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LOW-MASS X-RAY BINARIES IN GLOBULAR CLUSTERS: A NEW METALLICITY EFFECT

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ABSTRACT

Globular clusters (GCs) containing bright X-ray sources ($L_x > 10^{36}$ ergs s^{-1}), commonly associated with low-mass X-ray binaries (LMXBs), are found to be significantly denser and more metal-rich than normal non–X-ray clusters both in the Galaxy and in M31.

Within a framework where LMXBs in GCs are generated via tidal captures in high-density clusters and (2 + 1) encounters in low-density globulars, the higher incidence of LMXBs with increasing metallicity is shown to be *intrinsic* and not just a by-product of other effects.

Two possible mechanisms are examined: the first one assumes a dependence of the cluster IMF on metallicity as recently published in the literature. The number of observed LMXBs, more frequently occurring in metal-rich clusters, agrees with the predicted number of NS only if metallicity accounts for a minor contribution to the observed variation of the IMF slope. Other alternatives explored, such as the total variation of the observed IMF slopes is due to (1) just metallicity and (2) the combination of metallicity and position in the Galaxy lead to a clear-cut disagreement with the data. In turn, this result may indicate a flatter dependence of the cluster's IMF on metallicity than that deduced from observed cluster luminosity functions.

The second mechanism assumes that, at fixed cluster density, the rate of tidal captures depends on radius and mass of the capturing star. Based on standard stellar models, stars with higher metal content have wider radii and higher masses, hence the rate of tidal captures increases with increasing metallicity. Moreover, since the fixed binary separation and masses of the two components, metal-rich stars fill more easily the Roche lobe, as their radii are larger, there is an additional "evolutionary" reason to favor a higher incidence of LMXBs in metal-rich clusters. From the order of magnitude computations made, the new effect by itself could explain the observed ratio of 4 between the frequencies of X-ray clusters in the metal-rich and metal-poor groups we observationally determined. However, there is no reason to exclude that both mechanisms can be at work.

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

1. INTRODUCTION

Bright X-ray sources ($L_x > 10^{36}$ ergs s^{-1}) are thought to be binary systems where a neutron star is accreting mass from a companion (Lightman & Grindlay 1982), and they are commonly known as low-mass X-ray binaries (LMBXs).

In a recent review, Grindlay (1993) lists 12 galactic globular clusters (GGCs) from the *Einstein* and *ROSAT* surveys which contain LMBXs. The LMBX globulars belong mostly to the galactic disk (9 of 12), and exhibit, with the exception of M15, a quite high metal content and, with the exception of NGC 6712, high central density. Surprisingly enough, the above sample is not significantly overabundant in post–core collapse (PCC) clusters with respect to the whole GGC population. In fact, the fraction of LMBX globulars which seem to have undergone core collapse is the same as in the whole Galactic cluster system (Grindlay 1993). If cluster central density were the only crucial parameter favoring the formation of X-ray binaries, one would expect a very tight correlation between PCC morphology and LMXB population. Since this is not the case, another parameter may influence, besides high stellar density, the production of X-ray binaries in globulars.

In this note a comparison between the "X-ray" (XR) and "non–X-ray" (nXR) cluster populations in the Galaxy and in M31 is first presented, and then a working hypothesis which suggests that the "second parameter" involved in the production of LMXBs is actually the cluster metallicity is proposed.

2. THE DATABASE

2.1. *The Galaxy*

The X-ray survey of the Galaxy secured by *Einstein* and *ROSAT* satellites can be considered exhaustive at the luminosity level $L_x > 10^{36}$ ergs s^{-1}. Hence, the 12 GGCs listed in his Table 1 by Grindlay (1993) are adopted as bona fide LMBX globulars.

To carry out useful comparisons, a sample of 122 nXR GGCs was then taken from Zinn (1985). For all clusters, metallicities are taken from Zinn (1985), Armandroff & Zinn (1988), Armandroff (1989), and Armandroff, Di Costa, & Zinn (1992). Central luminosity densities, distances from the center of the Galaxy and from the Galactic plane are from Djorgovski (1993), while central velocity dispersions and M/L ratios are from Pryor & Meylan (1993).

