THE CONNECTION BETWEEN LOW MASS X-RAY BINARIES AND GLOBULAR CLUSTERS

Gregory R. Sivakoff
Advisor: Craig L. Sarazin
Department of Astronomy, University of Virginia

Abstract

Massive galaxies contain globular clusters (GCs: dense, spherical concentrations of millions of stars), which can be studied in the nearby universe using NASA’s Hubble Space Telescope. Increased stellar interactions, arising from the high stellar densities in GCs, are thought to efficiently form low-mass X-ray binaries (LMXBs), binary stars with one normal star (having a mass \( \lesssim M_{\text{Sun}} \)) and either a neutron star or black hole. At the distance of most nearby galaxies, the stars in an LMXB cannot be detected optically; however, LMXBs emit profuse amounts of X-rays, allowing their detection with NASA’s Chandra X-ray Observatory. We explore the optical properties of GCs containing LMXBs by combining data from Hubble and Chandra for eleven massive elliptical galaxies. Globular clusters that are more massive, smaller in extent, and contain more heavy elements are more likely to contain LMXBs. These results are part of a larger effort probing the formation and evolution of LMXBs, GCs, and ultimately their host galaxies.

Introduction

In a typical elliptical galaxy (classified optically by its ellipsoidal shape, in contrast to a spiral galaxy whose shape is dominated by a flattened disk with spiral structure) no star formation has occurred for billions of years. Since the most massive stars (stars with \( M \gtrsim 8M_{\text{Sun}} \)) burn their nuclear fuel quickly (\( t \lesssim 30\text{Myr} \)), the only remnants of massive stars in elliptical galaxies are stellar-mass black holes (BHs) and neutron stars (NSs). These objects, the end-states of massive stars, have such strong gravity that they are two of the most extreme types of objects in the Universe. By themselves, BHs/NSs are not detectable in nearby elliptical galaxies. If there is a normal star closely orbiting the BH/NS (i.e., a close binary star), the gravity from the BH/NS can pull off the outer envelope of the normal star. As the material from the stellar envelope accretes onto the BH/NS, the material reaches temperatures of millions of degrees, and emits X-rays. Since there are no massive stars in elliptical galaxies, these systems must be low-mass X-ray binaries (LMXBs; so named because the normal star has \( M \lesssim M_{\text{Sun}} \)).

The Chandra X-ray Observatory\(^1\) is one of NASA’s Great Observatories. Launched 1999 July 23, this satellite uses four nested pairs of grazing incidence (small angle reflection) paraboloid and hyperboloid mirrors to collect and classify individual X-ray photons with energies of 0.1–13 keV. Its ability to see details on \( \approx 0.5'' \) (the equivalent of being able to see the two headlights on a car from about 400 miles away) and its relatively large collecting area (400 cm\(^2\) at 1 keV) make it ideal for studying individual LMXBs in nearby elliptical galaxies. A single chip of the Advanced CCD Imaging Spectrometer (ACIS) has a \( \approx 8' \times 8' \) field-of-view (FOV); most nearby elliptical galaxies fit on a single chip. The large sample of bright LMXBs (\( L_X > 10^{37} \text{erg/s} \)) in elliptical galaxies (\( \approx 50–200 \) per galaxy, e.g., Sarazin et al. 2000, 2001; Angelini et al. 2001; Sivakoff et al. 2003) allows studies of LMXB formation and evolution that complement what we can do in our own Galaxy with its \( \approx 150 \) active LMXBs (\( L_X > 10^{36} \text{erg/s} \)).

The Hubble Space Telescope\(^2\) is also one of NASA’s Great Observatories. It was launched 1990 April 24, and has been upgraded by four service missions. Typical reflecting mirrors (a concave primary plus a convex secondary) collect the intensity of light with wavelengths (\( \lambda \)) from 200–2400 nm) depending on the instrument used. Since Hubble orbits above the atmosphere, its ability to see detail (called resolution) is diffraction limited; with a primary mirror of 2.4 m, its resolution at 1000 nm is \( \approx 0.1'' \) (the equivalent of being able to see the two headlights on a car from about 2000 miles away). At the distance of most of the nearby elliptical galaxies, Hubble can resolve objects with diameters that are \( \approx 20\) travr. In the last servicing mission, the Advanced Camera for Surveys (ACS) was installed. ACS samples its \( \approx 3' \times 3' \) FOV (twice that of the previous imaging instrument) at the best resolution Hubble can achieve.

