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SOME CONSTRAINTS ON THE EFFECTS OF AGE AND METALLICITY ON THE LOW-MASS X-RAY BINARY FORMATION RATE[1]

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ABSTRACT

We have studied the low-mass X-ray binary (LMXB) populations within and outside globular clusters (GCs) in NGC 4365 and NGC 3115. Using published age and metallicity constraints from optical and IR observations of their GCs, we do not find any evidence for an increase in the LMXB formation rate in the intermediate-age cluster population of NGC 4365, as has been proposed in some scenarios of dynamical LMXB formation in GCs. The old, metal-rich, red population of GCs in NGC 3115, on the other hand, is *at least* 3 times as efficient at creating LMXBs as the old, metal-poor, blue clusters. These data suggest that the higher formation efficiency of LMXBs in the red GC subsystems of many galaxies is largely a consequence of their higher metallicity. A comparison of the densities of field LMXBs in different galaxies does not reveal an obvious correlation with the age of the field stars, as predicted by models in which the LMXB formation rate in the field drops monotonically with time after an initial burst. This suggests that either a significant fraction of the field LMXBs are created in GCs and subsequently injected into the field or the LMXB formation rate has a more complex time evolution pattern.

Subject headings: galaxies: general — galaxies: individual (NGC 3115, NGC 4365) — galaxies: star clusters — globular clusters: general — X-rays: binaries — X-rays: galaxies

1. INTRODUCTION

The hard X-ray emission from elliptical and S0 galaxies has long been suspected of being associated with low-mass X-ray binaries (LMXBs; Trinchieri & Fabbiano 1985). With the advent of the *Chandra X-Ray Observatory*, it is now possible to directly identify and study LMXBs in external galaxies such as NGC 4697 (Sarazin, Irwin, & Bregman 2000) and NGC 4472 (Kundu, Maccarone, & Zepf 2002, hereafter KMZ; Maccarone, Kundu, & Zepf 2003, hereafter MKZ).

LMXBs are formed especially efficiently in globular clusters (GCs), most likely because of dynamical interactions in the core (Clark 1975; Fabian, Pringle, & Rees 1975). In the Galaxy, GCs account for $\lesssim$0.1% of the stellar mass but harbor ~10% of the $L_X \gtrsim 10^{36}$ ergs s^{-1} LMXBs (e.g., Verbunt 2003). *Chandra* studies reveal that an even higher fraction of LMXBs in early-type galaxies reside in GCs, ranging from 70% in NGC 1399 (Angelini, Loewenstein, & Mushotzky 2001), to 40% in NGC 4472 (KMZ; MKZ), and to a lower limit of 20% in NGC 4697 (Sarazin et al. 2000).

One of the surprising conclusions from our study of the GC-LMXB connection in NGC 4472 (KMZ) is that red GCs are $\approx$3 times more likely to host LMXBs than blue ones. Although a similar correlation is known to exist for the Galaxy (e.g., Grindlay 1987), the small number of LMXBs and clusters in the Galaxy makes it difficult to gauge the relative importance of various correlated GC properties. The rich GC systems of early-type galaxies and the wide range of GC properties in different galaxies allow us to isolate and understand the physical characteristics of GCs that drive LMXB formation. For example, the red colors of GC systems identified in broadband optical filters largely reflect a metal-rich population, but in different galaxies these clusters can also be younger than the blue GCs by varying amounts (e.g., Puzia et al. 2002, hereafter P02). It has also been argued that LMXBs may preferentially be created in younger GCs where the larger mass of the turnover stars increases the interaction rate in GCs (e.g., Di Stefano et al. 2002; also see Rappaport et al. 2001). The discovery of a significant population of intermediate-age GCs in NGC 4365 by P02 provides a unique sample to test for any effect of age on the LMXB formation rate. Furthermore, the P02 infrared study yields the only data set that constrains the ages and metallicities of large numbers of GCs in the inner regions of galaxies where the LMXB density is highest.

In this Letter, we compare the X-ray properties of GCs in NGC 3115 and NGC 4365 with the age and metallicity constraints placed by the P02 observations in order to isolate the primary physical property that drives the efficient formation of LMXBs in red GCs. We also probe the field LMXBs in early-type galaxies to ascertain whether they probe the age of the field stars.

