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THE BIRTHPLACE OF LOW-MASS X-RAY BINARIES: FIELD VERSUS GLOBULAR CLUSTER POPULATIONS

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ABSTRACT

Recent *Chandra* studies of low-mass X-ray binaries (LMXBs) within early-type galaxies have found that LMXBs are commonly located within globular clusters of the galaxies. However, whether all LMXBs are formed within globular clusters has remained an open question. If all LMXBs formed within globular clusters, the summed X-ray luminosity of the LMXBs in a galaxy should be directly proportional to the number of globular clusters in the galaxy regardless of where the LMXBs currently reside. We have compared these two quantities over the same angular area for a sample of 12 elliptical and S0 galaxies observed with *Chandra* and found that the correlation between the two quantities is weaker than expected if all LMXBs formed within globular clusters. This indicates that a significant number of the LMXBs were formed in the field and naturally accounts for the spread in field-to-cluster fractions of LMXBs from galaxy to galaxy. We also find that the "pollution" of globular cluster LMXBs into the field has been minimal within elliptical galaxies, but there is evidence that roughly half of the LMXBs originally in the globular clusters of S0 galaxies in our sample have escaped into the field. This is likely due to higher globular cluster disruption rates in S0s, resulting from stronger gravitational shocks caused by the passage of globular clusters through the disks of S0 galaxies that are absent in elliptical galaxies.

Subject headings: binaries: close — galaxies: elliptical and lenticular, cD — X-rays: binaries — X-rays: galaxies

1. INTRODUCTION

Composed of a neutron star or black hole primary and a low-mass, typically evolved secondary star that donates material to the primary via Roche lobe overflow, low-mass X-ray binaries (LMXBs) are the only luminous ($L_X > 10^{36}$ ergs s^{-1}) class of X-ray point source expected in significant numbers in the old stellar populations of S0 and elliptical galaxies. It came as no surprise that *Chandra*, with its subarcsecond spatial resolution, was able to resolve dozens if not hundreds of individual LMXBs in nearby early-type galaxies, which in some instances comprise the bulk of the X-ray emission from the galaxy. What was surprising was the discovery that a remarkably high percentage of the LMXBs reside within globular clusters of the host galaxies (e.g., Angelini et al. 2001; Kundu et al. 2002; Randall et al. 2004). Also unexpected was the variation in the fraction of LMXBs within globular clusters from galaxy to galaxy, ranging from almost 70% in NGC 1399 to a more modest 18% in NGC 1553 (Angelini et al. 2001; Sarazin et al. 2003).

In retrospect, the high fraction of LMXBs within globular clusters should not have been surprising. In the Milky Way, globular clusters host ∼10% of the Galaxy's LMXBs, despite the fact they constitute only ∼0.1% of the Galaxy's mass. Given that early-type galaxies have a higher fraction of their mass in globular clusters than do spiral galaxies, early-type galaxies would naturally produce more LMXBs within globular clusters than spiral galaxies of comparable mass, even if both types of galaxies produced similar numbers of field LMXBs.

The high stellar density within globular clusters is undoubtedly responsible for the disproportionately high number of LMXBs within them. The increased rate of multibody interactions within globular clusters serves to tighten existing binaries to the point that mass transfer from the secondary onto the compact accretor can occur much more frequently than in the field. The gravitational capture of a potential donor star by a lone neutron star or black hole is also much more likely within a globular cluster than in the field. Given the much higher (>100 times) efficiency of creating LMXBs within globular clusters than in the field, it is natural to ask if *all* (or nearly all) LMXBs are formed within globular clusters. This was first suggested by Grindlay (1984) for the case of Galactic X-ray bursting binaries and extended to LMXBs within early-type galaxies by White et al. (2002). In this scenario, LMXBs that currently reside in the field originally formed within globular clusters but were subsequently separated from the cluster either by a supernova kick imparted to the system once the primary evolved, through stellar encounters within the globular cluster, or through the tidal disruption/destruction of the the host globular cluster.

Many X-ray properties of the field LMXBs appear indistinguishable from the globular cluster LMXBs for the galaxies studied to date, suggesting a common origin of the two populations. Both the X-ray luminosity functions (Kundu et al. 2002; Jordàn et al. 2004) and bulk spectral properties (Maccarone et al. 2003; Irwin et al. 2003; Humphrey & Buote 2004) of the two populations are consistent with having been drawn from the same parent distribution. On the other hand, the variation in the fraction of LMXBs in globular clusters from galaxy to galaxy is more easily explained as the sum of a field population of LMXBs that scales with the mass of the galaxy and a globular cluster population of LMXBs that scales with the number of globular clusters, particularly if it can be confirmed that galaxies with a larger number of globular clusters have a higher fraction of their LMXBs within globular clusters than in galaxies with relatively few globular clusters. Indeed, previous studies have noted this trend in a few galaxies (Sarazin et al. 2003; Maccarone et al. 2003) that support this notion.

One potential method of determining whether the present-day field LMXB population originated within globular clusters or are indigenous to the field is to investigate the spatial distribution of the field LMXBs. If they formed in globular clusters, the LMXBs might be expected to follow the generally flatter spatial distribution of the globular clusters (e.g., Ashman & Zepf 1998), rather than the steeper de Vaucouleurs profile of the optical light. Observationally, this is a difficult effect to confirm. The limited number of field LMXBs in any given observation does not constrain their spatial profile particularly well. Furthermore, hot X-ray gas present in the galaxies will raise the detection limit of sources near the center of the galaxies, leading to an artificial flattening of the spatial distribution of the LMXBs. In addition, it is not at all clear if the ejected LMXBs will maintain the shape of the parent globular distribution, since different ejection mechanisms will lead to different field LMXB distributions. If the LMXBs are ejected from globular clusters via supernova kicks, the spatial distribution of the field LMXBs will be more extended, given that the expected kick velocity of several hundred km s^{-1} is approximately the same as the average space velocity of a globular cluster within a galaxy. Conversely, simulations show that tidal disruption/destruction of globular clusters is more efficient in the central regions of galaxies (e.g., Vesperini 2000), which would lead to a profile of stripped LMXBs that is steeper than the remaining globular clusters.