Globular clusters (GCs) are spherical concentrations of tens of thousands to million of stars (Binney & Tremaine 1987). The stars are so tightly packed that their density can reach \( 10^7 \) times the stellar density near the Sun. Since typical GCs are \( \approx 60\) travr in diameter, Hubble can resolve GCs in nearby elliptical galaxies. In the Milky Way, \( \approx 10\% \) of LMXBs are located in globular clusters; however, GCs account for a much smaller fraction of the optical light in the Galaxy. Globular clusters are more efficient at producing LMXBs (by a factor of \( \approx 300 \)) than the field. This greater efficiency is attributed to dynamical interactions of stars in the dense interiors.

---

\(^1\)See http://chandra.harvard.edu

\(^2\)See http://hubblesite.org

Sivakoff
of GCs (e.g., Katz 1975; Clark 1975).

Earlier work showed that the connection between GCs and LMXBs is stronger in elliptical galaxies than the Milky Way, with ~20–70% of the LMXBs being associated with GCs (Sarazin et al. 2000, 2001; Angelini et al. 2001; Kundu et al. 2002). Since massive elliptical galaxies also tend to have more GCs than the Milky Way, they are fertile grounds for exploring the LMXB-GC connection.

To study the LMXB-GC connection, we need to know the properties of both populations. The existing lists of GCs for elliptical galaxies are rather incomplete. Since atmospheric effects blend the GCs into the diffuse galaxy emission, ground-based observations generally do not detect GCs from the inner regions of elliptical galaxies, where most of their LMXBs are located. Additionally, GCs are not resolved in ground-based optical images of galaxies at the distance of most nearby elliptical galaxies; candidate GCs are identified by luminosities and (potentially) colors. Therefore, many of the candidate GCs may be unrelated faint optical objects. Since Hubble orbits the Earth, there are no atmospheric effects to blend the GCs into the diffuse galaxy emission. Hubble can detect GCs in the inner regions of galaxies and measure their shape. Prior to the installment of the ACS, only a small portion of a galaxy could be surveyed in a single observation. Taking advantage of the ACS capabilities, the ACS Virgo Cluster Survey & ACS Fornax Cluster Survey have obtained deep, high-resolution F475W and F850LP images of the central ≈ 3’ × 3’ of 144 nearby elliptical galaxies. One of their products is a sample of extragalactic GCs with unprecedented depth and uniformity. From these Hubble ACS images, thousands of GCs associated with these galaxies are identified and their positions, magnitudes, colors, metallicities (abundance of elements besides hydrogen and helium), and structural parameters are derived. We collaborate with the PIs of both surveys, comparing the LMXB and GC properties.

In this paper, we present preliminary results that explore the optical properties of GCs containing LMXBs. We combine data from Chandra and Hubble for eleven massive early-type galaxies, the ten brightest galaxies in the ACS-VCS and an additional nearby galaxy. This sample is the largest sample of galaxies comparing the connection between LMXBs and GCs to date. By comparing the properties of GCs that do and do not contain LMXBs, we find that GCs that are more massive, smaller in extent, and contain more heavy elements are more likely to contain LMXBs. These discoveries have implications for the formation and evolution of LMXBs in GCs. Future work will explore these implications and extend our discussion to the formation and evolution of GCs and their host galaxies.

