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DYNAMICAL FORMATION OF CLOSE BINARY SYSTEMS IN GLOBULAR CLUSTERS

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ABSTRACT

We know from observations that globular clusters are very efficient catalysts in forming unusual short-period binary systems or their offspring, such as low-mass X-ray binaries (LMXBs; neutron stars accreting matter from low-mass stellar companions), cataclysmic variables (white dwarfs accreting matter from stellar companions), and millisecond pulsars (rotating neutron stars with spin periods of a few milliseconds). Although there has been little direct evidence, the overabundance of these objects in globular clusters has been attributed by numerous authors to the high densities in the cores, which leads to an increase in the formation rate of exotic binary systems through close stellar encounters. Many such close binary systems emit X-radiation at low luminosities ($L_X \lesssim 10^{34}$ ergs s^{-1}) and are being found in large numbers through observations with the *Chandra X-Ray Observatory*. Here we present conclusive observational evidence of a link between the number of close binaries observed in X-rays in a globular cluster and the stellar encounter rate of the cluster. We also make an estimate of the total number of LMXBs in globular clusters in our Galaxy.

Subject headings: binaries: close — globular clusters: general — X-rays: binaries

Since the first evidence from the *Uhuru* and *OSO 7* satellites revealed a population of highly luminous ($L_X \gtrsim 10^{36}$ ergs s^{-1}) low-mass X-ray binaries (LMXBs) in globular clusters, it has been noted that the formation rate per unit mass of these objects is orders of magnitude higher in globular clusters than in the Galactic disk (Katz 1975; Clark 1975). This discovery stimulated a flurry of theoretical work in the formation of globular cluster LMXBs by the processes of two- and three-body encounters (Katz 1975; Clark 1975; Fabian, Pringle, & Rees 1975; Sutantyo 1975; Hills 1975, 1976; Heggie 1975). These dynamical formation scenarios (as opposed to the independent evolution of primordial binaries) are a natural explanation for the high occurrence of LMXBs in globular clusters since the stellar densities, and hence encounter rates, are much higher in the cores of globulars than other regions of the Galaxy. Verbunt & Hut (1987) showed that the 11 bright LMXBs known at that time in globular clusters (currently, there are 13 known; White & Angelini 2001) were consistent with being formed dynamically through close encounters.

The population of close binaries in a globular cluster, in turn, exerts a great influence on the dynamical evolution of the cluster. Heggie's law (Heggie 1975) tells us that close binaries tend to become even closer, on average, through encounters with single stars or other less close binaries. While doing so, they increase their binding energy by transferring significant energy to other stars in their environment. Even a modest population of primordial binaries contains a potential reservoir of binding energy that easily exceeds the kinetic energy of all single stars in the cluster. One of the consequences is that primordial binaries can postpone deep core collapse (Goodman & Hut 1989; Hut et al. 1992). For a general introduction and review, see Heggie & Hut (2003) and Meylan & Heggie (1997).

The interplay between stellar dynamics and stellar evolution, as external and internal factors modifying the binary properties, is highly complex, and many details of these processes are not well understood (Hut et al. 2003; Sills et al. 2003). The aim of this publication is to employ recent X-ray data to focus in a reasonably model-independent way on the gross environmental effects that clusters exert on their binary population and, in turn, on the feedback of the binaries in changing their environments. Our approach is to study the close binary populations of clusters that differ greatly in their physical properties. This has only recently become feasible in large part because of the *Chandra X-Ray Observatory*.

As the *Chandra* observations of 47 Tuc (Grindlay et al. 2001a), ω Centauri (Rutledge et al. 2002), NGC 6397 (Grindlay et al. 2001b), NGC 6440 (Pooley et al. 2002b), NGC 6626 (Becker et al. 2003), and NGC 6752 (Pooley et al. 2002a) have shown, high spatial resolution X-ray images are one of the most effective methods of finding large numbers of close binaries in globular clusters since many of them (quiescent LMXBs, cataclysmic variables [CVs], millisecond pulsars [MSPs], and coronally active main-sequence binaries) are low-luminosity X-ray emitters. This population of low-luminosity X-ray sources was first discovered by Hertz & Grindlay (1983a, 1983b) using data from the first fully imaging X-ray satellite, the *Einstein Obser-*