An alternative method of addressing this issue is to compare the total number of LMXBs to the total number of globular clusters in a galaxy for a sample of galaxies. If all LMXBs formed within globular clusters, there should be a linear relation between these two quantities regardless of where the LMXBs currently reside. On the other hand, if there is a significant population of LMXBs created in the field, the relation between the number of LMXBs and globular clusters should be weaker, as the field component becomes more dominant in galaxies with fewer globular clusters. This would also predict that the fraction of LMXBs found within globular clusters is larger for galaxies with more globular clusters per unit light, which could account for the measured spread in the fraction of LMXBs within globular clusters from galaxy to galaxy.

In practice, it is more feasible to determine the total X-ray luminosity emanating from LMXBs rather than the total number, since each observation in general has a different limiting luminosity for source detection. In addition, it is necessary to normalize both the total LMXB luminosity and the number of globular clusters by the optical light of the galaxy to compare galaxies of different physical sizes. The latter quantity is usually referred to as the globular cluster specific frequency and is defined as $S_N = N_{\rm tot}10^{0.4(M_V+15)}$ (Harris & van den Bergh 1981), where $N_{\rm tot}$ is the total number of globular clusters in the galaxy and M_V is the absolute visual magnitude of the galaxy. Such a comparison of $L_{\rm X}/L_{\rm opt}$ to S_N for a sample of galaxies was originally performed by White et al. (2002) using *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) data, who found a strong correlation between $L_{\rm X}/L_{\rm opt}$ and S_N. His best-fit relation of $L_{\rm X}/L_{\rm opt} \propto S_N^{1.2\pm0.4}$ was consistent with the hypothesis that all LMXBs were created within globular clusters. However, the uncertainty of the power-law exponent was large enough that a significant field population of LMXBs could not be excluded. The poor spatial resolution of *ASCA* did not allow individual LMXBs to be resolved and their luminosities added. Instead, $L_{\rm X}$ was estimated from performing a two-component spectral fit to simultaneously model the hot gas and LMXB components of the X-ray spectra. Such a method generally leads to large uncertainties in the flux of the LMXB component, especially for galaxies with much hot gas, since χ^2 fitting will attempt to fit the many soft energy channels at the expense of the fewer hard energy channels that constrain the LMXB component the best.

The ability of *Chandra* to resolve a large fraction of the LMXB population of early-type galaxies greatly reduces the uncertainties in $L_{\rm X}$, which allows better constraints to be put on the $L_{\rm X}/L_{\rm opt}$ versus S_N relation. Kim & Fabbiano (2004) have performed such a study with 14 early-type galaxies observed with *Chandra* and confirmed the result of White et al. (2002) of a connection between $L_{\rm X}/L_{\rm opt}$ and S_N. They did not, however, derive a slope between the two quantities. In this paper, we analyze the *Chandra* data for 12 early-type galaxies to determine the exact dependence of $L_{\rm X}/L_{\rm opt}$ on S_N to put constraints on the relative fraction of LMXBs created within globular clusters and in the field.

Our method for determining the $L_{\rm X}/L_{\rm opt}$ versus S_N relation differs from previous studies and is presented in detail in § 2. The inclusion of the high-S_N galaxy NGC 1399 in our sample requires special attention in order to accurately determine its $L_{\rm X}/L_{\rm opt}$ value and is discussed in § 4. Our best-fit $L_{\rm X}/L_{\rm opt}$ versus S_N relation is given in § 5, and a comparison of the predicted initial fraction of LMXBs within globular to their present-day observed values is given in § 6. Finally, we discuss our results in § 7.

2. THE METHOD

Our method for determining the dependence of $L_{\rm X}/L_{\rm opt}$ on S_N differs from previous methods in three important ways. First, we do not assume a simple power-law fit between the two quantities. If some LMXBs are truly formed in the field, we would expect $L_{\rm X}/L_{\rm opt}$ from these LMXBs to be a constant from galaxy to galaxy (assuming similar ages and stellar populations of the galaxies), while $L_{\rm X}/L_{\rm opt}$ from LMXBs within globular clusters should scale linearly with S_N:

$$(L_{\rm X}/L_{\rm opt})_{\rm total} = (L_{\rm X}/L_{\rm opt})_{\rm GC} + (L_{\rm X}/L_{\rm opt})_{\rm field} = AS_N + B, \quad (1)$$

where A and B are constants. Figure 1 illustrates the shape of the $L_{\rm X}/L_{\rm opt}$ versus S_N relation for a variety of scenarios. If all LMXBs were created in the field (case 1), there would be no dependence of $L_{\rm X}/L_{\rm opt}$ on S_N, so $A = 0$ and B is a positive constant. Conversely, if all LMXBs are formed within globular clusters (case 2), $L_{\rm X}/L_{\rm opt}$ would vary linearly with S_N, for which A is a positive constant and $B = 0$ (i.e., a galaxy with no globular clusters would not contain any LMXBs). Finally, if LMXBs were formed both within globular clusters and the field (case 3), A and B would both be positive constants. In this event, field LMXBs would dominate in low-S_N galaxies, while globular cluster LMXBs would dominate in high-S_N galaxies. Although case 1 has been definitively ruled out by the finding that 20%–70% of LMXBs are presently coincident with globular clusters, neither case 2 nor case 3 has been ruled out by previous studies. Note that the difference in the shape of the $L_{\rm X}/L_{\rm opt}$ versus S_N relation between cases 2 and 3 holds even if a significant fraction (or all, for that matter) of the LMXBs escaped from globular clusters into the field over the lifetime of the galaxy. In other words, LMXBs escaping from globular clusters cannot make a case 2 scenario look like a case 3 scenario, provided that large numbers of globular clusters are not completely destroyed.