### Galaxy Sample

We measured the optical properties of GCs using Hubble. Our sample includes the ten brightest galaxies in the ACS-VCS (NGC 4472, 4486, 4406, 4365, 4382, 4374, 4649, 4526, 4552, and 4621) and NGC 4697 a similarly bright galaxy that has been observed with the same setup as the ACS-VCS. These galaxies all had archival or proprietary data from Chandra that we used to identify the positions of X-ray sources. Since these galaxies are primarily archival, the observational setup varied between galaxies. Since the galaxies are the brightest, they are the most likely to have large populations of both LMXBs and GCs. Table 1 summarizes the properties of the galaxies and the Chandra observations. Columns 1 through 3 lists the galaxy name, distance to the galaxy (1 Mpc = 3.26 Mlyr), and optical magnitude in the B-band ($M_B$; magnitudes are a negative logarithmic measure of the observed flux; more negative magnitudes indicate brighter galaxies). Columns 4 through 6 list the Chandra observation identification number (OBSID), detec-

---

### Table 1

**PROPERTIES OF GALAXIES AND Chandra OBSERVATIONS**

<table>
<thead>
<tr>
<th>Galaxy Distance (Mpc)</th>
<th>$M_B$ (mag)</th>
<th>OBSID</th>
<th>Detector</th>
<th>$t_{exp}$ (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
</tr>
<tr>
<td>4365</td>
<td>23.2</td>
<td>-21.3</td>
<td>2015</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4374</td>
<td>18.7</td>
<td>-21.3</td>
<td>0803</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4382</td>
<td>17.9</td>
<td>-21.3</td>
<td>2016</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4406</td>
<td>18.0</td>
<td>-21.5</td>
<td>0318</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4472</td>
<td>16.8</td>
<td>-21.9</td>
<td>0321</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4486</td>
<td>15.7</td>
<td>-21.6</td>
<td>0352</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4472</td>
<td>16.8</td>
<td>-21.9</td>
<td>0321</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4486</td>
<td>15.7</td>
<td>-21.6</td>
<td>0352</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4472</td>
<td>16.8</td>
<td>-21.9</td>
<td>0321</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4486</td>
<td>15.7</td>
<td>-21.6</td>
<td>0352</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4472</td>
<td>16.8</td>
<td>-21.9</td>
<td>0321</td>
<td>ACIS-S3</td>
</tr>
<tr>
<td>4486</td>
<td>15.7</td>
<td>-21.6</td>
<td>0352</td>
<td>ACIS-S3</td>
</tr>
</tbody>
</table>
tor used, and the exposure time after removing periods of high backgrounds ($t_{exp}$). Since the ACIS-I chips are less sensitive then ACIS-S3, we only include data from ACIS-I when its exposure is $> 25\%$ of the ACIS-S3.

**Optical Sources from Hubble**

In the *Hubble* ACS-VCS, the center of galaxies were observed using two 360s exposures in the F475W band, two 560s exposures in the F850LP band, and one 90s F850LP exposure. For NGC 4697, the observations were virtually identical except for an additional 15s in each F475W exposure. In our sample over 10,000 optical sources were characterized by their magnitudes in both bands, sizes encompassing half of the light of the GC (hereafter the half-light size, $r_h$), and positions as determined by KINGPHOT (Jordán et al. 2005). All magnitudes were converted to absolute magnitudes ($G_{475}$ and $Z_{850}$) using the distances derived from surface brightness fluctuation measurements of the optical observations (S. Mei et al. 2006, in preparation). We used magnitude, color ($0.5 < G_{475} - Z_{850} < 1.9$), and size criteria to select 7,084 likely GCs. In elliptical galaxies, there are often two populations of GCs, blue-GCs and red-GCs, that probably represent two different epochs of star-formation. For each galaxy, we used the division point in the $G_{475} - Z_{850}$ color following Peng et al. (2006a) to divide the GCs into blue-GCs and red-GCs; these division point ranged from 1.10 to 1.23. The positions of the GCs were also converted into the distance from each galaxy’s center, $d_{GC}$. Since galaxies have intrinsically different sizes, we have rescaled these distances by the galaxies’ effective radii, $r_{eff}$, which are the galactic equivalent of the half-light radii. We summarize the observed properties of the GCs in our sample in Figures 1 and 2.