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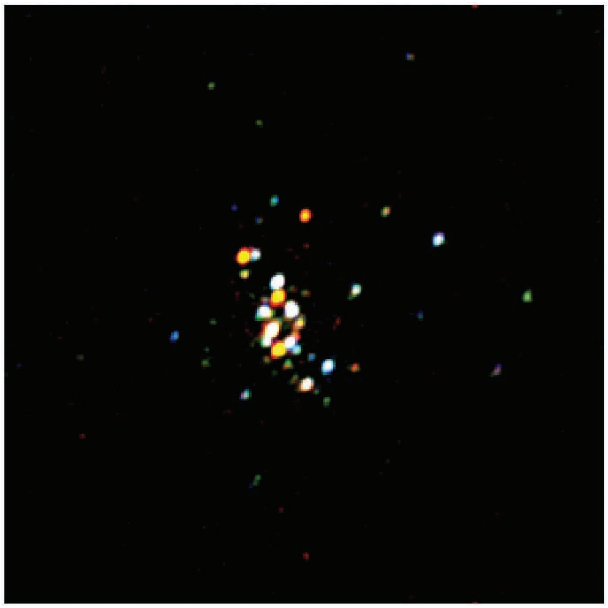

FIG. 1.—*Chandra* image of the globular cluster NGC 6266. This 63 ks observation was made with the ACIS-S3 chip on 2002 May 12. Photons in the range of 0.5–1.2 keV are shown in red, 1.2–2.5 keV photons in green, and 2.5–6 keV photons in blue. The image is 2′.46 on a side, corresponding to the cluster's half-mass diameter. Fifty-one sources are detected in this observation using the wavelet-based algorithm WAVDETECT supplied by the *Chandra* X-ray Center. The image has been smoothed by convolution with a two-dimensional Gaussian with an FWHM of 1″, which corresponds to the telescope's point-spread function. A more detailed analysis of this data is in preparation.

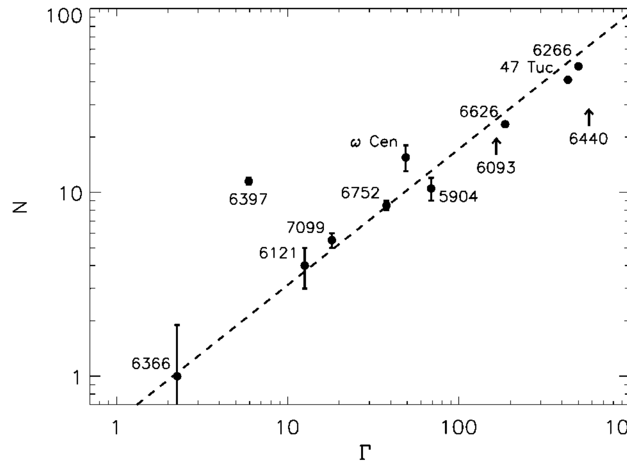

FIG. 2.—Number of globular cluster X-ray sources (N) with $L_X \gtrsim 4 \times 10^{30}$ ergs s^{-1} vs. the normalized encounter rate Γ of the cluster. The normalization has been chosen such that $\Gamma/100$ is roughly the number of LMXBs in a cluster or, for the cases $\Gamma < 100$, the percent probability of the cluster hosting an LMXB. An arrow indicates a globular cluster for which the *Chandra* observation did not reach the required sensitivity.

vatory. Later observations with the X-ray imaging satellite *ROSAT* expanded the known population of these objects; in observations of 55 globular clusters with *ROSAT*, 57 low-luminosity X-ray sources were discovered (Verbunt 2001).

Because these systems are on average heavier than most other members of a globular cluster, they sink in the cluster's gravitational potential to the crowded center, thus requiring high spatial resolution telescopes to resolve them. The advantage of *Chandra*'s subarcsecond spatial resolution is clearly seen in the image of the globular cluster NGC 6266 (Fig. 1), one of the richest clusters observed to date. Fifty-one sources are detected within the cluster's 1′.23 half-mass radius. Approximately two or three are background sources (see below). Not only can *Chandra* resolve the sources, it also has the energy resolution to distinguish spectral differences among them. In the image, photons in the range 0.5–1.2 keV are shown in red, those in the range 1.2–2.5 keV are shown in green, and those in the range 2.5–6 keV are in blue.