Second, it is vitally important to calculate $L_{\rm X}/L_{\rm opt}$ only within the same angular area for which S_N was determined. It is well established that S_N is a strong function of galactic radius, as the integrated S_N determined out to a radius of $10'$ or more from ground-based observations can be as much as a factor of 5 higher than when determined within the *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 (WFPC2) field of view (Kundu & Whitmore 2001a, 2001b; Kissler-Patig 1997). Comparing $L_{\rm X}/L_{\rm opt}$, which was determined over the entire *Chandra* ACIS-S $8' \times 8'$ field of view, to S_N, determined either in the $150''$ chevron-shaped field of view of the *HST* WFPC2 or from large angular

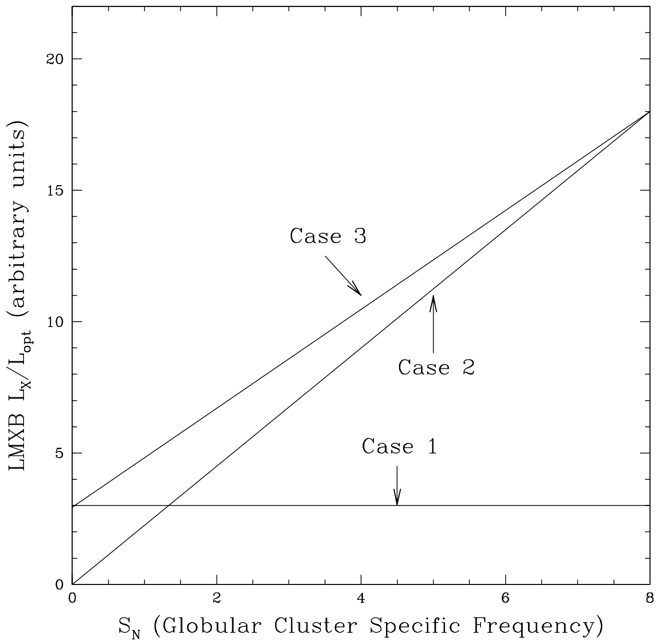

FIG. 1.—Predicted relations between L_X/L_{opt} and the globular cluster specific frequency S_N if all LMXBs are formed in the field (case 1), if all LMXBs are formed within globular clusters (case 2), and if LMXBs formed in both the field and within globular clusters (case 3).

(>10′ radius) area ground-based observations, will undoubtedly lead to erroneous results given the strong dependence of S_N on galactic radius.

Third, in determining the total X-ray luminosity from the sum of the sources, we exclude sources more luminous than 5×10^{38} ergs s^{-1}. The few most luminous sources in a typical early-type galaxy generally contribute a significant fraction of the total X-ray luminosity from LMXBs. Thus, the determination of $L_{X,\,total}$ can be greatly affected by random Poisson fluctuations in the number of the few most luminous LMXBs, especially for smaller galaxies that are only expected to have two to three sources with $L_X > 5\times10^{38}$ ergs s^{-1}. In fact, for the sample of galaxies we study here, we find that the fraction of the total flux emanating from $>5\times10^{38}$ ergs s^{-1} sources ranges anywhere from 0% to 35%. However, by excluding sources more luminous than 5×10^{38} ergs s^{-1} and only including galaxies large enough such that the integrated luminosity from sources below 5×10^{38} ergs s^{-1} is at least 5×10^{39} ergs s^{-1}, no one source will contribute more than 10% to the total flux, thereby minimizing the effect of an overabundance or deficit of high-luminosity sources on $L_{X,\,total}$.

3. OBSERVATIONS AND DATA REDUCTION

We constructed a sample of every normal early-type galaxy that satisfied the following criteria: (1) it was observed by the *Chandra* ACIS-S for at least 10 ks, (2) the literature S_N value was constrained to at least 50% accuracy and the value of the V-band luminosity each author used to determine S_N over the reported angular area is stated, (3) the total LMXB luminosity was at least 5×10^{39} ergs s^{-1} (see above), and (4) it did not contain so much hot gas that determination of the unresolved LMXB emission would be problematic, unless literature S_N values were available in a well-defined angular region outside the core of the galaxy (such as NGC 1399 below). This yielded a total of 12 galaxies, listed in Table 1.

The data for each galaxy were processed in a uniform manner following the *Chandra* data reduction threads. The data were calibrated with the most recent gain maps at the time of reduction. Pileup was not an issue even for the brightest sources, and no correction has been applied. Energy channels above 6 keV were ignored, since these channels introduce significantly more noise than source signal. Sources were detected using the "Mexican-Hat" wavelet detection routine *wavdetect* in CIAO in an 0.3–6.0 keV band image. We then culled the source list to include only those sources that were detected at the >3 σ level. All images created were corrected for exposure and vignetting. For each source a local background was determined from a circular