From the magnitude, colors, and sizes, we can derive physical parameters that might impact the formation and evolution of LMXBs in GCs. We calculate the GC mass ($M$) directly from the Z-band magnitude,

$$M = Y_Z 10^{-0.4 (M_{Z_{850}} - M_{Z_{475}})} ,$$

where the mass-to-light ratio, $Y_Z \equiv 1.45$, is predicted by the synthetic PEGASE models (Fioc & Rocca-Volmerange 1997), and $M_{Z_{475}} = 4.512$ is the absolute Z-band magnitude of the Sun from calcpht in IRAF. There is a correlation between $r_h$ and $G_{475} - Z_{850}$ that may indicate that the size encompassing half of the mass of the GC (hereafter the half-mass size, $r_{h,M}$) differs from the half-light size (e.g., Jordán 2004; Jordán et al. 2005). We therefore calculated

$$r_{h,cor} = r_h 10^{0.17((G_{475} - Z_{850}) - 1.2)}$$

following Jordán et al. (2005), and assumed this was the half-mass size.

The dynamical formation model of LMXBs in GCs is the leading explanation for the larger efficiency of LMXB production in GCs compared to the fields of galaxies. In this model, the binary is either formed by tidal capture or through exchange interactions between a NS/BH and an existing binary. In both cases, the encounter rate ($\Gamma$) is thought to depend on the properties of GCs at their cores; $\Gamma \propto \rho_0^{3/2} r_c^2$, where $\rho_0$ is the core density, $r_c$ is the core radius, and the virial theorem has been assumed\(^3\) to connect core velocities to densities and radii. Although these parameters are not directly measurable at the distance of the Virgo cluster, we can create a proxy,

$$\Gamma_h = \left(\frac{M}{2\pi}\right)^{1.5} (r_{h,M})^{-2.5},$$

where we have assumed that the relation between core structural parameters and the parameters at a half-mass radius (dictated by the concentration, $c$) is the same for all GCs. Although the latter assumption is not strictly true, it need only be true that the distribution of $c$ not depend on other parameters. If GCs with higher concentrations are more likely to contain LMXBs, than the $\Gamma_h$ we calculate will underpredict the interaction rate.

**X-ray Sources from Chandra**

To identify the discrete X-ray source population, we applied a wavelet detection algorithm (the CIAO wavedetect program) on $\sqrt{2}$ scales ranging from 1 to 32 pixels with a source detection threshold of $10^{-6}$ to the ACIS S3 or I chips. Source detection did not occur in regions with an exposure of less then 10% of an observation. To maximize S/N, we analyzed the wavelet detection results from combined observations when available. We used the coordinate list generated by WAVDETECT in ACIS Extract 3.34 (Broos et al. 2002) to refine the source positions. This was accomplished by determining the mean positions of events in source extraction regions consistent with the X-ray point spread functions (PSFs) at the sources’ positions. Most of the regions encircled 90% of the X-ray PSF at $\approx 1.5$ keV. For sources whose median photon energy was not $\approx 0.6$--2.6 keV, we determined the PSF at either $\approx 0.3$ keV or $\approx 4.5$ keV. We used a lower percentage of the PSF in the cases of a few sources whose regions would otherwise have overlapped.

The *Chandra* observations do not have uniform sensitivity; the luminosity of a source with 20 counts is listed in Figure 4. For the purposes of this paper, we considered all 675 detected X-ray sources that were also in the FOV of the *Hubble* observations. Since NGC 4486 has complex gas emission in its center that may lead to false detections, we excluded X-ray sources in regions match-
Fig. 1.— Scatterplot of GC magnitudes \((Z_{850})\) versus GC colors \((G_{475} - Z_{850})\), with integrated histograms of the properties above and to the right of the scatterplot. GCs unmatched to LMXBs are indicated by small black dots and unfilled black histograms (scaled down by a factor of 10). Blue GCs with LMXBs are indicated by filled blue squares and histograms. Red GCs with LMXBs are indicated by filled red circles and histograms. The histograms of the GCs with LMXBs are stacked on each other. GCs that are redder (larger \(G_{475} - Z_{850}\)) and brighter (more negative \(Z_{850}\)) are more likely to contain LMXBs.
Fig. 2.— Scatterplot of GC galactocentric distances ($d_{GC}$) versus observed GC half-light sizes ($r_h$), with integrated histograms of the properties above and to the right of the scatterplot. The symbols follow that of Figure 1. GCs that are smaller (lower $r_h$) are more likely to contain LMXBs. The galactocentric distance does not appear to affect whether a GC contains an LMXB.
Fig. 3.— Scatterplot of estimated GC half-light sizes ($r_{h,cor}$) versus GC colors ($G_{475} - Z_{850}$), with integrated histograms of the properties above and to the right of the scatterplot. The symbols follow that of Figure 1. There is no color dependence of $r_{h,cor}$, indicating we have successfully removed the color dependence of half-light radius $r_h$. GCs that are redder (larger $G_{475} - Z_{850}$) and smaller in extent (lower $r_{h,cor}$) are more likely to contain LMXBs.