2.2. *M31*

M31 is less obvious to deal with and an accurate selection of the samples must be done before making any further analysis and comparison.

The X-ray surveys carried out with *Einstein* in M31, presented and discussed by Long & van Speybroeck (1983, hereafter LVS), Crampton et al. (1984, hereafter CCHSV), Trinchieri & Fabbiano (1991, hereafter TF) and those made with *ROSAT*

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by Primini, Forman, & Jones (1993, hereafter PFJ) covered at sufficiently high-resolution only quite small areas centered on the bulge of the galaxy. As a consequence, the available samples are surely incomplete.

In order to be homogeneous, the present selection was limited to sources found with the HRI cameras operated on both satellites, which were sufficiently similar in spatial resolution and wavelength range. In their analysis, TF consider a sort of strip oriented along the M31 major axis, extended $\sim 2°$ in Decl. and ~ 3 minutes in R.A. (see their Fig. 1). Within this region, we selected a sample of 26 XR globulars, most of which have multiple identifications made by various authors (LVS; CCHSV; TF; PFJ). These identifications were checked by independently cross-correlating all the detected X-ray sources listed by the different authors with the revised catalog of M31 globular cluster candidates (hereafter Bo catalog) constantly updated by the Bologna Group (Battistini et al. 1980, 1987, 1993; Federici et al. 1993; Fusi Pecci et al. 1993b). Adopting error boxes either slightly smaller or larger than previously used by other authors, exactly the same 26 identifications were found. It is therefore safe to assume this sample is reliable enough to be used as truly representative of the XR globulars in M31. Table 1 reports the list of the 26 XR GCs included in our sample and some useful data discussed below.

In order to construct a corresponding sample of nXR clusters to make comparisons and tests as for the Milky Way population, the list of cluster candidates (classes A and B) identified in the same region considered in the X-ray survey was also extracted from the Bo catalog. In total, excluding all candidates whose spurious nature has so far been verified, 171 objects were found. The much larger distance which separates us from M31 than from our own Galaxy GCs makes to measure intrinsic structural parameters and metallicity a much harder task. In fact, at M31 ($d \sim 700$ kpc), (1 pc corresponds to $\sim 0\farcs3$, and only *HST* data can yield fully reliable structural parameters for the M31 clusters (Fusi Pecci et al. 1993a).

However, in order to be able to make educated guesses, a rough estimate of the intrinsic structure of the M31 clusters was made following the same procedures previously adopted by our group (Buonanno et al. 1982; Battistini et al. 1982). The chosen observable is simply the half-width at one-fourth of the height—$W_{1/4}$—of the two-dimensional fit of the cluster image, normalized to the arbitrary scale of a reference plate (see also Battistini et al. 1987, 1994). Using the available data, this quantity is now available for almost all the XR (25 our of 26) and nXR (158 out of 171) clusters. We report in column (1) of Table 1 the individual values for XR globulars.

The whole data set for the remaining M31 clusters, and for the whole Galaxy sample, can be found in the above quoted papers or can be obtained upon request and therefore is not reproduced here. Note that here $W_{1/4}$ runs opposite to the density, i.e., clusters having small $W_{1/4}$—values are expected to be actually highly concentrated objects. The substantial reliability of these estimates, at least at a first order, has been repeatedly checked with other measures from the ground (Crampton et al. 1985; Cohen & Freeman 1991) and with *HST* (Fusi Pecci et al. 1993a). On the other hand, nothing better is available at this stage for the considered sample.

Metallicity estimates ([Fe/H]) by Huchra, Brodie, & Kent (1991) are based on accurate spectral calibrations and can be assumed to be free from any bias induced by the quite strong reddening affecting many of the considered objects and were therefore adopted. However, we must note that while Huchra et al. (1991) list metallicities for 21 out of 26 XR globulars (i.e., $\sim 80\%$ of the total sample), they give values for only 68 nXR clusters ($\sim 40\%$ of the total sample). Other estimates based on proper calibrations of photometric colors have been made by various authors including our group, but since reddening effects may have influenced the observables, they were not used in order to prevent contamination of the sample.

