ON THE NATURE OF X-RAY SOURCES IN EARLY-TYPE GALAXIES

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ABSTRACT

We show that the observed relationship between the fraction of low-mass X-ray binaries (LMXBs) found in globular clusters (GCs) and the globular cluster specific frequency for early-type galaxies is consistent with a LMXB formation model in which the field population of LMXBs is formed in situ via primordial binary formation. The suggestion that a significant fraction of the field LMXB population in early-type galaxies was formed in GCs is not required by the data. Finally, we discuss observational studies which test this model more thoroughly.

Subject headings: binaries: close — X-rays: binaries — X-rays: galaxies — galaxies: elliptical and lenticular — globular clusters: general

1. INTRODUCTION

Low angular resolution studies of early-type galaxies found that the X-ray emission from these systems typically consists of two components, a soft, thermal component from hot gas, and a harder, power-law component attributed to unresolved X-ray binaries (e.g., Matsumoto et al. 1997). The superb angular resolution of the Chandra X-ray Observatory has allowed for a significant fraction of the power-law component to be resolved into point sources, confirming the binary nature of the hard component (e.g., Sarazin et al. 2000). Early-type galaxies are generally dominated by stellar populations older than 1 Gyr. Thus, the majority of X-ray binaries in these galaxies are low-mass X-ray binaries (LMXBs), rather than the short-lived (~ 10^7 yr) high-mass variety. LMXBs consist of a neutron star (NS) or black hole (BH) accreting material from a ≤ 1 M⊙ donor.

A number of early-type galaxies have been studied with Chandra in an effort to understand the LMXB population of these galaxies. Combined X-ray and optical studies have found that 20–70% of the LMXBs in early-type galaxies are associated with globular clusters (GCs: Angelini et al. 2001; Blanton et al. 2001; Sarazin et al. 2001, 2003; Kundu et al. 2002, 2003; Maccarone et al. 2003; Syakov et al. 2003; Humphrey & Buote 2004; Jordan et al. 2004; Randall et al. 2004). This is significantly larger than the roughly 10% of LMXBs found in GCs, denoted by \( f_{\text{LMXB,GC}} \), is equal to

\[
    f_{\text{LMXB,GC}} = \frac{N_{\text{LMXB,GC}}}{N_{\text{LMXB,GC}} + N_{\text{LMXB,F}}},
\]

where \( N_{\text{LMXB,GC}} \) and \( N_{\text{LMXB,F}} \) are the numbers of LMXBs found in GCs and the field, respectively.

It has long been recognized that GCs produce ~ 100 times more LMXBs per unit mass than the field of the Galaxy. This enhanced formation efficiency is attributed to dynamical interactions between NSs and stars in the dense environments of GCs (e.g., Clark 1975). Observational evidence suggests that ~ 4% of GCs have a bright (\( L_X \gtrsim 5 \times 10^{37} \) erg s⁻¹) LMXB regardless of the host galaxy morphological type (e.g., Kundu et al. 2002). Given the similarities in the average properties of GCs in all galaxies (e.g., Ashman & Zepf 1998), this constant LMXB formation efficiency is not surprising and is a measure of the efficiency of dynamical formation mechanisms. We then expect that \( N_{\text{LMXB,GC}} \) is proportional to the number of GCs in the galaxy. The number of GCs is equal to \( N_{\text{GC}} \) times the galaxy luminosity in the appropriate units. For our purposes, it is more interesting to give \( N_{\text{LMXB,GC}} \) in terms of the galaxy mass, so we assume a fixed mass-to-light ratio for our sample galaxies. Therefore, we find that

\[
    N_{\text{LMXB,GC}} \propto S_N M_*,
\]

where \( M_* \) is the stellar mass of the galaxy. Here, and throughout, we neglect differences in the stellar mass-to-light ratio of our sample galaxies as we are primarily...
concerned with early-type systems. Were we to compare early- and late-type galaxies, it would more appropriate to use the mass normalized GC specific frequency (e.g., Ashman & Zepf 1998).

LMXBs in the field of the Galaxy are the descendants of primordial binaries containing a massive star. LMXBs have a long (~1 Gyr) lag time between star formation and the X-ray active phase (White & Ghosh 1998) and therefore track the star formation history over long timescales. For a single starburst model for star formation in early-type galaxies, the number of LMXBs formed from primordial binaries will be a function of the stellar mass involved in the star formation event and the time since star formation occurred. Initially, the number of active LMXBs will increase until ~1 Gyr and then begin to decrease with time (White & Ghosh 1998). The exact time dependence of the LMXB population is unknown. In addition, complex star-formation histories, such as small starbursts associated with mergers, will complicate the time dependence for any galaxy. For our model, we assume that the time dependent variation of the field LMXB population is small when comparing different early-type galaxies. Under this assumption, $N_{\text{LMXB,F}}$ is simply proportional to $M_\star$.