2. OBSERVATIONS AND DATA ANALYSIS

We have analyzed the 36 ks archival *Chandra* ACIS-S3 image of NGC 3115 observed on 2001 June 14 (principal investigator: J. A. Irwin) and the 41 ks image of NGC 4365 observed on 2001 June 2 (principal investigator: C. L. Sarazin). Using the procedure laid out in KMZ and MKZ, we identify 149 X-ray point sources in NGC 4365 and 90 objects in NGC 3115 in the 0.5–8 keV band. The bulk of these sources are LMXBs. Only 10–15 of the candidates in each galaxy are expected to be contaminating objects such as background active galactic nuclei (Brandt et al. 2000; Mushotzky et al. 2000). Neither of these galaxies show evidence of significant emission from bright, hot gas that might affect point-source detection even in the innermost regions of the galaxies.

The *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 (WFPC2) *V*- and *I*-band observations of NGC 3115

[1] Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555, and on observations made with the *Chandra X-Ray Observatory*.

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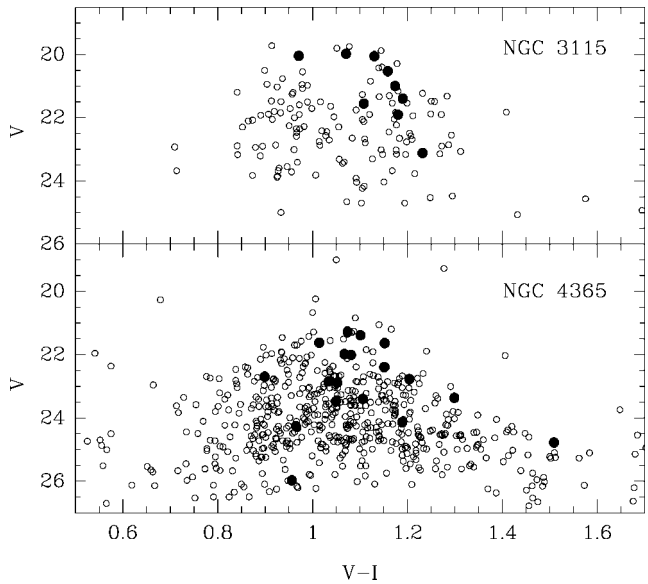

FIG. 1.—Color-magnitude diagrams for the GC candidates in NGC 3115 and NGC 4365. Filled circles represent clusters with LMXB counterparts.

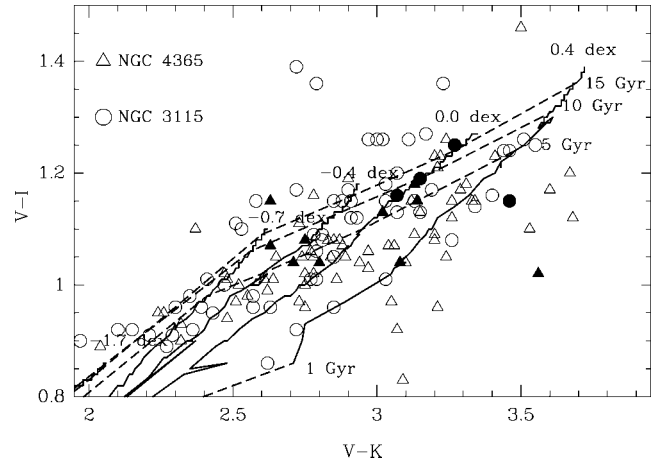

FIG. 2.—$V-I$ vs. $V-K$ color-color plot of the GCs in NGC 4365 and NGC 3115 from P02. Dashed and solid lines indicate G. Bruzual & S. Charlot (2000, private communication) isochrones and isometallicities for various fiducial values, assuming a Salpeter initial mass function. Filled circles mark GC-LMXBs.

and NGC 4365 have been analyzed by us in Kundu & Whitmore (1998, 2001a) and P02. P02 have also analyzed ground-based *K*-band images of these galaxies. We refer the reader to these papers for details of the data reduction and analysis of their GC systems. We achieved 0″.3 rms relative astrometric accuracy between the optical and X-ray sources by bootstrapping the *HST* and *Chandra* positions using the procedure outlined in MKZ. We adopt a distance modulus of 29.93 mag for NGC 3115 and 31.55 mag for NGC 4365 (Tonry et al. 2001).

