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 ($L_x \lesssim 10^{34}$ 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; Hut 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-
using a wavelet-based algorithm available from the coni et al. (2001). The uncertainty in the number of sources in ground sources based on the relationship of Giac-log diamus of the cluster and subtract the estimated number of back-

cluster, we count all sources detected within the half-mass ra-

limit.) To estimate the number of sources associated with the

6440—were not observed long enough to reach this luminosity

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 de-
tected within the cluster’s 1′/23 half-mass radius. Approxi-
mately 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 prop-
erties 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 $4 \times 10^{37}$ 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 ra-
dius of the cluster and subtract the estimated number of back-
ground 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 $R \propto \rho^2/\sigma$, where $\rho$ is the density and $\sigma$ 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 $\Gamma$ (Table 1). The forms of $\rho$ and $\sigma$ 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 ver-
sion of his catalog. The normalizations are set by the central values $\rho_0$ and $\sigma_0$ (which differs from the analysis of Verbunt & Hut, who estimated $\sigma_0$ 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 $\rho$ cor-
relation 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 $\Gamma$, cluster mass $M$, central density $\rho_0$, core radius $r_c$, and half-mass relaxation time $t_R$. In most cases, we find correlations, but the best is be-

between $N$ and $\Gamma$ (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 $\Gamma$ and $M$ are naturally correlated: keeping the cluster size and the concentra-
tion parameter constant while increasing $M$ will increase $\Gamma$. 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 $\Gamma$ and a more loose correlation be-
tween $N$ and $\Gamma$, 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 $\Gamma$ but worsen the correlation with $M$. We plot $N$ versus $\Gamma$ (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 iden-
tified by the cluster’s NGC designation or other name. A power-

law fit (not including the lower limits) indicates that $N \propto$
that there are many remaining uncertainties concerning the pre-
main-sequence binaries, which are expected to be primordial,
enriched in X-ray sources, which is exactly what is observed.
The combination of a high central density as a good place to
find evidence of a deficiency of low-mass stars in this cluster.
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 encoun-
ters 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 con-
firmed by the evidence presented in Figure 2 and Table 2. Note
that there are many remaining uncertainties concerning the pre-
cise 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 ex-
change 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).

Bypassing these complexities, the simple encounter fre-
quency adopted here, density squared divided by velocity, de-
scribes 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 be-
tween two single stars to be proportional to $G$; hence, $N$ would
be linearly proportional to $G$. The result $N \propto G^{0.74 \pm 0.36}$ is con-
sistent 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 $\sim200$ 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 $10^{38}$ 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)

\begin{table}[h]
\centering
\caption{Spearman $\rho$ Correlation Coefficients of $N$ versus Various Cluster Properties}
\begin{tabular}{lcc}
\hline
Parameter & Spearman $\rho$ & Probability$^a$ \\
\hline
$\Gamma$ & 0.855 & 0.9984 \\
$M_0$ & 0.758 & 0.9889 \\
$v_0$ & 0.588 & 0.9261 \\
$\rho_0$ & 0.418 & 0.7709 \\
r & -0.054 & 0.1190 \\
\hline
\end{tabular}

$^a$ Probability that Spearman $\rho$ is different from zero. A correlation coefficient
of zero corresponds to the data being uncorrelated.
\end{table}
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) be-
cause 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 co-
efficient 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 Γ/100 is roughly
the number of LMXBs in the cluster. The interpretation of Γ
in clusters with low encounter rates is then the percent prob-
ability that the cluster will host an LMXB. For example, for
every cluster like NGC 7099 (with Γ ≈ 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 esti-
mating Γ is applicable to only about one-third of the clusters
since νo is known for only that many. We therefore use the estimate
for Γ described by Verbunt (2003), in which the vol-
tume integral of R is taken only out to the core radius, over
which the density and velocity dispersion are roughly constant.
Then, Γ ∝ [∫ r0 v0 ρ0 dr0]. The virial theorem relates νo, ρo, and
r0 via νo ∝ 3ρ0 r0. Therefore, we can estimate the encounter rate
for each cluster by Γ ∝ ρ0 r0.2.