Plugging the relationships for $N_{\text{LMXB,GC}}$ and $N_{\text{LMXB,F}}$ into Equation (1) and rearranging, we find

$$f_{\text{LMXB,GC}} = \left(1 + \frac{C}{S_N}\right)^{-1},$$

where $C$ is a constant that accounts for the formation efficiencies in GCs and the field, and the mass-to-light ratio of the galaxies. To test this model, we have accumulated data from the literature for 9 early-type galaxies with both Chandra observations and GC identifications. Table II gives the values of $S_N$ and the calculated fraction of LMXBs found in GCs. We then fit this data with a function of the form

$$f_{\text{LMXB,GC}} = \left(A + \frac{B}{S_N}\right)^{-1},$$

where $A$ and $B$ were both allowed to vary. We find that $A = 1.19 \pm 0.19$ and $B = 3.9 \pm 1.0$, with a reduced chi-squared for the fit of 0.74. The data and best-fit function are shown in Figure 1. For reference, we have included a data point for the Milky Way with $S_N = 0.5$ and $f_{\text{LMXB,GC}} \approx 0.1$ (Harris 1991; Liu et al. 2001). The Milky Way data point includes both the disk and bulge contributions. As we see, the data follow the expected trend from our model. Therefore, we conclude that the field population of LMXBs in early-type galaxies was formed in the field from primordial binaries. While it is intriguing that the best-fit model also fits the Milky Way data point, it should be noted that for a luminosity limit similar to those found in studies of early-type galaxies, the fraction of LMXBs in GCs in the Milky Way is highly uncertain due to low number statistics, difficulties in determining the distance to Galactic LMXBs, and the issue of including transient systems in the statistics. As noted earlier, mass-to-light ratio differences may also be important when comparing the GC specific frequency across morphological types.

We can also compare the prediction of this model to other observed properties of the LMXBs in early-type galaxies. White et al. (2002) found that $L_X/L_{\text{opt}}$ for the hard spectral component in early-type galaxies was proportional to $S_N^{1 \pm 0.4}$. Assuming that the total X-ray luminosity of the LMXBs can be approximated by $L_{X,\text{total}} = (L_X) N_{\text{LMXB}}$, where $L_X$ is an average X-ray luminosity per binary, assuming the same average luminosity for GC and field systems (see Sarazin et al. 2003), and $N_{\text{LMXB}}$ is the total number of LMXBs in the galaxy, our model would predict that $L_{X,\text{total}}/L_{\text{opt}}$ varies linearly with $S_N$. While not the same relationship found by White et al. (2002), we find that the data is equally well fit by our model. It has also been shown that $N_{\text{LMXB}}$ and $L_{X,\text{total}}$ in early-type galaxies is proportional to the stellar mass of the galaxies with a weak dependence on the morphological type (Gilfanov 2004). Our model would also predict that $N_{\text{LMXB}}$ and $L_{X,\text{total}}$ is proportional to the stellar mass of the galaxies with some dependence on the GC specific frequency which could yield the morphological type difference seen. It should be noted that Gilfanov (2004) suggest that statistics and inaccurate calibration of the near-infrared mass-to-light ratio may cause some of the morphological dependence seen in their data. Our model would predict that the dependence on $S_N$ would be in the order of a factor of 1.5 given the galaxies in the Gilfanov (2004) sample, similar to what was measured. However, the inclusion of late-type galaxies may actually decrease the significance of this effect given the expected difference in the field LMXB population formation. A further study encompassing early-type galaxies with a larger range of $S_N$ values is warranted.

The high ($L_X \gtrsim 5 \times 10^{37}$ erg s$^{-1}$) observed luminosities of the LMXBs in early-type galaxies has been used to suggest that such systems could not have formed from primordial binaries since the X-ray lifetimes of such systems would be much shorter than the stellar age of the galaxy. The general argument is that at $5 \times 10^{37}$ erg s$^{-1}$ and with a 1 $M_\odot$ companion, the system would have an X-ray active phase of less than $\approx 100$ Myr. There are

![Fig. 1.- Fraction of the LMXB population found in GCs (given in percent) plotted versus the GC specific frequency, $S_N$ for 9 early-type galaxies. The best-fit model is overplotted. Included is a data point for the Milky Way LMXB population which was not used in the fit.](image-url)
many difficulties with this conclusion. First, the lag time between binary formation and LMXB activity can be quite long. If the companion is a 1 $M_\odot$ donor that starts mass transfer after the donor has turned off the main sequence, then the binary was formed more than 10 Gyr ago. For systems which start mass transfer on the main sequence, the time between the formation of the binary and start of mass transfer is dictated by either gravitational radiation or magnetic braking, both of which have characteristic timescales on the order of a few Gyr (e.g., Pfahl et al. 2003).