Sivakoff 6
Fig. 4.— Summary bar graphs of the number of LMXBs in the Hubble field-of-view for each galaxy (NGC). The number of LMXBs unmatched to GCs (field-LMXBs) are indicated by black. The statistical number of false matches, indicated by grey, have been removed from the number of LMXBs truly matched to blue-GCs and red-GCs, indicated by blue and red respectively. The number of LMXBs within 1″ of both a red-GC and a blue-GC are indicated by purple; it is unlikely that these sources are field-LMXBs.

Analysis Technique

Given X-ray source positions from Chandra observations and optical source positions from HST-ACS observations, X-ray and optical sources within 1″ of each other (after a relative astrometry correction using a cross-correlation technique for each galaxy) were considered to be matched. The X-ray detections in GCs were all considered to be low-mass X-ray binaries (LMXBs). We separated the GCs into two sub-populations, those that clearly contained an LMXB at our detection levels (indicated by a subscripted X), and those that clearly did not (indicated by a subscripted nX). If an LMXB was within 1″ of multiple GCs (18 LMXBs fell in this category), those GCs were not included in either sub-population. We found 270 GCs that contained an LMXB at our detection levels and 6,488 GCs that clearly did not.

By randomizing the position angles of a source list, assuming both circular profiles and profiles matching the galaxies’ elliptical isophotes, we can predict the number of false matches within a given matching radius for each galaxy. As indicated in Figure 4, only a small fraction of matched LMXBs and GCs are false. Over the entire sample, we expect 25 false and 245 true matches.

From Figures 1 and 2, it is clear that LMXBs are found more often in GCs that are brighter (15.6σ), are redder (6.6σ), and have smaller half-light radii (8.1σ); distance (1.6σ) does not play a strong role. We have used the non-parametric Wilcoxon rank-sum tests to quantify these results. Given that redder GCs are more likely to contain LMXBs and have smaller half-light radii, we also examined our estimate of the half-mass radii (Figure 3); GCs that are smaller in extent are still more likely to contain LMXBs (5.9σ). Prior work indicated brighter and redder extragalactic GCs are more likely to contain...
The percentage of GCs containing an LMXB as a function of GC magnitudes ($Z_{850}$), colors ($G_{475} - Z_{850}$), half-mass sizes ($r_{h,cor}$), and galactocentric distances ($d_{GC}$). GCs that are brighter, are redder, and have smaller half-mass radii are more likely to contain LMXBs. The bins were set by requiring 27 GCs with LMXBs per bin.

LMXBs (e.g. Sarazin et al. 2003; Kundu et al. 2003); our work places these results are very high confidence levels. The relation with size has not been presented before, although there were indirect indications of this relation in Jordán et al. (2004).

An alternate way of examining these relations is through binning the GCs by the different parameters and looking for non-uniform probabilities of GCs containing an LMXB. We display these results (binning by the properties of 27 GCs with LMXBs per bin) in Figure 5. All errors are corrected properly assuming Poisson statistics (i.e., strict confidence intervals are calculated as opposed to using the $\sqrt{N}$ approximation). These plots have been corrected for the average false identification of a matched GC-LMXB, folding in the error for estimating the average false number of identifications.

**Interpretation**

The rough relation indicated in Figure 5 for magnitude, combined with the mass-magnitude relation suggest a power-law dependence on the GC mass. Since brighter GCs have more stars, one might expect a linear relation with the number of stars, which is traced by mass. On the other hand, the dynamical formation model for LMXBs in GCs suggests a steeper relation ($9M^{1.5}$).