To explore the relationship between a cluster's physical properties and its close binary population, we used published results and available data for the 12 clusters so far observed with *Chandra*. We searched each cluster for sources to a limiting luminosity of about 4×10^{30} ergs s^{-1} (in the 0.5–6 keV range) using a wavelet-based algorithm available from the *Chandra* X-ray Center. (Two of the clusters—NGC 6093 and NGC 6440—were not observed long enough to reach this luminosity limit.) To estimate the number of sources associated with the cluster, we count all sources detected within the half-mass radius of the cluster and subtract the estimated number of background sources based on the log N– log S relationship of Giacconi et al. (2001). The uncertainty in the number of sources in a cluster in Figure 2 is due to the uncertainty in the estimates for the number of background objects (Table 1).

Following Verbunt & Hut (1987), we estimate the encounter rate per unit volume (R) of a cluster as $R \propto \rho^2/v$, where ρ is the density and v is the velocity dispersion. For each cluster (except NGC 6440), we perform a volume integral of this quantity from the center to the half-mass radius to obtain our estimate for the encounter rate Γ (Table 1). The forms of ρ and v as functions of radius are easily obtained from the models developed by King (1966), which can be specified by the parameters tabulated by Harris (1996) in the 2003 February version of his catalog. The normalizations are set by the central values ρ_0 and v_0 (which differs from the analysis of Verbunt & Hut, who estimated v_0 by the virial theorem), which we obtained from the Harris catalog and the catalog of Pryor & Meylan (1993), respectively, and are listed in Table 1.

We have searched for correlations (using the Spearman ρ correlation coefficient) between the number of X-ray sources in a cluster (N) and the physical parameters that we expect to be important in determining N, such as the encounter rate Γ, cluster mass M, central density ρ_0, core radius r_c, and half-mass relaxation time t_h. In most cases, we find correlations, but the best is between N and Γ (Table 2). The next best correlation that we find is with M. Higher M on average corresponds to larger N, but most of that variation stems from the fact that Γ and M are naturally correlated: keeping the cluster size and the concentration parameter constant while increasing M will increase Γ. If encounters were not to play a role in the formation of X-ray sources, one would expect a tight (in first approximation linear) correlation between N and M and a more loose correlation between N and Γ, contrary to what we find. As an additional check, we estimated N for two clusters not observed deeply enough, NGC 6093 and NGC 6440, by extrapolating their observed luminosity functions, and we find that these estimates improve the correlation with Γ but worsen the correlation with M.

We plot N versus Γ (in normalized units described below) in Figure 2. Clusters not observed deeply enough to reach our luminosity limit are indicated by arrows. Each point is identified by the cluster's NGC designation or other name. A power-law fit (not including the lower limits) indicates that $N \propto$

TABLE 1
GLOBULAR CLUSTERS OBSERVED WITH *CHANDRA*

Globular Cluster (1)	Concentration (c) (2)	$\log \rho_0$ ($L_\odot$ pc^{-3}) (3)	v_0 (km s^{-1}) (4)	Γ (5)	Exposure Needed (ks) (6)	Sources Detected (7)	Background Sources Expected (8)
NGC 6440	1.70	5.28	...	626[a]	150[b]	24	1–2
NGC 6266	1.70	5.14	14.3	500	63	51	2–3
47 Tuc	2.03	4.77	11.5	434	18	45	3–5
NGC 6626	1.67	4.75	8.6	186	40	26	2–3
NGC 6093	1.95	4.76	12.4	166	80[c]	17	1–2
NGC 5904	1.83	3.91	5.7	69	45	16	4–7
ω Cen	1.24	3.12	16.0	49	26	28	10–17
NGC 6752	2.50[d]	4.91	4.5	38	11	11	2–3
NGC 7099	2.50[d]	5.04	5.6	18	42	7	1–2
NGC 6121	1.59	3.82	4.2	13	5	6	1–3
NGC 6397	2.50[d]	5.68	4.5	5.9	6	12	0–1
NGC 6366	0.92	2.42	1.3	2.3	24	4	2–4