3. LMXBs IN GLOBULAR CLUSTERS

In order to determine the fraction of LMXBs in GCs, we consider only the X-ray sources that lie within the WFPC2 field of view. Thirty-six of the LMXB candidates in NGC 3115 and 44 in NGC 4365 meet this criterion (we eliminated the source corresponding to the nucleus of each galaxy, which may be associated with their central black holes). Nine of these LMXBs in NGC 3115 and 23 in NGC 4365 are within 0″.5 of a GC and are considered to be matches. There is a natural break in the LMXB-GC angular separation at this distance, and no further candidates are added in either galaxy when the matching radius is increased to 0″.7. Thus, 25% of the LMXBs in NGC 3115 are associated with GCs, and 40% in NGC 4365.

The optical color distributions of GCs in many early-type galaxies are known to be bimodal (e.g., Kundu & Whitmore 2001a, 2001b). This is usually attributed to differences in the metallicity distributions of the subpopulations of old GCs. While NGC 3115 has a bimodal color distribution (Kundu & Whitmore 1998), NGC 4365 is one of the few galaxies with a confirmed unimodal distribution (Kundu & Whitmore 2001a). In each bimodal GC system where the LMXB population has been studied—e.g., the Galaxy (Bellazzini et al. 1995) and NGC 4472 (KMZ)—the red GCs have a significantly higher fraction of LMXBs than the blue ones.

The color-magnitude diagrams of the NGC 3115 and NGC 4365 GCs are plotted in Figure 1, with LMXB hosts represented by filled symbols. It is apparent that the red GCs in NGC 3115 are preferred sites for LMXB formation. We showed in Kundu & Whitmore (1998) that there are roughly equal numbers of red and blue GCs in the WFPC2 image of NGC 3115 with a dividing color between $V-I = 1.03$ and $V-I = 1.06$. Any choice of partition between red and blue GCs within this color range places eight of the nine GC-LMXBs in the red GC system of NGC 3115. Even if one were to conservatively assign the GC-LMXB with $V-I = 1.07$ that is near the cusp of the color distribution to the blue population, the efficiency of LMXB formation in red GCs is at least 3 times that in blue GCs. On the other hand, the GC-LMXBs in NGC 4365 show no strong preference for redder GCs. The $\langle V-I \rangle = 1.10 \pm 0.03$ mean color of the GC-LMXBs is only marginally redder than the $\langle V-I \rangle = 1.06 \pm 0.01$ value of the 546 GCs within the color range $0.6 < V-I < 1.4$.

4. DISCUSSION

4.1. *Are LMXBs Formed More Efficiently in Young Globular Clusters?*

Using *K*-band observations to break the age-metallicity degeneracy that plagues optical colors, P02 showed that the broad optical color distribution of NGC 4365 GCs is due to the presence of a significant fraction (≈50% in the field of view) of intermediate-age (∼5 Gyr) GCs. This interpretation has been confirmed by spectroscopic observations of a handful of GCs by Larsen et al. (2003). P02 also showed that both the metal-poor and the metal-rich GCs in NGC 3115 appear to be old (∼12 Gyr). In Figure 2, we plot the $V-K$ versus $V-I$ distribution of the GCs (and GC-LMXBs) in NGC 4365 and NGC 3115. While the age of an individual GC is only constrained to several gigayears and [Fe/H] to a few tenths of a dex, the differences in the overall GC system properties of the two galaxies, in particular the intermediate-age population of NGC 4365, can clearly be seen. We refer the reader to P02 for details. Note that the P02 observations are largely limited by the depth of the *K*-band data. Thus, only a subsample of the Figure 1 GCs have age-metallicity constraints.