Finally, the projected galactocentric distances (R_{GC} in kpc) are taken from Battistini et al. 1987 ($d_{M31} = 651$ kpc).

TABLE 1

THE DATA BASE OF THE M31 X-RAY GLOBULARS

Name[a]	[Fe/H]	$W_{1/4}$	R_{GC}	Identifications
Bo5 (G51)	−0.68	4.46	7.97	1, 2, 3
Bo45 (G108)	−0.94	4.73	4.07	1, 2, 3
Bo78 (G140)	...	4.98	1.20	4
Bo82 (G144)	−0.86	4.78	3.00	1, 2, 3, 4
Bo86 (G148)	−1.74	5.01	1.00	1, 2, 3, 4
Bo96 (G158)	−0.26	4.57	0.88	2, 3, 4
Bo107 (G169)	−1.18	4.64	0.81	1, 2, 3, 4
Bo110 (G172)	−1.00	4.58	2.43	4
Bo124	...	3.28	0.18	2, 3
Bo127 (G185)	−1.08	4.86	0.27	1
Bo128 (G187)	...	4.83	0.94	4
Bo135 (G192)	−1.62	4.69	2.85	1, 2, 3, 4
Bo138	...	4.46	0.61	4
Bo143 (G198)	+0.09	4.58	0.81	1, 2, 3, 4
Bo144	...	4.96	0.55	1, 2, 3, 4
Bo146	−0.43	4.86	0.67	1, 2, 3, 4
Bo147 (G199)	−0.24	4.73	1.19	1, 4
Bo148 (G200)	−1.53	4.74	0.78	1, 2, 3, 4
Bo153	−0.08	4.89	0.96	1, 2, 3, 4
Bo158 (G213)	−1.08	4.89	1.98	1, 2, 3, 4
Bo161 (G215)	−1.25	4.39	1.42	4
Bo185 (G235)	−1.03	4.32	1.90	1, 4
Bo213 (G264)	−0.99	4.52	3.93	1, 2, 3
Bo225 (G280)	−0.70	5.03	3.88	1, 2, 3
Bo375 (G307)	−1.23	...	7.82	1, 2, 3
Bo386 (G322)	−1.21	4.66	11.70	1, 2, 3

[a] Bo = Battistini et al. 1987, G = Crampton et al. 1985.
REFERENCES.—(1) LVS, (2) CCHSV, (3) TF, (4) PFJ.

3. RESULTS

Having at hand the data for the four sets of clusters described above, one can immediately compute average values of the various parameters and verify whether any significant difference emergences between the various groups. In Table 2, therefore, the mean values obtained for each considered parameter for XR and nXR globulars in the Galaxy and in M31, respectively, are listed. For the metallicities, the weighted means and the corresponding associated errors were computed making use of the available estimates of the uncertainties for each single object.

3.1. *Cluster Density*

The difference in average density between the two groups in the Galaxy ($\langle \log \rho_0 \rangle_{nXR} = 3.41 \pm 0.16$ and $\langle \log \rho_0 \rangle_{XR} = 4.93 \pm 0.26$) it is quite large. A Kolmogorov-Smirnov (K-S) test shows that the two samples are drawn from different populations at a $\sim 99.7\%$ ($\sim 3\ \sigma$) confidence level.

Keeping in mind that $W_{1/4}$ is anticorrelated to the cluster density, in M31 $W_{1/4}^{XR} = 4.36 \pm 0.07$ has to be compared with $W_{1/4}^{nXR} = 5.00 \pm 0.04$. The K-S test applied to the two distributions shows that they are different at $\sim 98.8\%$ (i.e., $2.5\ \sigma$) confidence level. Hence, though less significant, but it is not a surprise given the lower quality of the input data, it seems

TABLE 2

MEAN VALUES OF THE GC'S SAMPLES

	[Fe/H]		log ρ_0		R_{GC}		$\|Z_{GP}\|$	
SOURCE	N	Mean[a]	N	Mean	N	Mean	N	Mean
Milky Way:								
XR	12	-1.17 ± 0.04	10	4.93 ± 0.26	12	4.57 ± 1.39	12	1.54 ± 0.65
nXR	122	-1.41 ± 0.01	99	3.41 ± 0.16	120	13.47 ± 1.89	120	7.46 ± 1.37
M31:								
XR	21	-1.06 ± 0.04	25	$4.36^b \pm 0.07$	26	2.45 ± 0.55	...	...
nXR	68	-1.22 ± 0.03	158	$5.00^b \pm 0.04$	171	3.32 ± 0.19	...	...