From Figure 5, a semi-logarithmic dependence on color is suggested for $G_{475} - Z_{850} \lesssim 1.4$. If this dependence was due to a property that differs between the blue-GC population and the red-GC population (e.g., formation history), we would expect to see a step-function relation. We believe the smooth monotonic rise is the strongest evidence to date suggesting changes in GC metallicity affect the probability a GC contains an LMXB. There are several ideas that could explain the relation between metallicity and the likelihood a GC will contain an LMXB. First, metal-rich stars may have larger radii and masses compared to metal-poor stars (Bellazzini et al. 1995). This would make it easier to form LMXBs. Ivanova (2006) suggested that higher convection in metal-rich stars leads to a larger magnetic field that could also make it easier to form LMXBs in higher metallicity systems. Third, metal-rich GCs may produce more NSs/BHs per unit mass; for instance, the initial number of stars as a function of mass (IMF) could vary (Grindlay 1987). A larger number of NSs/BHs would increase the number of LMXBs that can form. Fi-
nally, irradiation-induced winds, which would be weaker in metal-rich stars due to more efficient metal line cooling, slow down the evolution of LMXBs in metal-rich clusters (Maccarone et al. 2004). With a longer lifetime, more LMXBs would be observed at any given time since their formation in the more metal-rich clusters.

In Figure 5, there also appears to be a rough power-law dependence on half-mass size. The dynamical formation theory for LMXBs in GCs suggests this power-law should be $(r_{h,3M})^{-2.5}$.

Since there are three properties that all appear to affect the probability a GC contains an LMXB, we must perform a simultaneous fit. We have assumed the expected number of LMXBs in a GC ($\lambda$) has the following dependence on GC properties:

$$\lambda = A \, M^{\alpha} \, 10^{(G_{475} - Z_{850})/2.5} \, (r_{h,3M})^{\delta}, \quad (4)$$

where the normalization ($A$) and exponents ($\alpha, \beta, \text{and} \, \delta$) must be fitted. The expected number of LMXBs in a GC can be converted to a probability that there are no LMXBs, $P_{N,L} = e^{-\lambda}$, and the probability that there is at least one LMXB, $P_{X,i} = 1 - e^{-\lambda_i}$. One can then maximize the log likelihood for a given form of $\lambda$, $\psi = \ln([\prod P_{N,L}]/[\prod P_{X,i}])$, where the products are taken over the lists of GCs with no LMXBs and GCs with LMXBs. Since the log likelihood can be related to $\Delta \chi^2$, $\psi = -\Delta \chi^2/2$, we can use the change in log likelihood for one degree of freedom (dof) to determine one-dimensional errors (1$\sigma$) on each varying parameter. We derive $\alpha = 1.086^{+0.054}_{-0.056}$, $\beta = 0.78^{+0.12}_{-0.11}$, and $\delta = -1.90^{+0.20}_{-0.20}$. We can apply this dependence of $\lambda$ for all detected GCs to predict the percentage of GCs containing LMXBs as a function of GC magnitude, color, and half-mass size (Figure 6) and bin these predictions to calculate a $\chi^2 = 22.6$ (7.8 + 12.8 + 2.0) for 26 dof.

The index for mass is almost consistent with a simple scaling to the number stars in a GC; however, the existence of relations with size and color clearly indicate other effects play a role. Principal component analysis among the properties of GCs with LMXBs indicates the first eigenvector is dominated by a combination of mass and half-mass radius, while the second is dominated by color. The combination of mass and half-mass radius is inconsistent with a linear dependence of $\lambda$ on $r_h$; instead, it is best fit by a $r_h^{0.728^{+0.040}_{-0.040}}$ dependence. The dependence of $\lambda$ with interaction rate matches the galactic value found by Pooley et al. (2003) of $\lambda \propto r_h^{0.742^{+0.036}_{-0.036}}$. The dependence of $\lambda$ with color is consistent with that found in Jordán et al. (2004), which used data just from NGC 4486 to rule out models where metallicity-dependent stellar sizes affect LMXB formation.