Figure 2 reveals that all the GCs in the P02 sample that host LMXBs in NGC 3115 are metal-rich and have solar or higher metallicity. Given the old ages (≳10 Gyr) of both the red and blue GCs in this galaxy, our observations strongly suggest that metallicity is a significant parameter that drives the formation of LMXBs in GCs. It appears likely that the higher efficiency of LMXB formation in the red GCs of galaxies with clearly bimodal optical color distributions such as NGC 4472 (KMZ)

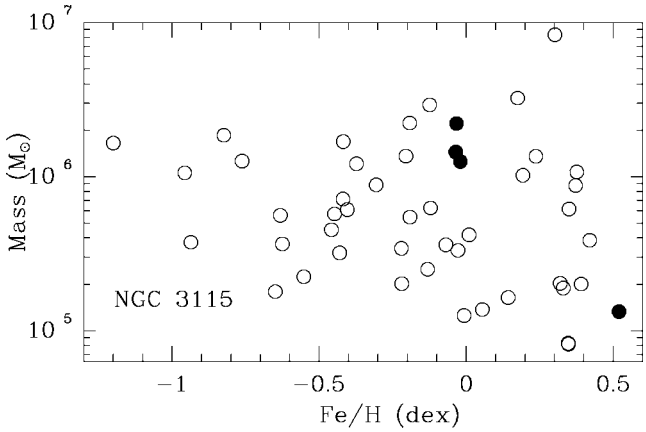

FIG. 3.—Metallicity vs. mass distribution for the GCs in NGC 3115 using the optical and IR colors of P02 and the G. Bruzual & S. Charlot (2000, private communication) models. Filled circles represent GC-LMXBs. Typical uncertainties in [Fe/H] of individual GCs are several tenths of a dex (see P02).

is also driven by metallicity effects. On the other hand, the GC system of NGC 4365, which spans a large range of ages, does not reveal any obvious correlation of LMXB efficiency with GC age. Specifically, there is no evidence that intermediate-age GCs are more likely to host LMXBs. Although the specific choice of age separating the intermediate-age and old GCs is fairly arbitrary, a typical choice of 5 Gyr actually gives a slightly *higher* fraction of LMXBs in old GCs (≈20%) than in young ones (≈10%).

However, there are strong selection effects due to the *K*-band photometric limits (P02), coupled with the fact that younger GCs are brighter, and the strong preference of LMXBs to form in the brightest GCs (Fig. 1 and KMZ). We showed in KMZ that the luminosity effect implies that a roughly equal number of LMXBs are formed per unit GC mass at all luminosities. Thus, in order to fairly judge the effect of age and/or metallicity one should compare the LMXB formation efficiency for GCs of equal mass. To this end, we used the ages and metallicities of individual GCs and the implied G. Bruzual & S. Charlot (2000, private communication) model luminosities to estimate the masses of the GCs. We note here in passing that the LMXB fraction per unit mass of GCs in our sample is $10^{-7}\ M_{\odot}^{-1}$ and indeed roughly constant for all GC masses.

Figure 3 shows the [Fe/H] versus mass distribution of GCs and GC-LMXBs in NGC 3115. In conjunction with Figures 1 and 2, it is apparent that the red GCs are favored sites for LMXB formation owing to the higher metallicities of these clusters. Figure 4 plots the age and metallicity versus mass distributions of the NGC 4365 GCs. The bottom panel of Figure 4 shows no strong correlation of LMXB formation rate with GC metallicity in NGC 4365. It is not clear if this is due to selection effects, such as the fact that the *K*-band data undersample the fainter metal-poor GCs in this more distant galaxy, or possible physical processes, e.g., the metallicity dependence is not continuous but a threshold effect above which the efficiency of LMXB formation increases. More significantly, the top panel of Figure 4 shows no evidence that younger GCs form LMXBs more efficiently. We attempted to separate the sample into young and old populations using a range of dividing ages from 4 to 8 Gyr (see P02) to search for any evidence of a higher LMXB formation rate in young GCs. For a dividing age of 8 Gyr, the LMXB density is $1.1(\pm 0.4) \times 10^{-7}\ M_{\odot}^{-1}$ for the young GCs and $0.7(\pm 0.5) \times 10^{-7}\ M_{\odot}^{-1}$ for the old ones. Conversely, dividing the populations at 4 Gyr yields $0.7(\pm 0.5) \times 10^{-7}\ M_{\odot}^{-1}$ for the young population and $1(\pm 0.4) \times 10^{-7}\ M_{\odot}^{-1}$ for the old GCs. Furthermore, we point out that if the efficient formation of LMXBs in the red GCs of the Galaxy and M31 is due to their ~2 Gyr younger age compared to the blue clusters, we would expect to see a significantly larger difference in LMXB formation efficiencies between the young and the old GCs in NGC 4365 due to their larger age spread. Given that roughly half the GCs in our WFPC2 image are young (P02), our data clearly do not support this premise. Also, the deep $V-I$ observations indicate that ≈3% of the NGC 4365 GCs host LMXBs, which is similar to the ≈4% fraction observed in other galaxies (KMZ).