[a] Weighted mean.
[b] $W_{1/4}$ values.

confirmed that also the M31 globulars containing LMXBs are denser than normal clusters.

In Figure 1*a*–1*b*, the cumulative distributions for the two considered quantities (log ρ_0 in the Galaxy and $W_{1/4}$ in M31) have been plotted, where the *solid line* is for the XR globulars and the *dotted line* for the nXR clusters, respectively.

3.2. *Distance from the Galactic Center and the Galactic Plane*

As shown also from the cumulative distribution in Figure 2*a*, the K-S test applied to the distribution of the distances from the Galactic center (R_{GC}) for XR and nXR clusters indicates, at ~92% significance level, that they are drawn from different parent populations. This marginal indication could also be simply a by-product of the fact that high-density clusters are more frequent at small R_{GC}.

Concerning the height with respect to the Galactic plane ($|Z_{GP}|$; see Fig. 3), the probability that the two samples are extracted from the same parent population is only ~3%. However, one should note that the detected difference is mostly based on a few XR clusters located very close to the Galactic plane (see § 4.2 for further discussion).

For the two groups (XR and nXR) in M31 the situation appears similar. In fact the K-S test applied to the distributions of Figure 2*b*, the two populations are different at a ~99.1% confidence level (*i.e.*, 2.6 σ). However, this effect could also be due to a possible bias in the cluster selections and in the mapping of the X-ray observations. For instance, while in the Galaxy both the optical and X-ray cluster surveys are probably complete, many low-luminosity clusters are surely still missing in the inner regions of M31, and this would alter the relative distributions (see Battistini et al. 1980, 1987; Federici et al. 1993; Fusi Pecci et al. 1993b for discussions on selection bias in the M31 cluster survey). Unfortunately, the available data make it impossible for M31 to carry out any test concerning $|Z_{GP}|$, as was done for the Galaxy.

3.3. *Metallicity*

The weighted mean metallicity for the 12 XR GCs in the Galaxy turns out to be $\langle[Fe/H]\rangle_{XR} = -1.17 \pm 0.04$. This figure is higher than that obtained for the nXR sample $\langle[Fe/H]\rangle_{nXR} = -1.41 \pm 0.01$, which is in good agreement with the average value determined for the whole cluster system in the Galaxy for instance by using data from Zinn (1985) or Huchra et al. (1991). A K-S test applied to the two distributions indicates that the hypothesis that they are extracted from the same population can be rejected at 99.9% confidence level (i.e., $> 3\ \sigma$). Thus the evidence is very strong and, as said, not new.