TABLE 1

Chandra SAMPLE OF GALAXIES

Galaxy	Type	Distance (Mpc)	M_V	L_X/L_B [a]	S_N	$L_{X,limit}$ (ergs s^{-1})	C_{res} [b]	C_{unres} [c]	C_{gas} [d]
NGC 1553	S0	18.5	−22.0	4.7 ± 0.9	0.5 ± 0.1[e]	1.8×10^{38}	122	567	1153
NGC 3379	E1	10.6	−20.9	4.3 ± 0.3	0.5 ± 0.1[f]	4.1×10^{37}	598	383	208
NGC 4406	S0/E3	17.1	−22.1	6.8 ± 1.3	0.8 ± 0.1[f]	2.6×10^{38}	93	554	4320
NGC 4494	E1	17.1	−21.5	4.4 ± 0.8	0.9 ± 0.3[f]	1.8×10^{38}	165	108	63
NGC 4621	E5	18.3	−21.7	5.0 ± 0.5	1.2 ± 0.3[f]	1.5×10^{38}	307	231	61
NGC 4552	E	15.3	−21.3	8.0 ± 0.6	1.2 ± 0.2[f]	4.9×10^{37}	1057	1408	10602
NGC 3115	S0	9.7	−21.1	5.9 ± 0.4	1.3 ± 0.1[g]	3.0×10^{37}	931	637	292
NGC 4365	E3	20.4	−22.0	8.0 ± 0.6	2.1 ± 0.6[f]	1.0×10^{38}	603	709	801
NGC 1332	S0	22.9	−21.5	7.0 ± 0.8	2.2 ± 0.7[e]	1.4×10^{38}	354	893	3325
IC 1459	E3	29.2	−22.5	8.1 ± 1.2	2.3 ± 0.8[f]	1.8×10^{38}	349	1073	3047
NGC 4278	E1/2	16.1	−21.0	12.5 ± 0.8	3.6 ± 1.0[e]	7.6×10^{37}	488	908	320
NGC 1399	E1	20.0	−22.0	12.9 ± 1.8	4.7 ± 1.0[h]	7.2×10^{38}	1235	1752	20980
NGC 1399	...	...	...	18.0 ± 2.6	7.3 ± 1.6[h]	7.2×10^{38}	1141	1517	16875

[a] In units of 10^{29} ergs s^{-1} $L_{B_\odot}^{-1}$, where L_X is in the 0.3–10 keV band and only includes sources with individual X-ray luminosities below 5×10^{38} ergs s^{-1}. Both L_X and L_B are determined only within the stated field of view.
[b] Background-subtracted counts from resolved LMXBs with $L_X < 5\times10^{38}$ ergs s^{-1} in the area of interest.
[c] Background-subtracted counts from unresolved LMXBs in the area of interest.
[d] Background-subtracted counts from diffuse gas in the area of interest.
[e] Globular cluster specific frequency from Kundu & Whitmore (2001a).
[f] Globular cluster specific frequency from Kundu & Whitmore (2001b).
[g] Globular cluster specific frequency from Kundu & Whitmore (1998).
[h] Globular cluster specific frequency from Ostrov et al. (1998) for 30″−90″ and 90″−150″ annular regions.

annular region with an inner radius that was set to 1.5 times the semimajor axis of the source extraction region and an outer radius chosen such that the area of the background annulus was 5 times the area of the sources extraction region. Care was taken to exclude neighboring sources from the background annuli of each source in crowded regions. For the diffuse emission, background was taken from the same S3 chip well away from the detectable galactic emission.

For our study, we only included sources that fell within the angular area covered by the optical telescope used to determine S_N. For all galaxies except NGC 1399, this was the familiar chevron-shaped *HST* WFPC2 field of view. For NGC 1399, we considered sources within two separate annular rings that were $30''$–$90''$ and $90''$–$150''$ in extent, for comparison to S_N determined in these annular bins by Ostrov et al. (1998) from ground-based observations. For each source, the 0.3–6.0 keV count rate was converted into a flux using a $\Gamma = 1.56$ power-law model, a value typical of the integrated flux from LMXBs in early-type galaxies (Irwin et al. 2003). Unabsorbed fluxes were then determined assuming Galactic hydrogen column densities from Dickey & Lockman (1990) and converted to 0.3–10 keV luminosities assuming surface brightness fluctuation distances of Tonry et al. (2001). The luminosities of each of the sources except the central source (which might be a low-luminosity active galactic nucleus [AGN] rather than an LMXB) were summed to yield $L_{\rm X,\,resolved}$ for each galaxy. To this we added an estimate of the total luminosity of unresolved LMXBs that were either below the detection threshold of the observation or for which crowding at the center of the galaxy precluded their individual detection. To estimate $L_{\rm X,unresolved}$, we tried performing spectral fitting of the diffuse emission to simultaneously model the hot gas (APEC) and unresolved LMXB (power-law) components within XSPEC, but doing so consistently led to a best-fit model that underestimated the 2–6 keV flux by 10%–20%. Evidently, complexities in modeling the hot gas (the effects of temperature gradients and nonsolar abundance ratios) have led the fitting routine to attempt to minimize χ^2 in the numerous, gas-dominated soft energy channels at the expense of the fewer LMXB-dominated hard energy channels. We therefore use an alternative method to determine $L_{\rm X,unresolved}$ in which we assume that the diffuse emission above a certain energy is not contaminated by emission from the hot gas in these galaxies, leaving unresolved LMXBs as the sole source of the diffuse emission. Gas at a temperature of 0.7 keV typically contributes a negligible number of counts above 2 keV given the *Chandra* response, while gas at 0.3 keV contributes negligibly above 1 keV. Starting with the 3–6 keV background-subtracted diffuse flux, we estimated the 0.3–10 keV luminosity of unresolved sources assuming the same $\Gamma = 1.56$ power-law model as was assumed for the resolved sources. We then stepped down the low-energy bound of the diffuse flux determination in 0.5 keV increments until the extrapolation to the 0.3–10 keV band failed to yield a value consistent with the extrapolation from using higher low-energy cutoffs (indicating that hot gas was contributing to the diffuse flux) and calculated the unresolved LMXB luminosity using a lower energy cutoff that was one 0.5 keV increment higher. This estimate for $L_{\rm X,\,unresolved}$ was added to $L_{\rm X,\,resolved}$ to yield $L_{\rm X,\,total}$ for all sources in each galaxy. For most of the galaxies in the sample the resolved source flux represented between 25% and 50% of the total LMXB flux. The 1 σ uncertainty in the luminosity was calculated accordingly from the total number of counts for each galaxy and ranged from 7% to 20%.