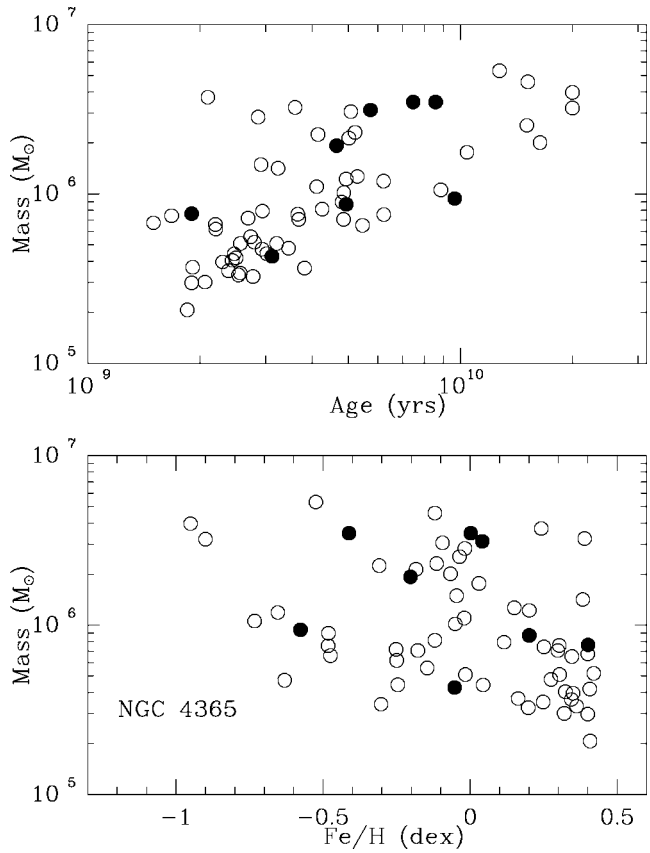

FIG. 4.—*Top*: Age vs. mass for the NGC 4365 GCs. The uncertainty in the age of an individual GC is a few gigayears (see P02). *Bottom*: Metallicity vs. mass distribution.

Thus, we conclude that the efficiency of LMXB formation in a GC shows no obvious correlation with the age of the GC. However, the larger fraction of LMXBs seen in the red GC systems of NGC 3115, and likely the other galaxies with clearly bimodal GC color distributions, appears to be related to the higher metallicities of these clusters. There is no convincing theoretical model that explains this metallicity effect. Systematic variations as a function of metallicity in the dynamical properties of clusters, the dynamical binary formation rates, or the efficiency of mass transfer in LMXBs are all possibilities at this time. These observations lay the preliminary observational goalposts for understanding the formation of LMXBs in GCs. Deeper optical and *K*-band observations of large samples of extragalactic GCs will clearly be invaluable in probing the observational signatures in more detail.

4.2. *Do Field LMXBs Trace the Age of Field Stars?*

Models of LMXB formation due to the evolution of binaries in the field suggest that the rate of formation of bright LMXBs

decreases monotonically after an initial peak (White & Ghosh 1998; Wu 2001). If this is the case, the properties of the field LMXBs may be used to probe the star formation history of the host galaxy. In this scenario, the vast majority of the bright LMXBs in the Milky Way must be associated with recent star formation in the Galactic disk. However, we have discovered 27 field LMXBs with $L_X > 3 \times 10^{36}$ ergs s^{-1} within the WFPC2 image of NGC 3115 and, we estimate, ≈50 in the entire ACIS-S3 frame. There are roughly twice as many LMXBs of comparable luminosity in the Galaxy. Thus, one would require either continuous star formation in a region of NGC 3115 with mass comparable to the Milky Way disk or a significant star formation episode in the recent past to account for the field LMXBs in NGC 3115. There is no clear evidence for recent star formation in either the GCs or the field stars in NGC 3115 (P02), strongly suggesting that the LMXB formation rate does not correlate trivially with the age of the stellar system.