Since LMBX clusters are mostly disk objects and are usually

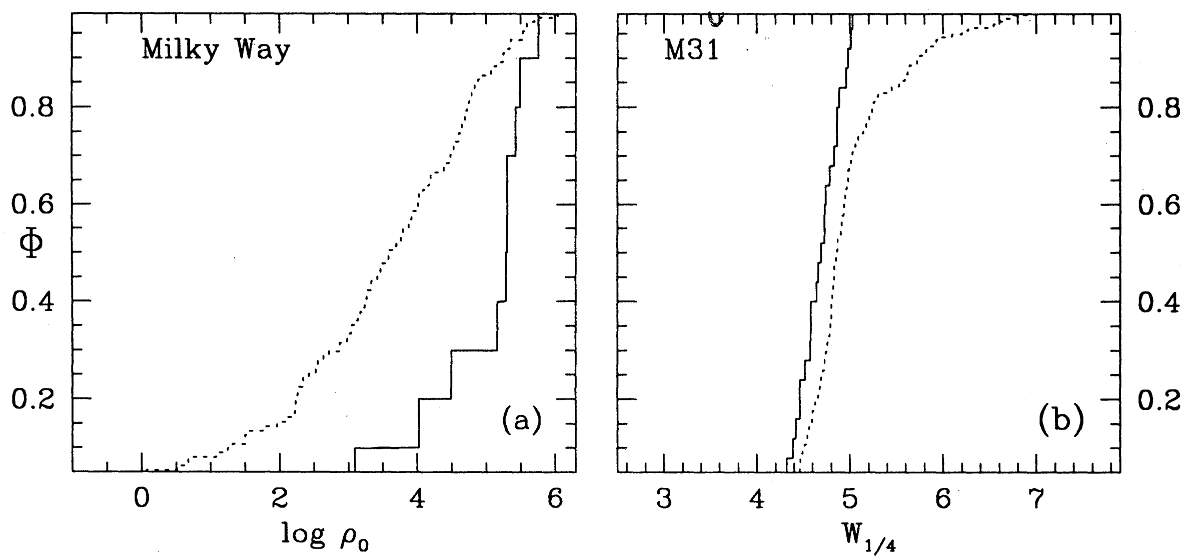

FIG. 1.—log-central density cumulative distributions (Φ) of the nXR (*dashed line*) and XR (*solid line*) globular clusters in the Galaxy (*a*) and in M31 (*b*), respectively. Note that in (*a*) ρ_0 is the adopted cluster central density, while in (*b*) $W_{1/4}$ is the half-width at $\frac{1}{4}$ of the height of the two-dimensional fit of the cluster image (normalized to an arbitrary scale) which is at first order anticorrelated to the cluster central density (see §§ 2 and 3.1).

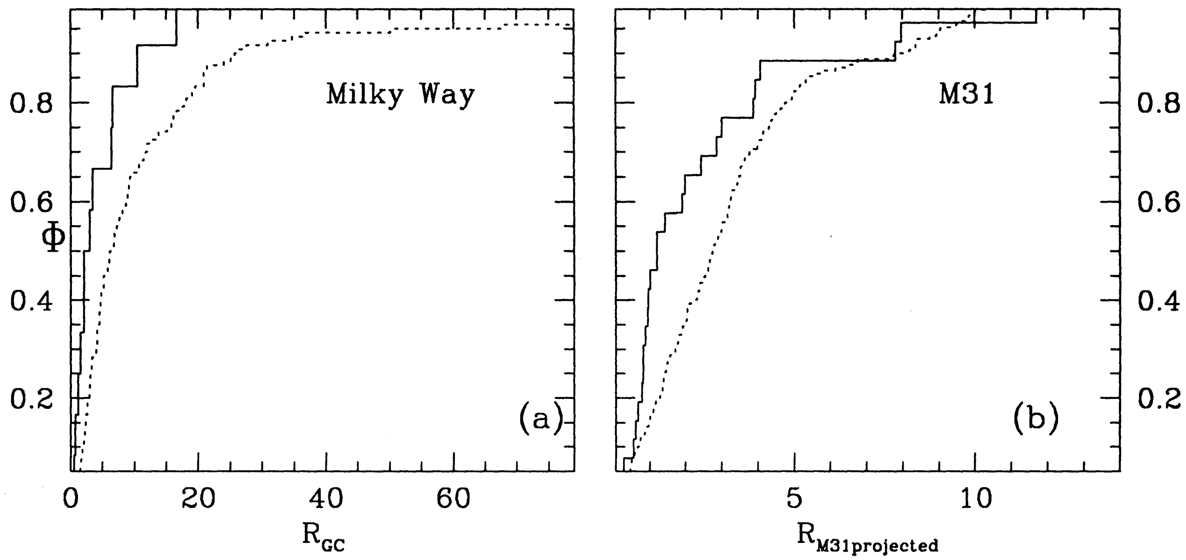

FIG. 2.—Radial cumulative distributions (Φ) of the nXR (*dashed line*) and XR (*solid line*) globular clusters in the Galaxy (*a*) and in M31 (*b*), respectively (units in kiloparsecs). Note that in (*a*) R_{GC} is the adopted distance from the Galactic center, while in (*b*) $R_{M31_{proj}}$ is the projected distance from the center of M31 (§§ 2 and 3.2).

metal-rich, one might interpret the detected metallicity difference to be *not germane*, but simply a secondary consequence of the primary dependence on density and membership to the disk-cluster family. However, before extending further the discussion it is worth carrying out a similar check for the M31 samples.