A fraction (typically 5%) of the observed X-ray flux emanates from unrelated foreground/background sources along the line of sight to the galaxy. Using the $\log N$-$\log S$ relation of Mushotzky et al. (2000), we have determined the expected number and integrated flux of such sources over the angular area studied and subtracted this flux from the observed flux.

The foreground/background source-corrected $L_{\rm X,total}$ was normalized by the optical light of the galaxy that fell within our angular region of interest. We used the same V-band luminosities from the literature that provided the values of S_N. Historically, $L_{\rm X}/L_{\rm opt}$ has been given in terms of the B-band luminosity ($L_{\rm X}/L_B$), so for comparison to previous studies, we convert the V-band luminosities to B band using published $B - V$ values. Since all the galaxies in our sample have nearly identical $B - V$ values, the choice to use B-band luminosities rather than V-band luminosities has a minimal impact on the results.

4. THE CASE OF NGC 1399

Since most of the galaxies in our sample have globular cluster specific frequencies at or below 2.0, the addition of a galaxy with a very high S_N value such as NGC 1399 would considerably improve the constraint on the $L_{\rm X}/L_B$ versus S_N relation. Unfortunately, the hot gas within NGC 1399 is about 1 keV. At this temperature and given the large amount of gas that NGC 1399 contains, the gas is still contributing appreciably to the flux at 3 keV. In addition, the gaseous flux from NGC 1399 fills the entire S3 chip, making background subtraction problematic. As a result, our method of estimating the unresolved LMXB emission from the amount of diffuse emission in the hard energy band will not work.

An alternative way of estimating the integrated LMXB luminosity from NGC 1399 is to use the fact that the X-ray luminosity functions of the sources within early-type galaxies are fairly regular, at least for sources less luminous than 5×10^{38} ergs s^{-1}. From the other galaxies in our sample for which the detection limit was below 10^{38} ergs s^{-1}, we calculated the fraction of the total integrated flux emanating from sources with luminosities in the range $(1–5)\times10^{38}$ ergs s^{-1}, i.e., $f = \sum L_{{\rm X},i}\ [(1–5)\times 10^{38}\ {\rm ergs\ s^{-1}}]/\sum L_{{\rm X},i}\ (<5\times10^{38}\ {\rm ergs\ s^{-1}})$, and found that f was reasonably similar from galaxy to galaxy, ranging from 34% to 48%, with a mean of 41% and a standard deviation of 5%. We then determined the luminosity from resolved sources in the range $(1–5)\times10^{38}$ ergs s^{-1} for NGC 1399 and divided this luminosity by 0.41 ± 0.05 to yield the total luminosity from LMXBs in NGC 1399. This was done separately for two annular rings $30''$–$90''$ and $90''$–$150''$. The detection limit for this observation of NGC 1399 was 7×10^{37} ergs s^{-1}, so we can be reasonably assured of detecting all sources above 10^{38} ergs s^{-1} outside of $30''$. For the inner $30''$ the high X-ray surface brightness of the hot gas precluded the detection of all but the most luminous sources, rendering this technique ineffective for this region.

5. THE $L_{\rm X}/L_B$ VERSUS S_N RELATION

The $L_{\rm X}/L_B$ versus S_N relation for the galaxies in our sample is shown in Figure 2. We fit a linear model of the form $L_{\rm X}/L_B = AS_N + B$ to the data using a linear regression algorithm that accounts for errors in both quantities (see Fasano & Vio 1988). Here $L_{\rm X}/L_B$ is in units of 10^{29} ergs s^{-1} $L_{B_\odot}^{-1}$. Without including the two data points from NGC 1399, the best-fit coefficients are $A = 2.72 \pm 0.47$ and $B = 2.87 \pm 0.50$ (1 σ uncertainties). Note that the two data points for NGC 1399 lie near the best-fit relation, indicating that our alternative technique for determining $L_{\rm X}/L_B$ for NGC 1399 is reasonable. If we include NGC 1399, the best-fit constants are $A = 2.41 \pm 0.33$ and $B = 3.12 \pm 0.39$.

The best-fit relation between $L_{\rm X}/L_B$ and S_N most closely resembles the prediction of case 3 shown in Figure 1. Here B differs from 0 at the 8.0 σ level and strongly argues that a significant

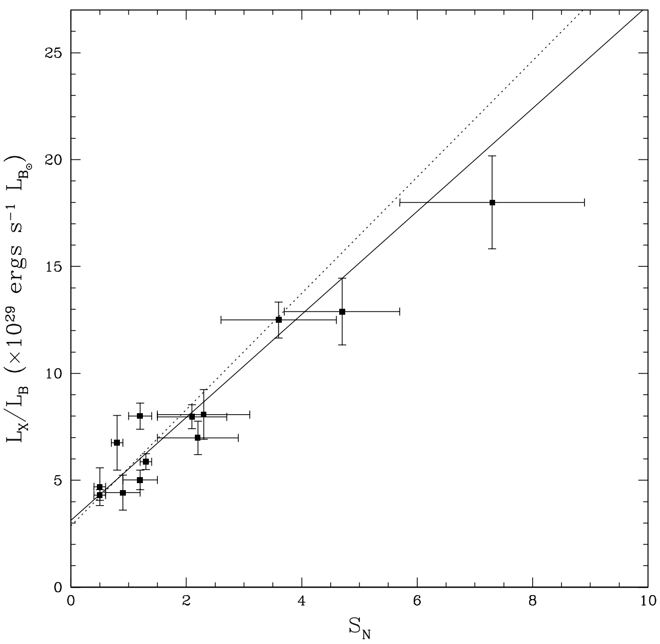

FIG. 2.—L_X/L_B relation for the 12 galaxies in our sample (with two data points from NGC 1399) with 1 σ uncertainties for both quantities. The dotted line represents the best-fit relation if NGC 1399 is omitted, while the solid line represents the best-fit relation if NGC 1399 is included in the fit. In both cases, the y-intercept of the relation is clearly different from 0, indicating that some of the LMXBs are formed in the field.

fraction of LMXBs were truly formed in the field, rather than having been formed within globular clusters and later escaped. If the latter had occurred, we would still expect a linear relation through the origin (case 2).