To further search for age effects, we plot the local specific frequencies, S_N, of GCs, GC-LMXBs, and field LMXBs of NGC 3115, NGC 4365, NGC 1399, and NGC 4472 as a function of host galaxy absolute magnitude in Figure 5. The local S_N is defined as $N \times 10^{0.4(M_{V(\mathrm{FOV})}+15)}$, where N is the number of relevant candidates and $M_{V(\mathrm{FOV})}$ is the absolute magnitude of the host galaxy within the WFPC2 field of view. LMXBs fainter than 2×10^{37} ergs s^{-1} have been eliminated for the nearby NGC 3115 system in order to minimize selection bias. The LMXB values have been arbitrarily multiplied by 20 to facilitate comparison with the GC values of S_N.

Figure 5 reveals that broadly the GC and GC-LMXB specific frequencies track each other, which essentially reiterates our suggestion (KMZ) that the overall efficiency of LMXB formation in GCs is similar in different galaxies. The S_N of field LMXBs also appears to be similar in the inner regions of these galaxies. However, if all LMXBs brighter than $\gtrsim 2 \times 10^{36}$ ergs s^{-1} are formed in regions with continuous or recent bursts of star formation, as suggested by Wu (2001), NGC 4365, which is likely to have a component of intermediate-age stars in the field, should have a higher value of $S_{N(\mathrm{field})}$. The approximately several gigayear delay in the peak of the LMXB formation rate suggested by White & Ghosh (1998) should have further enhanced the field LMXB density in NGC 4365 at the present epoch. No obvious enhancement is seen in Figure 5.

Thus, we conclude that our present data set does not support a scenario in which the LMXB formation efficiency decreases monotonically after an initial peak. It is possible that a large fraction of present-day LMXBs reflect an old stellar population where Roche lobe overflow in a moderately tight binary is triggered by the evolution of a donor star off the main sequence (e.g., Podsiadlowski, Rappaport, & Pfahl 2002). Alternately, a significant fraction of field LMXBs may actually have been created in GCs and subsequently injected into the field (MKZ) by either GC destruction (e.g., Vesperini 2000, 2001) or dynamical kicks (e.g., Phinney & Sigurdsson 1991). Finally, we note that in much of this Letter we have implicitly assumed that our snapshot study accurately reflects the relative densities of various populations of LMXBs. Follow-up *Chandra* observations are necessary to quantify possible differences in the transient LMXB populations (Piro & Bildsten 2002) that may affect these conclusions.

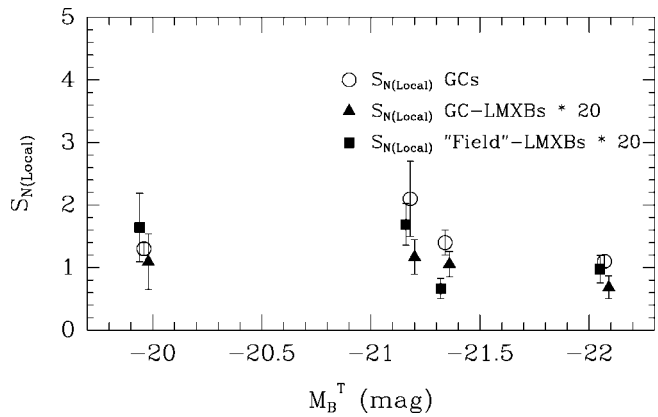

FIG. 5.—Local specific frequency of GCs, GC-LMXBs, and field LMXBs in (*from left to right*) NGC 3115, NGC 4365, NGC 1399, and NGC 4472, as a function of the total *B*-band absolute magnitude of the galaxies. Arbitrary small offsets along the *x*-axis have been applied to the values of S_N for clarity.

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ERRATUM: "SOME CONSTRAINTS ON THE EFFECT OF AGE AND METALLICITY ON THE LOW-MASS X-RAY BINARY FORMATION RATE" (ApJ, 589, L81 [2003])

Arunav Kundu, Thomas J. Maccarone, Stephen E. Zepf, and Thomas H. Puzia

The number of low-mass X-ray binaries in NGC 4365 that are within 0″.5 of a globular cluster and considered to be matches is 18, not 23 as mistakenly reported in the first paragraph of § 3. The correct number is used elsewhere in the above Letter. The fraction of low-mass X-ray binaries that are associated with globular clusters in NGC 4365 is indeed 40% as noted later in the same paragraph. We thank W. Lewin for alerting us to this error.