As noted in the previous section, in the list by Huchra et al. (1991) the metal content only for a subsample of the clusters lying in the selected area can be found. However, the weighted mean metallicity for the 68 nXR globulars in M31 turns out to be ($\langle[Fe/H]\rangle_{nXR} = -1.22 \pm 0.03$), in very good agreement with the average values obtained by Huchra et al. (1991) for all 150 clusters in their sample ($\langle[Fe/H]\rangle = -1.21 \pm 0.02$).

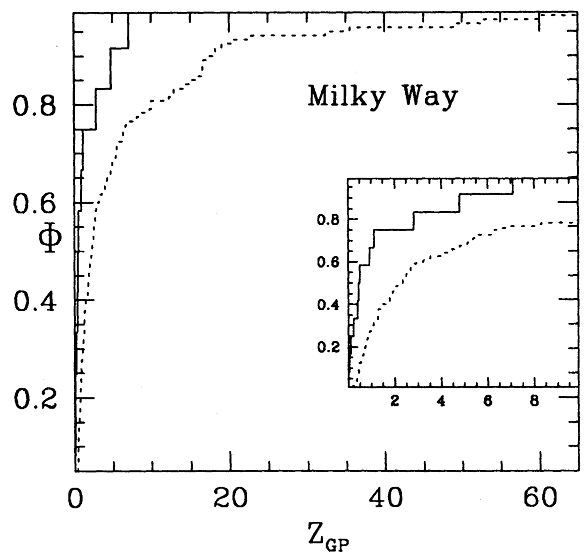

FIG. 3.—Cumulative distributions (Φ) of the nXR (*dashed line*) and XR (*solid line*) globular clusters in the Galaxy with respect to $|Z_{GP}|$ (kpc)—the height on the Galactic plane. A zoomed plot has also been inserted to show that most of the difference between the two distributions is actually found for very small values of $|Z_{GP}|$. In particular 75% of the XR sample is located within the first kiloparsecs from the Galactic plane.

Hence, though far from being complete, the adopted sample seems to be fairly representative of the whole set of clusters observed in M31 by Huchra et al. (1991). Based on the same data set, the XR cluster population yields a weighted mean $\langle[Fe/H]\rangle_{XR} = -1.06 \pm 0.04$, i.e., higher than the nXR group. The hypothesis that the two distributions are extracted from the same parent population can be rejected at a ~93% (~1.85 σ) confidence level.

Admittedly, the statistical significance for the difference between the two M31 cluster samples is lower than in the Galaxy. However, first, it should be emphasized that both differences go in the same direction, and, second, there are reasons to believe that the real difference could even be larger. In fact, we must recall that (1) since the surveyed area covers mostly the inner regions of M31, the selected nXR clusters could represent the metal-rich tail of the clusters distribution in M31 (as shown for instance by the trend with the projected radius displayed in their Figure 2 by Huchra et al. 1991), and (2) the errors in [Fe/H] are quite large in the M31 sample (~ ±0.3 dex), and tend to smear out the difference.

In summary, though at a smaller level of significance, the result found from the M31 samples is considered fully consistent with that obtained for the Galaxy. The comparison of the metallicity cumulative distributions of the XR and nXR clusters are reported in Figures 4*a* for the Galaxy and 4*b* for M31.