We again use the catalog of Harris (1996) for these param-
eters, with the updates for Terzan 5 by Heinke et al. (2003).
From adding the encounter rates of all clusters (Γω), we esti-
mate that roughly 100 LMXBs reside in our Galaxy’s globular
clusters. Of these 100 expected LMXBs, there are 13 persist-
ently 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 Γω, by definition. The summed encounter rate of the other 10 clusters that have been observed deeply
down to determine their entire LMXB content is 5% of Γω.
These clusters host between four and seven LMXBs, in good
agreement with our predictions. Efforts are underway to un-
cover 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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REFERENCES

Baumgardt, H., Hut, P., Makino, J., McMillan, S., & Portegies Zwart, S. 2003a, ApJ, 582, L21
Baumgardt, H., Makino, J., Hut, P., McMillan, S., & Portegies Zwart, S. 2003b, ApJ, 589, L25
Becker, W., et al. 2003, ApJ, submitted (astro-ph/0211468)
Clark, G. W. 1975, ApJ, 199, L143
Dauphole, B., Ghez, M., Colin, J., Ducourant, C., Odenkirchen, M., & Tuch-olke, H.-J. 1996, A&A, 313, 119
Fabian, A. C., Pringle, J. E., & Rees, M. J. 1975, MNRAS, 172, 15P
Gendre, B., Barret, D., & Webb, N. 2003, A&A, 403, L11
Giaccioni, R., et al. 2001, ApJ, 551, 624
Goodman, J., & Hut, P. 1989, Nature, 339, 40
Grindlay, J. E., Heinke, C., Edmonds, P. D., & Murray, S. S. 2001a, Science, 292, 2290
Grindlay, J. E., Heinke, C. O., Edmonds, P. D., Murray, S. S., & Cool, A. M. 2001b, ApJ, 563, L53
Harris, W. E. 1996a, AJ, 112, 1487
Heggie, D. C. 1975, MNRAS, 173, 729
Heggie, D. C., & Hut, P. 2003, The Gravitational Million-Body Problem (Cam-
bridge: Cambridge Univ. Press)
Heinke, C. O., Edmonds, P. D., Grindlay, J. E., Lloyd, D. A., Cohn, H. N., & Lugger, P. M. 2003, ApJ, in press (astro-ph/0303141)
Hertz, P., & Grindlay, J. E. 1983a, ApJ, 267, L83
Hills, J. G. 1975, AJ, 80, 809
Hills, J. G. 1976, MNRAS, 175, 1P
Hut, P., et al. 1992, PASP, 104, 981
———. 2003, NewA, 8, 337
Katz, J. I. 1975, Nature, 253, 698
King, I. R. 1966, AJ, 71, 64
Meylan, G., & Heggie, D. C. 1997, A&A Rev., 8, 1
Piotto, G., Cool, A. M., & King, I. R. 1997, AJ, 113, 1345
Pooley, D., et al. 2002a, ApJ, 569, 405
———. 2002b, ApJ, 573, 184
Pryor, C., & Meylan, G. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of
Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco: ASP), 357
Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., & Zavlin, V. E. 2002, ApJ, 578, 405
Sills, A., et al. 2003, NewA, 8, 605
Sutantyo, W. 1975, A&A, 44, 227
Trager, S. C., King, I. R., & Djorgovski, S. 1995, AJ, 109, 218
Verbunt, F. 2001a, A&A, 368, 137
———. 2003, in ASP Conf. Ser. 296, New Horizons in Globular Cluster
Astronomy, ed. G. Piotto, G. Meylan, S. G. Djorgovski & M. Rielo (San Francisco: ASP), in press (astro-ph/0210057)
Verbunt, F., & Hut, P. 1987, In The Origin and Evolution of Neutron Stars,
ed. D. J. Helfand & J. H. Huang (Dordrecht: Reidel), 187
Webb, N. A., Gendre, B., & Barret, D. 2002, A&A, 381, 481
White, N. E., & Angelini, L. 2001, ApJ, 561, L101