It is also important to recognize that the mass-transfer rates observationally inferred may not accurately reflect the long-term mass-transfer rates due to short-timescale fluctuations, such as the disk ionization instability or X-ray irradiation of the companion (e.g., van Paradijs 1996, Binning & Ritter 2001). Due to such effects, intrinsically low ($\sim 10^{-10} M_\odot$ yr$^{-1}$) mass-transfer rate systems can masquerade as high mass-transfer rate systems. All of the BH LMXBs in the Milky Way, as well as a comparable number of NS systems, exhibit X-ray outburst phases where the maximum luminosity is a significant fraction of the Eddington limit for the compact object. These systems, commonly referred to as soft X-ray transients (SXTs), are thought to have low mass-transfer rates from the donor such that the accretion disk is unstable to the disk ionization instability (van Paradijs 1996). In SXTs, the systems undergo outbursts lasting days to months (and even years in some cases) and then return to a quiescent state. The recurrence time can be as short as a year or longer than the history of X-ray astronomy. While the disk instability model works well in predicting which systems are likely to undergo this phenomena, it provides no clues as to the length of the X-ray outbursts or recurrence times. Other transient phenomena, such as the effect of X-ray irradiation on the donor (e.g., Binning & Ritter 2004), can also cause intrinsically low mass-transfer systems to have observed luminosities much higher than expected.

3. GLOBULAR CLUSTER CONTRIBUTION TO FIELD LMXBS

It has been suggested that GCs may contribute to the field LMXB population through ejection of LMXBs or disruption of the clusters (e.g., White et al. 2002). These alternatives have been invoked for a number of reasons including the expected short X-ray active lifetimes of LMXBs formed from primordial binaries and the similarities in the X-ray properties of the field and GC populations of LMXBs. But it is important to recognize that once LMXBs leave the GC environments, either through ejection or disruption, they will evolve like primordial binaries and would have similar X-ray active lifetimes. Therefore, GC formation of field LMXB scenarios require a constant input of LMXBs into the field to account for the observed population.

The same dynamical processes that form LMXBs in GCs would be responsible for the ejection of these systems. Therefore, the number of LMXBs ejected from GCs in any galaxy would be proportional to the number of GCs or $S_N M_\star$. If all of the field LMXBs were due to ejections, we would expect no dependence of $f_{\text{LMXB,GC}}$ on $S_N$. Our data rule out this scenario at greater than the 99.99% confidence level. While not required, we can not rule out that some small fraction of the field LMXB population was ejected from GCs with the current data. The upper limit on the fraction of the field population due to ejections is dependent on $S_N$. For $S_N = 2.0$, we find that $\lesssim 20\%$ of the field population of LMXBs could have been ejected from GCs.

Theoretical studies of GC disruption find that a significant fraction of the GCs in a galaxy will be disrupted with the exact fraction showing some dependence on the galaxy properties (e.g., Vesperini 2000, Fall & Zhang 2001). If we assume that disruption of a GC does not change the probability for LMXB formation in the cluster, then to fully account for the number of LMXBs seen in the field of early-type galaxies, the number of disrupted clusters must be between 0.5–4 times the number of GCs currently observed. Such numbers push the limits of what is expected from current models for GC disruption (Vesperini 2000), but LMXBs from disruptions cannot be ruled out. One difficulty though, is that a significant fraction of the disruptions may occur early in the history of the galaxy, in the first $\lesssim 3$ Gyr. At early times, the dynamical interactions in GCs may be less efficient at producing LMXBs (e.g., Davies & Hansen 1998).

4. DISCUSSION

We have shown that the observed relationship between the fraction of LMXBs found in GCs and the GC specific frequency in early-type galaxies is consistent with the field population of LMXBs forming in situ via primordial binary formation. To test our model, better data for both $f_{\text{LMXB,GC}}$ and $S_N$ are required. In current studies, only a fraction the LMXB population in early-type galaxies can be compared to the GC population due to differences in the field of views of the instruments. More thorough coverage of the Chandra field of view by GC studies will improve the statistics for $f_{\text{LMXB,GC}}$. The values for $S_N$ are also subject to observational uncertainties due to uncertainties in the estimates of both the number of GCs and the optical magnitude of the galaxies. Of particular note is the recent revision in $S_N$ for NGC 1399 (see Dirsch et al. 2003).