One potential cause of bias in a study of this nature stems from the fact that LMXBs are observed to occur in red globular clusters 3 times more often than in blue globular clusters, both within the Milky Way (Grindlay 1993) and in nearby elliptical galaxies (Kundu et al. 2002; Sarazin et al. 2003). A galaxy with a higher fraction of red globular clusters would create more LMXBs than a galaxy with a lower fraction of red globular clusters, even if both galaxies had the same total number of globular clusters. This would create scatter in the L_X/L_B versus S_N relation that might bias the results drawn from it. To test whether this has affected our results, we determined the fraction of red clusters in each galaxy in our sample, using the $V-I$ histograms of the globular clusters for each galaxy published in the literature (Kundu & Whitmore 1998, 2001a, 2001b). We considered a globular cluster to be blue if its $(V-I)_0 < 1.1$ and red if its $(V-I)_0 > 1.1$ (following Kundu et al. 2002). The observed colors were corrected for Galactic extinction. For the galaxies in our sample the red fraction of globular clusters varied from 24% to 48%. Previous studies have found that red clusters have a $\sim$6% chance of harboring a $>10^{37}$ ergs s^{-1} LMXB, while blue clusters have a $\sim$2% chance. Given these fractions, we found that a galaxy with a red globular cluster fraction of 48% will produce about 30% more LMXBs than a galaxy with a red globular cluster fraction of only 24%, neglecting the presence of field LMXBs. If field LMXBs are included and are assumed to comprise roughly half of the total LMXBs in a galaxy, the difference in the total number of LMXBs (and hence L_X/L_B) between the two galaxies diminishes to 15%, or $\pm$8% from the mean. This is on the order of the statistical uncertainties of each galaxy in our sample. Furthermore, the red fraction of globular clusters is uncorrelated with S_N for the galaxies in our sample, eliminating the possibility that this effect introduces any systematic bias to the L_X/L_B versus S_N relation. Thus, while a varying fraction of red clusters in a galaxy can introduce some scatter in the L_X/L_B versus S_N relation, it is not enough to change the overall results of this study.

Another possible source of bias is if a nonnegligible fraction of the unresolved hard X-ray flux emanated from a large population of weak X-ray emitters (i.e., RS CVn systems, cataclysmic variable, M stars, or some other unknown X-ray emitter) rather than LMXBs. If the summed X-ray luminosity of such sources scales linearly with the mass of the galaxy, then this would account for at least part of the derived $(L_X/L_B)_{\rm field}$ value that we had assumed to be exclusively from LMXBs, and the removal of such a component from the L_X/L_B versus S_N relation would diminish the statistical need for a field-born population of LMXBs (i.e., B would be lowered and less constrained). To investigate this, we have analyzed an archival 38 ks *Chandra* observation of the bulge of M31, which we assume can serve as an adequate template for the X-ray population of old stellar populations like those within the galaxies of our sample. We found that 86% of the 2–6 keV flux was resolved into point sources with luminosities exceeding 1.5×10^{36} ergs s^{-1}. Thus, if there is a hidden population of weak X-ray emitters within old stellar populations, they contribute less than 14% to the hard X-ray flux, or equivalently, less than 14% of our best-fit B value.

It should be noted that a nonzero y-intercept implies that all or most LMXBs in the field formed in the field only if we assume that a significant number of globular clusters were not destroyed after the ejection of the LMXB (or if the LMXB survived the process that destroyed the globular cluster). If many globular clusters were destroyed, this would have the effect of reducing S_N while leaving L_X/L_B unchanged, shifting the true L_X/L_B versus S_N relation to the left. Thus, it might be possible that if all LMXBs were formed within globular clusters (case 2), the present-day L_X/L_B versus S_N relation could resemble case 3

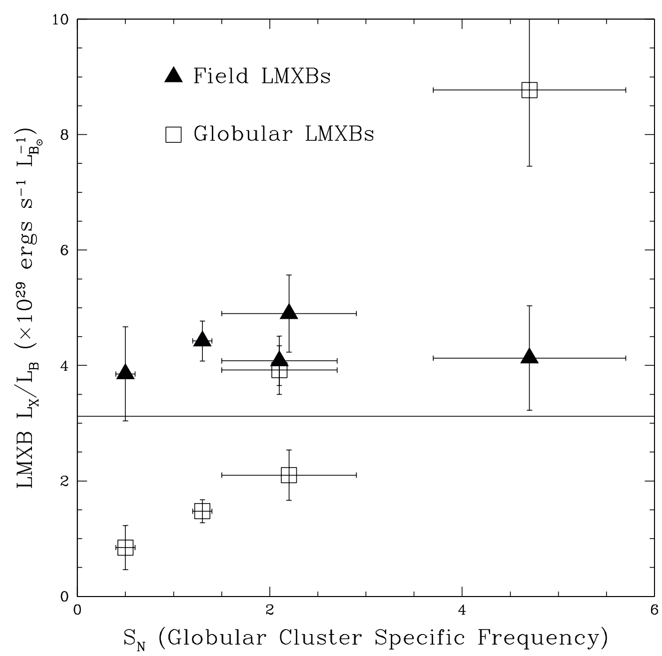

FIG. 3.—L_X/L_B relation for which L_X/L_B has been broken into its *observed* globular cluster and field components for NGC 1553, NGC 3115, NGC 4365, NGC 1332, and NGC 1399. The solid horizontal line represents the predicted initial field L_X/L_B value. The fact that the data points lie above this line (especially the S0 galaxies NGC 3115 and NGC 1332) indicates that the field has been polluted to some extent by LMXBs that have escaped from globular clusters.