NOTE.—Cols. (2) and (3): From Harris 1996; col. (4): from Pryor & Meylan 1993, except for NGC 6440; col. (5): given in the normalized units described in the text; col. (6): based on detecting a 4×10^{30} ergs s^{-1} source at the distance and absorption of the cluster; col. (7): the total number of sources detected within the half-mass radius; col. (8): based on the $\log N$– $\log S$ relationship of Giacconi et al. 2001 given the length of the exposure and area of the sky surveyed.
[a] Estimated from $\rho_0^{1.5} r_c^2$ since v_0 is not known.
[b] The actual exposure time was only 25 ks.
[c] The actual exposure time was only 50 ks.
[d] Set to this value because a better fit could not be obtained (see Trager, King, & Djorgovski 1995).

$\Gamma^{0.74}$, with errors on the power-law index of ± 0.36. This correlation offers the first quantitative, empirical link between the encounter rate (over a range of almost 3 orders of magnitude) and the number of exotic close binaries in a globular cluster and suggests that most of these systems are formed dynamically through some sort of encounter.

Note that there is one cluster, NGC 6397, that falls significantly outside the otherwise good fit in Figure 2. Interestingly, this cluster has a high central density and a tidal radius that is far smaller than would be expected for its current location relative to the Galactic center, suggesting that it describes a highly eccentric orbit around the Galactic center (Dauphole et al. 1996), which has caused enhanced tidal stripping and disk shocking during each perigalacticon passage. Piotto, Cool, & King (1997) find evidence of a deficiency of low-mass stars in this cluster. The combination of a high central density as a good place to make X-ray sources together with significant tidal mass loss would create an efficient distillation process whereby the binaries remain in the core and many single stars are stripped from the outer regions of the cluster, leading to a “high grade” cluster enriched in X-ray sources, which is exactly what is observed.

The relationship in Figure 2 deals with a mixture of (at least) three different kinds of sources (quiescent LMXBs, CVs, and MSPs) that are expected to be primarily formed through encounters in globular clusters. (In addition, a small number of main-sequence binaries, which are expected to be primordial, are represented in Fig. 2.) These expectations are now confirmed by the evidence presented in Figure 2 and Table 2. Note that there are many remaining uncertainties concerning the precise theoretical predictions of the formation rates of LMXBs, CVs, and MSPs. For each separate category, there are several different formation channels, such as tidal capture and exchange reactions involving encounters between single stars and binaries or between binaries and binaries. The only good way to get a quantitative handle on the whole mix is to do detailed simulations for individual clusters (Baumgardt et al. 2003a, 2003b).

TABLE 2
SPEARMAN ρ CORRELATION COEFFICIENTS OF N VERSUS VARIOUS CLUSTER PROPERTIES

Parameter	Spearman ρ	Probability[a]
Γ	0.855	0.9984
M	0.758	0.9889
t_h	0.588	0.9261
ρ_0	0.418	0.7709
r_c	−0.054	0.1190

[a] Probability that Spearman ρ is different from zero. A correlation coefficient of zero corresponds to the data being uncorrelated.

Bypassing these complexities, the simple encounter frequency adopted here, density squared divided by velocity, describes how often a cluster member comes close to another, taking into account gravitational focusing. First of all, it does not discriminate between different objects (main-sequence stars, giants, white dwarfs, neutron stars, and binaries of all types), and second, it neglects possible velocity dependencies in three-body and four-body interactions in encounters between single stars and binaries. If there were no correlations between the abundances of objects involved in encounters with, say, the total mass of a cluster, then we would expect encounters between two single stars to be proportional to Γ; hence, N would be linearly proportional to Γ. The result $N \propto \Gamma^{0.74 \pm 0.36}$ is consistent with the simplest prediction, a slope of unity.

The next important step is to examine this relationship for each individual class of objects, but this requires identifying each of the ~200 sources represented in Figure 2, which is an ongoing and very time-consuming process, for which the X-ray data alone are not sufficient. Only three clusters so far—47 Tuc (Grindlay et al. 2001a), NGC 6397 (Grindlay et al. 2001b), and NGC 6752 (Pooley et al. 2002a)—have had the X-ray (*Chandra*), optical (*Hubble Space Telescope*), and radio data necessary to identify a substantial number of sources. About 50% of the sources in 47 Tuc, 75% of those in NGC 6397, and 80% of those in NGC 6752 have been identified to date.