A measurement of a time-dependence in the number of field LMXBs per unit galaxy mass would also verify our model. This measurement requires good estimates of the stellar age of galaxies. In addition, understanding how both stellar age measurements and LMXB populations are affected by complex star-formation histories is necessary to interpret the results. Trager et al. (2000) found that galactic age estimates from single stellar population models are heavily weighted by young stars. No comparable study of the theoretical prediction for LMXB populations has been performed. As noted previously, White et al. (2002) found that the total X-ray luminosity attributed to LMXBs in early-type galaxies was not correlated with stellar age, but their analysis included the contributions from both field and GC LMXBs. The GC LMXBs are not expected to be dependent on the stellar age of the galaxy, and therefore the inability to separate GC and field LMXBs, due to the low spatial resolution of ASCA, may explain why no age dependence was found in the White et al. (2002) study.

The spatial distribution of GCs is generally more extended than the galaxy light (e.g., Ashman & Zepf 1998). In addition, GC spatial profiles flatten at small radii.
Our model predicts that given the different formation sites for GC and field LMXBs, there would be similar radial distribution differences seen in the LMXB population. Kundu et al. (2002) found that the radial profiles of field and GC LMXBs were roughly similar, although their study was limited in the number of systems (30 and 42 for GC and field LMXBs, respectively) and the radial extent sampled. Better coverage of the LMXB and GC populations is necessary, especially at the inner and outer regions of the galaxies where the GC and optical light profiles are the most different. Two additional effects must also be considered: i) how supernova kicks will affect the distribution of primordial binaries in the field, and ii) how the preference of GC LMXBs to be located in red, rather than blue, GCs (Angelini et al. 2001; Kundu et al. 2002; Sarazin et al. 2003; Jordan et al. 2004) affects the GC LMXB distribution.

Given the different formation mechanisms for field and GC LMXBs, it is reasonable to assume that the distributions of the physical parameters (i.e., orbital period, donor mass, and mass transfer rates) will be different. This, in turn, could yield differences in the observed luminosity function. Yet how different the luminosity function will be is unknown. At present, no theoretical study of the predicted physical parameters of GC LMXBs exists. Such a study is essential in determining if a luminosity function difference is expected and/or measurable. Also, a better understanding of how transient behavior affects the observed luminosity function is also necessary. Multi-epoch observations of LMXBs in early-type galaxies will provide more information on the transient behavior of LMXBs, although longer observations are required to distinguish between real transient behavior (luminosity changes of more than 3 orders of magnitude) and the factor of ~10 variability commonly seen in persistent LMXBs (Liu et al. 2001 and references therein).

Finally, it has been suggested that the lack of spectral differences between field and GC LMXBs supports a common origin for these systems (Maccarone et al. 2003). There is no observational evidence for differences in the spectral parameters of field and GC LMXBs in the Milky Way (e.g., Christian & Swank 1997). Therefore, it is unlikely that any spectral differences would be seen, particularly given the low spectral sensitivity studies of LMXBs in early-type galaxies.

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TABLE 1

| Galaxy     | S_N | N_{LMXB,GC} | N_{LMXB} | f_{LMXB,GC} (%) | Refs^b |
|------------|-----|-------------|----------|----------------|--------|
| NGC 1332   | 2.2 ± 0.7 | 9           | 30       | 30.0 ± 7         | 1.2    |
| NGC 1399   | 5.1 ± 1.2 | 26          | 38       | 68.0 ± 6         | 3.4    |
| NGC 1553   | 1.5 ± 0.5 | 2           | 11       | 18.0 ± 9         | 5.6    |
| NGC 3115   | 1.6 ± 0.4 | 9           | 36       | 25.0 ± 8         | 7.8    |
| NGC 4365   | 4.3 ± 0.6 | 18          | 37       | 49.0 ± 9         | 5.9    |
| NGC 4472   | 3.6 ± 0.6 | 30          | 72       | 42.0 ± 5         | 10.11  |
| NGC 4486   | 14 ± 4    | 60          | 96       | 63.0 ± 6         | 12.13  |
| NGC 4649   | 6.7 ± 1.4 | 22          | 47       | 47.0 ± 6         | 5.14   |
| NGC 4697   | 2.35 ± 0.15 | 32         | 89       | 36.5 ± 5         | 15.16  |

^a The total number of X-ray point sources covered by the field of view of the optical globular cluster catalogs.

^b References: (1) Kundu & Whitmore (2001), (2) Humphrey & Buote (2004), (3) Binning et al. (2001), (4) Angelini et al. (2001), (5) Kissler-Patig (1997), (6) Sarazin et al. (2003), (7) Puzia et al. (2004), (8) Kundu et al. (2003), (9) Sivakoff et al. (2005), (10) Rhode & Zepf (2001), (11) Maccarone et al. (2003), (12) McLaughlin et al. (1992), (13) Jordan et al. 2004, (14) Randall et al. 2004, (15) Jordan et al. 2005, in prep., (16) Sivakoff et al. 2005, in prep.
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