TABLE 2
FRACTION OF LMXBs WITHIN GLOBULAR CLUSTERS

Galaxy	S_N	Initial Percentage (from Eq. [2])	Measured Percentage
NGC 1553	0.5 ± 0.1	28 ± 4	18^{+9}_{-12} [a]
NGC 4472	1.1 ± 0.1	46 ± 2	42^{+7}_{-6} [b]
NGC 3115	1.3 ± 0.1	50 ± 2	25^{+9}_{-8} [c]
NGC 4649	1.4 ± 0.2	52^{+3}_{-4}	47^{+6}_{-9} [d]
NGC 4365	2.1 ± 0.6	62^{+6}_{-8}	49^{+6}_{-10} [a]
NGC 1332	2.2 ± 0.7	63^{+6}_{-9}	30^{+11}_{-9} [e]
NGC 1399 (30″–90″)	4.7 ± 1.0	78^{+3}_{-4}	68^{+8}_{-9} [f]

[a] Sarazin et al. (2003).
[b] Kundu et al. (2002).
[c] Kundu et al. (2003).
[d] Randall et al. (2004).
[e] Humphrey & Buote (2004).
[f] Angelini et al. (2001).

if enough globular clusters were destroyed. However, this cannot be accomplished by simply destroying the same fraction of globular clusters in each galaxy (dividing the original S_N of each galaxy by a constant), as this would still lead to a best-fit relation through the origin, which is not seen. What would be required is that some galaxies have lost a much higher fraction of their globular clusters than other galaxies. From Figure 2, even if we assume that the galaxies with $S_N > 2$ have not lost any globular clusters, it would require that the two lowest S_N galaxies (NGC 1553 and NGC 3379) have lost about two-thirds of their globular clusters (i.e., they had an original S_N of $\sim$1.5) if the original L_X/L_B versus S_N relation were to go through the origin. While the globular cluster destruction rates of Vesperini (2000) predict such a high destruction rate for galaxies less massive than 10^{10} $M_\odot$, NGC 1553 and NGC 3379 have masses approaching 10^{12} $M_\odot$, given their absolute visual magnitudes and a reasonable M/L ratio. Vesperini (2000) predicts that galaxies of this mass should only lose about 10% of their original globular cluster population. Furthermore, NGC 1553 and NGC 3379 have absolute visual magnitudes comparable to the $S_N > 2$ galaxies (Table 1), so it is unclear why these galaxies should lose such a high fraction of their globular clusters while the other galaxies do not. Finally, the destruction of such a large number of globular clusters in certain galaxies would lead to much more pollution of LMXBs into the field than in galaxies that lost few globular clusters. This would lead to a large dispersion in the measured L_X/L_B values of the field LMXBs. In Figure 3 we show the L_X/L_B versus S_N relation, where L_X/L_B has been broken into its *observed* field and globular cluster components for the galaxies in our sample for which observed fractions of LMXBs within globular clusters appear in the literature (and listed in the fourth column of Table 2). Whereas $(L_X/L_B)_{\rm globular}$ is a strong function of S_N, $(L_X/L_B)_{\rm field}$ is not any higher in the $S_N = 0.5$ galaxy than it is for $S_N > 2$ galaxies, indicating that it has not undergone significantly more pollution than galaxies with higher S_N.

6. THE INITIAL AND PRESENT-DAY FRACTIONS OF LMXBs WITHIN GLOBULAR CLUSTERS

The nonzero y-intercept of the L_X/L_B versus S_N relation demonstrates that LMXBs are formed within the field, but it does not eliminate the possibility that at least some of the present-day field population was ejected from globular clusters. If some of the present-day field LMXBs actually were created in and later escaped from globular clusters, we would expect the present-day fraction of LMXBs within globular clusters to be smaller than the initial fraction of LMXBs within globular clusters. The latter quantity can be predicted from our L_X/L_B versus S_N relation and can be given in terms of the best-fit constants A and B along with S_N for each galaxy:

$$\text{Initial \% of LMXBs within GCs} = \frac{(L_X/L_B)_{\rm GC}}{(L_X/L_B)_{\rm total}} = \frac{AS_N}{AS_N + B}. \qquad (2)$$

It is important to keep in mind that nowhere in the determination of the L_X/L_B versus S_N relation (and therefore the determination of the initial fraction of LMXBs within globular clusters) did we use the knowledge of the *observed* (present-day) fraction of LMXBs within globular clusters. Thus, the comparison of the initial fraction of LMXBs formed within globular cluster to the present-day observed fraction is not tautological in nature. In Table 2 we compare the initial and measured fractions of LMXBs formed within globular clusters for those galaxies for which such a measurement exists in the literature. We have also included NGC 4472 and NGC 4649, two galaxies we excluded from our original sample because they contain large amounts of $\sim$1 keV gas that prevents an accurate determination of the unresolved LMXB flux. There is good agreement between the initial and measured fractions of LMXBs within globular clusters for the four elliptical galaxies (NGC 4472, NGC 4649, NGC 4365, and NGC 1399), where the measured fraction is only slightly lower than the initial fraction, indicating that relatively few LMXBs have escaped from globular clusters in these galaxies. However, for the three S0 galaxies (NGC 1553, NGC 3115, and NGC 1332) the measured fraction is about a factor of 2 less than the initial fraction, indicating that a significant number of globular cluster LMXBs have escaped into the field in these galaxies. This is illustrated further in Figure 3, where it can be seen that the field L_X/L_B values of the S0 galaxies NGC 3115 and NGC 1332 (NGC 1553 has large statistical uncertainties) are several sigma above the best-fit predicted initial L_X/L_B value of 3.12×10^{29} ergs s^{-1} $L_{B_\odot}^{-1}$ (our best-fit constant B from § 5), with the difference being from LMXBs ejected from globular clusters into the field. Such an effect is seen to a lesser extent in the elliptical galaxies NGC 4365 and NGC 1399, where fewer LMXBs were ejected from LMXBs.

