the X-ray binary populations with cosmic time and came to a similar conclusion: that the specific luminosity of LMXBs per unit stellar mass in the Universe is decreasing by about an order of magnitude between the redshift z = 1 and z = 0.

The reason for this discrepancy is not clear. On the one hand, the Fragos et al. calculations consider primordial binaries only and do not include dynamically formed systems in GCs. Therefore, their results could be reconciled with our observa-
tions if one assumed that the absolute majority of LMXBs are of dynamical origin. Quantitatively, in order to allow more than a ten-fold decrease in the numbers of primordial LMXBs between 5.5 and 9.5 Gyrs and still be compatible with our observations, the contribution of primordial systems should be less than a few per cent in the ~ 10 Gyrs old galaxies. This would also imply that, on average, dynamically formed LMXBs contribute ≳ 95 – 99% to the LMXB population at the redshift z = 0. We consider this possibility unlikely because it would contradict the evidence presented in this paper and in other studies (e.g., Juett 2005, Kundu et al. 2007, Voss et al. 2009, Zhang et al. 2011).

Another important caveat is that Fragos et al. (2008) considered coeval stellar populations. Similar complications complicate stellar age determinations, so the discussion of Sect. 7.1 applies here fully. Quantitatively, however, significant deviations from the SSP assumption in galaxies with young SSP ages would be required in order to account for the observed discrepancy between theory and our observations. Indeed, the single-starburst calculations by Fragos et al. (2012) in Fig. 2) predict a ~ 100-fold decrease in the specific LMXB luminosity between 2 and 10 Gyrs. Such a drop in the LMXB populations can be reconciled with our results only by assuming that the fraction of young stars in galaxies with the youngest SSP ages (e.g., NGC 4382 – 1.6 Gyrs and NGC 5866 – 1.8 Gyrs) is actually rather small, ≲ 10−5. Detailed data about the star-formation history and stellar age structure of galaxies with young SSP ages is needed in order to see if this possibility is feasible.

9. Summary

The main goal of this paper was to study the dependence of the population of LMXBs on stellar age. To this end, we collected 20 nearby early-type galaxies, which were observed by Chandra to sufficient depth, and had the stellar age measured.

1. We found that older galaxies tend to host more LMXBs per unit stellar mass than younger ones (Fig. 5). The correlation has large scatter, with the points occupying the dynamical range by a factor of 4. When averaged over young (t < 6 Gyrs) and old (t > 6 Gyrs) subsamples, the specific frequency of LMXBs with $L_X > 5 \times 10^{37}$ erg/s varies from 4.17 ± 0.27 to 6.27 ± 0.26 per 10^10 $M_\odot$. Interpretation of this dependence is complicated by the rather strong correlation between the GC content of the galaxy and its stellar age. We presented evidence suggesting that an important factor is the intrinsic evolution of the distributions of LMXBs with time. Its effect is enhanced by the larger GC content of older galaxies, resulting in larger numbers of dynamically formed binaries in them.

2. Our results appear to challenge recent population synthesis calculations by Fragos et al. (2008, 2012), predicting a more than ~ten-fold decrease of the primordial LMXB population between ~ 5.5 and 9.5 Gyrs (a hundred-fold decrease between 2 and 10 Gyrs). This discrepancy can be understood under rather extreme assumptions about the contribution of the dynamically formed LMXBs and/or the fraction of truly young stellar populations in the galaxies with young SSP ages. The caveats to the comparison of our data with calculations of Fragos et al. (2008, 2012) are discussed in Sect. 8.2.

3. There is clear evolution of the XLF with age: the one of younger galaxies is steeper in the entire studied luminosity range, log($L_X$) ≥ 37.5, than the one of younger galaxies (Fig. 6). A similar result was also reported by Kim & Fabbiano (2010).

4. Young galaxies host a significant population of (ultra-) luminous X-ray sources with luminosity exceeding 10^{39} erg/s. We estimate their specific frequency of ≳ 8.8 ± 3.2 sources per 10^{12} $M_\odot$ in the young subsample. Such sources are significantly less frequent in the old subsample (~ 1 source against ~ 7), with the 90% upper limit of ~ 2.9 sources per 10^{12} $M_\odot$.

5. As a byproduct of this study, we compiled a list of six black hole candidates in GCs, of which five were previously known and one is identified for the first time (Table 5).

Acknowledgements. This research made use of Chandra archival data provided by Chandra X-ray Center and the 2MASX Large Galaxy Atlas data provided by NASA/IPAC infrared science archive. Aks Bogdán acknowledges support provided by NASA through Einstein Postdoctoral Fellowship grant number PF1-120081 awarded by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-03060. We also wish to thank Rasmus Voss, Andrew Cooper, Diederik Kuijssen, Jungha Gu, and Jingying Wang for the discussions which have greatly improved the quality of this paper.

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Zhongli Zhang et al.: Stellar age dependence of LMXB population in early-type galaxies