However, it has become clear that *Chandra* data alone are sufficient to identify the quiescent LMXBs in a cluster as distinct from the other three source types based on their luminosities and broadband spectral properties. In a globular cluster, only LMXBs and CVs are more luminous than 10^{32} ergs s^{-1}, and quiescent LMXBs have a much softer spectrum than CVs so that a ratio of the number of photons detected in a soft band (0.5–1.5 keV) to the number detected in a hard band (1.5–6 keV) suffices to distinguish the two. We have tested these selection criteria on the securely identified quiescent LMXB in NGC 6440 (Pooley et al. 2002b) as well as known quiescent LMXBs not located in globular clusters: Aql X-1, Cen X-4, MXB 1659−298, KS 1731−260, and 4U 2129+47. Using archival *Chandra* data, we find that the criteria successfully identify all of them.

We apply these selection criteria to the 12 clusters observed with *Chandra* and use the results of *XMM-Newton* observations of NGC 6205 (Gendre, Barret, & Webb 2003) and NGC 6656 (Webb, Gendre, & Barret 2002) to determine the LMXB content of 14 globular clusters. A total of 19–22 LMXBs have been found in these clusters, with some having multiple LMXBs and some having none. A picture is emerging that appears to confirm the idea of Verbunt & Hut (1987) that the number of LMXBs is proportional to the encounter frequency (Γ) of the cluster. A power-law fit similar to that in Figure 2 was done for the globular clusters containing *multiple* LMXBs, and we find that the best-fit power-law index is 0.97, indicating a nearly linear relationship. The errors on the power-law index are rather large (± 0.5) because of the small number of LMXBs (15) involved in the fit. A similar correlation was reported by Gendre et al. (2003), who assumed a linear relationship a priori. The (nonparametric) Spearman ρ correlation coefficient between the number of LMXBs and Γ is 1.0, and the Pearson r linear correlation coefficient is 0.85, indicating a high degree of linear correlation. We take the relationship to be linear for the following discussion.

We have normalized Γ in Figure 2 such that $\Gamma/100$ is roughly the number of LMXBs in the cluster. The interpretation of Γ in clusters with low encounter rates is then the percent probability that the cluster will host an LMXB. For example, for every cluster like NGC 7099 (with $\Gamma \approx 20$) that hosts an LMXB, there should be, on average, four similar clusters that do not. It is therefore not surprising to see a few LMXBs in clusters with low encounter frequencies.

To estimate the total number of LMXBs expected in the 140 known Galactic globular clusters, we simply need to add the encounter rates of all clusters. However, our method for estimating Γ is applicable to only about one-third of the clusters since v_0 is known for only that many. We therefore use the estimate for Γ described by Verbunt (2003), in which the volume integral of R is taken only out to the core radius, over which the density and velocity dispersion are roughly constant. Then, $\Gamma \propto [(\rho_0^2 r_c^3)/v_0]$. The virial theorem relates v_0, ρ_0, and r_c via $v_0 \propto \sqrt{\rho_0} r_c$. Therefore, we can estimate the encounter rate for each cluster by $\Gamma \propto \rho_0^{1.5} r_c^2$.

We again use the catalog of Harris (1996) for these parameters, with the updates for Terzan 5 by Heinke et al. (2003). From adding the encounter rates of all clusters (Γ_{tot}), we estimate that roughly 100 LMXBs reside in our Galaxy's globular clusters. Of these 100 expected LMXBs, there are 13 persistently or transiently bright globular cluster LMXBs, most of which have been known for almost 20 years. With the 19–22 quiescent LMXBs discovered by *Chandra* and *XMM-Newton* in the past few years, the known population is about one-third of the expected total. We can check for consistency in the following way. The encounter rates of the four clusters whose 15 LMXBs were used in the power-law fit mentioned above add up to 15% of Γ_{tot}, by definition. The summed encounter rate of the other 10 clusters that have been observed deeply enough to determine their entire LMXB content is 5% of Γ_{tot}. These clusters host between four and seven LMXBs, in good agreement with our predictions. Efforts are underway to uncover the rest of the expected LMXB population in globular clusters. These numbers will prove extremely useful in testing models of cluster evolution and LMXB formation.

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