7. DISCUSSION

The shape of the L_X/L_B versus S_N relation for the 12 early-type galaxies in our sample strongly argues that the number of LMXBs in a galaxy does not scale directly with the number of globular clusters the galaxy contains. We have demonstrated that the nonzero y-intercept of the L_X/L_B versus S_N relation is not the result of large-scale globular cluster destruction or a variation in the red-to-blue globular cluster ratio but instead can only be explained in terms of a population of LMXBs that formed within the field.

These field LMXBs are most likely primordial binary systems formed during the the last major star formation episode of the galaxies 5–12 billion years ago. Obviously, these sources cannot be persistent X-ray emitters, since the mass accretion rates needed to power the observed X-ray luminosities would consume all the mass of a $<$1 $M_\odot$ donor star in $<10^8$ yr. The onset of the X-ray active phase of the LMXB may be delayed by several billion years in wider binary systems if the donor star is required to enter its red giant phase in order to overflow its Roche lobe. In addition, wide binaries are expected to be transient in nature, with LMXBs with periods of >1 day expected to be in their "off" stage >75% of the time (Piro & Bildsten 2002), further lengthening the lifetime of an LMXB system. On the other hand, LMXBs within globular clusters are most likely short-period systems owing to the fact that frequent stellar encounters will serve to tighten the orbit of an existing binary, leading to persistent X-ray emission in these systems (again from Piro & Bildsten 2002). This expected transient nature of long-period primordial LMXBs and persistent nature of short-period dynamically created LMXBs could be used as a means of confirming that present-day field LMXBs were created in the field if multiepoch X-ray observations find that field LMXBs are transient whereas globular cluster LMXBs are persistent emitters. The largely transient nature of field LMXBs would also imply that the efficiency of creating LMXBs in the field is much higher than previously thought, since at any given time we are only observing the small fraction of the total field LMXB population that happen to be in their "on" ($L_X > 10^{37}$ ergs s^{-1}) state.

Given that S_N generally increases with galactic radius (Ashman & Zepf 1998), equation (1) predicts that L_X/L_B should increase with increasing galactic radius. This is in fact seen in NGC 1399, for which the measured L_X/L_B increases by about 50% as S_N increases from 4.7 in the $30''$–$90''$ annular bin to 7.3 in the $90''$–$150''$ annular bin. The fraction of LMXBs found within globular clusters should also increase as a function of radius as the number of globular cluster LMXBs increases (per unit light), whereas the number of field LMXBs remains constant (also per unit light). Deeper *Chandra* observations will test this prediction, although considerable care will be needed to account for the fact that contamination by background AGN is more prevalent at larger radii, and failure to account for this will lead to an underestimate of the true fraction of LMXBs within globular clusters. Also, the effects of possible radial gradients in the red/blue ratio of globular clusters will need to be properly accounted for in determining the fraction of LMXBs within globular clusters as a function of radius.

Another key result of this study is that the fraction of LMXBs currently within globular clusters of S0 galaxies is only half of the initial fraction of LMXBs within globular clusters predicted from the L_X/L_B versus S_N relation. This effect is not seen in the elliptical galaxies in our sample, for which the predicted initial fractions of LMXBs within globular clusters is consistent with (albeit slightly lower than) the measured fractions. It is unlikely that the higher than expected fraction of field LMXBs in S0s is the result of LMXBs forming more efficiently in the fields of S0s than in ellipticals, since the required number of "extra" field LMXBs would lead to $(L_X/L_B)_{\rm total}$ values for S0s that are a factor of 2 greater than in elliptical galaxies with the same S_N, and $(L_X/L_B)_{\rm field}$ values that are 3 times higher. Previous studies have indicated that there are no discernible differences in the properties of globular clusters within S0 and elliptical galaxies that might account for the increased escape rate of LMXBs from globular clusters within S0 galaxies. Kundu et al. (2001a, 2001b) found that mean colors, mean half-light radii, and luminosity functions of the globular clusters found in samples of S0 and elliptical galaxies were statistically identical. This would argue that the LMXB ejection mechanism does not involve processes internal to the clusters such as supernova kicks. Another reason why supernova kicks are not favored is that such a kick would remove the neutron star or black hole from the globular cluster only a few million years after the formation of the cluster. Spending such a short period of time within the cluster would eliminate the advantage that globular clusters have in creating LMXBs (Maccarone et al. 2003), meaning that these LMXBs would effectively be primordial binaries too. Instead, it is more likely that LMXBs within globular clusters of S0 galaxies have been removed by the tidal disruption (but not destruction) of globular clusters. This effect is expected to be more pronounced within S0 galaxies than in elliptical galaxies, owing to the presence of disks in S0s that are lacking in ellipticals. Gravitational shocks caused by the passage of a globular cluster through a disk are much stronger than passage through a bulge distribution (Fall & Zhang 2001), leading to a greater number of LMXBs ejected from globular clusters in S0 galaxies than in ellipticals. Clearly, more observations are needed to confirm this hypothesis. If the field LMXBs in S0s are composed of a mix of primordial binaries and LMXBs ejected from globular clusters, then the former should be transient X-ray emitters while the latter should be persistent emitters. On the other hand, field LMXBs within elliptical galaxies should nearly all be transient. Once again, multiepoch X-ray observations of the field LMXBs could confirm this picture if the predicted ratio of persistent-to-transient field LMXBs is measured.

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