3.4. *A Two-dimensional Approach*

Since, as shown by Djorgovski (1991), in GGCs there are correlations between, for instance, Galactic position and metallicity and central density and metallicity, two-dimensional K-S tests (Fasano & Franceschini 1987; Press et al. 1992) on the Galactic data sets were performed. The XR and nXR samples turn out to be extracted from different parent population in any plane formed by coupling the quoted parameters, at a confidence level always greater than 99%. However, this result does not contribute any additional information since it appears as a natural consequence of the combinations of the differences separately detected via the one-dimensional tests and the implicit correlations linking the driving parameters.

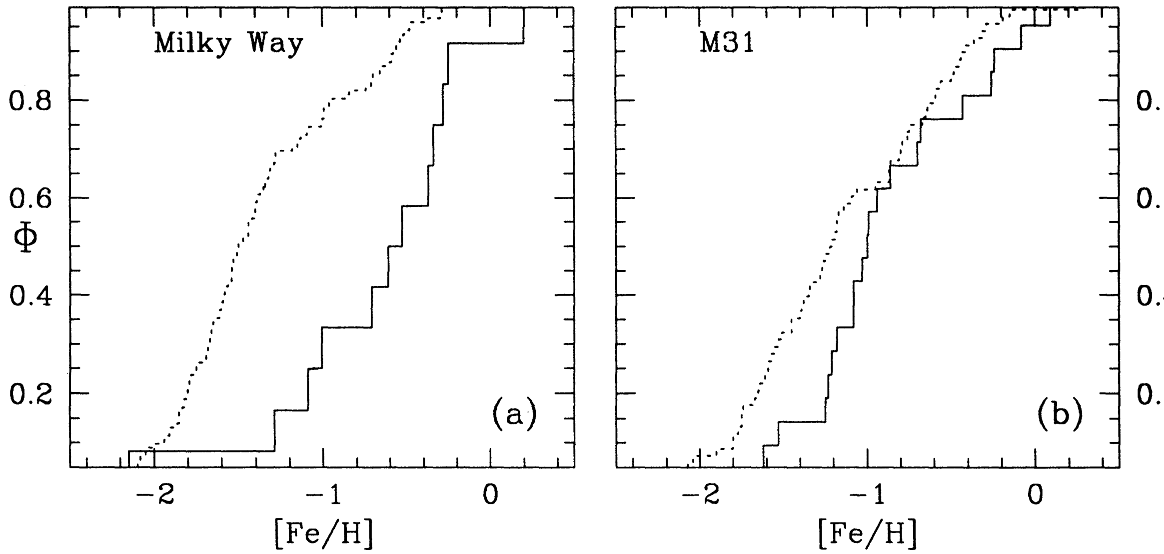

FIG. 4.—Metallicity cumulative distributions (Φ) of the nXR (*dashed line*) and XR (*solid line*) globular clusters in the Galaxy (*a*) and in M31 (*b*), respectively (see §§ 2 and 3.3).

4. DISCUSSION AND A NEW PROPOSED METALLICITY EFFECT

The basic new result of the present paper for the samples of XR and nXR clusters in the Galaxy and M31 is that in both galaxies the XR clusters seem to belong to a more metal-rich population than nXR globulars. The question is thus: is metallicity a critical parameter to increase the incidence of LMXBs or, since disk clusters are in general more metal-rich than halo objects, the detected difference is just a by-product of other primary effects?

4.1. *Preliminary Observations*

So far there have been two basic answers to the above question: (1) yes, the dependence on metallicity is just a secondary by-product; (2) no, it is germane, and (Grindlay 1987) it is due to the claimed correlation between metallicity and the slope of the cluster initial mass function (IMF) (cf. McClure et al. 1986). Within this second scenario, metal-rich clusters would have flatter IMFs and, in turn, more neutron stars (NSs), the seeds to originate LMXBs.

As it is well known, LMXBs are thought to be binary systems in which a NS is accreting mass by the Roche lobe from a companion. The first condition to fulfill to generate LMXBs is that a sufficient number of NSs with velocities below the escape velocity from the cluster are formed (Hut, Murphy, & Verbunt 1991). Then, the NS should be somehow captured to form a binary system. Until now, two main mechanisms have been proposed (see for references Hut et al. 1991, 1992): (1) 1 + 1 encounters (i.e., two-body tidal captures); (2) 2 + 1 encounters (i.e., exchange with a preexistent binary in which the lightest star is ejected from the system, leaving the NS bounded in the new binary system). The crucial parameter for both mechanisms seems to be the density of the environment.