From Figure 6, we see that the declining efficiency for a GC with $G_{475} - Z_{850} > 1.4$ to contain an LMXB can be reproduced although we assume no break in the relation between color and $\lambda$. This suggests that the masses and half-mass radii of GCs at these colors may be different than at bluer colors. One possible explanation is contamination by diffuse stellar clusters, which are redder, fainter cousins of GCs (e.g., Larsen & Brodie 2000; Peng et al. 2006b).

**Conclusions & Future Work**

By comparing the optical properties of GCs that do and do not contain LMXBs in a sample of eleven galaxies, we clearly show that GCs that are brighter (more massive) and redder are more likely to contain LMXBs confirming the findings of Sarazin et al. (2003) and Kundu et al. (2003). Additionally, we find that GCs that have smaller half-light radii are more likely to contain...
LMXBs. This paper presents the first clear indication that GC half-mass radius affects the likelihood a GC will contain an LMXB. We believe the detailed dependence of a GC containing an LMXB on color in our data is the strongest evidence to date that GC metallicity (i.e., the abundance of elements heavier than helium) affects LMXB formation and evolution.

The indices measuring the dependence of the expected number of GCs containing LMXBs against mass and half-mass radius appear to be correlated. This is highly suggestive that the likelihood of a GC containing an LMXB as a function of dynamical properties is not solely due to the greater number of stars in more massive GCs. We interpret the expected number of GCs containing LMXBs against mass (and half-mass radius) appear to be correlated. This is consistent with the theoretical prediction of being proportional to $\Gamma_0^{0.728 \pm 0.040} \times 10^{(G_{d} - Z_{850}) (0.78 - 0.12)}$. While this is inconsistent with the theoretical prediction of being proportional to $\Gamma_0$, it is consistent with the galactic data of Pooley et al. (2003). We believe that this is the most direct evidence to date that dynamical formation plays a primary role in forming LMXBs in the dense stellar environs of GCs.

These results are part of a larger effort probing the formation and evolution of LMXBs, GCs, and, ultimately their host galaxies. The relations between GC properties and their likelihood to contain LMXBs, particularly with regards to GC encounter rates and metallicity, appear to probe the formation and evolution of LMXBs. Further X-ray and optical studies of the LMXB-GC connection will allow us to address these issues in greater detail. We are working to perform similar analysis in the other nearby galaxy cluster, Fornax, as well as more detailed studies of particularly interesting galaxies. Future work with this sample and other galaxies will compare the X-ray properties of the LMXBs that are in GCs to those that are not (i.e., field-LMXBs). In the fields of galaxies, where total mass is high and stellar density is low, the primordial LMXB scenario (both stars in the binary forming together) dominates for in-situ formation; however, some dynamically-formed LMXBs may have escaped from the GCs they were formed in. Field-LMXBs that are formed dynamically in GCs trace the history of GCs and their interaction with the host galaxy. Field-LMXBs that are formed primordially trace the star formation history of the galaxy. We hope to develop our understanding of the origin of field-LMXBs (primordial, dynamically-formed, or a combination of the two) so that we may use LMXBs to constrain galaxy histories.

Acknowledgments

We thank Patrick Côté, Andres Jordán, and the rest of the ACS Virgo Cluster Survey team for access to and help with their optical data. We also thank Elizabeth Blanton, Joel Bregman, and Adrienne Juett for their very helpful advice. Support for this work was provided by the National Aeronautics and Space Administration through Chandra awards GO3-4099X, AR4-5008X, GO4-5093X, and GO5-6086X, issued by the Chandra X-ray Observatory, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060. Support for Program numbers HST-GO-10003.01-A, HST-GO-10597.03-A, and HST-GO-10582.02-A was provided by NASA through grants from the Space Telescope Science Institute, which is operated by AURA under NASA contract NAS5-26555. This research was also partially supported by the Celerity Foundation and the F. H. Levinson Fund. G. R. S. acknowledges the receipt of Achievement Award for College Scientists and Virginia Space Grant Consortium Aerospace Graduate Research fellowships.

References