For example, with mechanism 1 a detailed calculation of the rate of the basic phenomenon is available (see eq. [3.6] in Lee & Ostriker 1986), which shows that the rate of tidal capture increases by a factor $\sim 10^6$–10^7 if stellar density in the clusters varies over the range of densities covered by Galactic GCs. In particular, only for high-density clusters (with $\log \rho_0 > 4$) the mechanism is really efficient. Concerning the binary exchange mechanism, the situation is less straightforward. Hut et al. (1991) report that mechanism 2 has a cross section which is more than two orders of magnitude larger than that for NS capture by a main-sequence star. Davies, Benz, & Hills (1993) agree and emphasize that, if a GC contains a sufficiently large binary population, mechanism 2 outnumbers the encounters expected via mechanism 1. Moreover, they present simulations of 2 + 1 encounters between a NS and two different kind of binaries: tidal capture or hardened primordial binaries. Their main conclusion is that the vast majority of NS-exchange in binaries are generated by encounters involving primordial binaries.

On the other hand, for instance, according to Bailyn (1993), the cluster binary population is dominated by primordial systems only in "dynamically young" clusters (sparse, low-density GC) while they were heavily destroyed (due to stellar encounters) in "dynamically old" systems (PCC or high-density clusters).

This statement has been confirmed by Hut et al. (1992), who moreover point out that, in order to compare the efficiency of the two mechanisms, one has to take into account the rate of binary destruction, so that "In PCC clusters most binaries will be ejected or destroyed in less than an Hubble time. Collision products (e.g., LMXBs, pulsars, CVs) are thus most likely formed by two-body processes."

Adopting the framework summarized above, one may expect that LMXBs in high-density or PCC clusters are formed mainly via two-body encounters (i.e., mechanism 1). In the low-intermediate density clusters, having still a high percentage of survived primordial binaries, 2 + 1 encounters should be more efficient in generating systems which can evolve into LMXBs. For instance, in the extreme case of NGC 6712 (the lowest density cluster in the Galaxy containing a LMXB) the LMXB observed could have a different origin with respect to those found in high-density clusters such as NGC 6441, NGC 7078, etc. In fact, NGC 6712 has a probability to form LMXBs via two-body encounters $\sim 10^5$–10^6 times smaller than the high-density clusters.

The idea that cluster star density plays a basic role in the LMXB formation and evolution seems therefore beyond any reasonable doubt. However, a new natural mechanism by which the detected influence of metallicity on LMXB frequency could be explained as a "germane" important effect and not as a simple by-product is presented in what follows.

4.2. *Testing Possible Metallicity Effects*

Figure 5 shows the distribution of the Galactic XR GCs (*filled dots*) with respect to the nXR clusters (*open dots*) in a density-metallicity plane. The plot appears peculiar: the cluster distribution has a well-defined triangular shape. In fact, clusters with high metallicity and low density are clearly lacking. This is probably due to a complex history of cluster formation, evolution, and survival. Though interesting, we postpone this discussion to a forthcoming paper (Bellazzini et al. 1995).

In order to get a quantitative indication of the influence of the metal content on the LMXB formation rate in GCs we selected from the available sample in Figure 5 the densest clusters ($\log \rho_0 > 5$). One obtains a roughly *isodense* subsample where the two-body tidal capture is efficient and is probably the dominant mechanism to produce LMXBs. Then, this subsample was divided into two metallicity groups: the *first*, including GCs with [Fe/H] < -1, and the *second* with [Fe/H] > -1.

Finally, it is easy to compute the XR to total globulars ratio in the two metallicity groups (i.e., the relative frequency of XR clusters in each metallicity bin): $R_R = N_{XR}/N_{tot} = 0.64 \pm 0.24$ for the metal-rich group and $R_P = N_{XR}/N_{tot} = 0.15 \pm 0.11$ for the metal-poor one. The quoted errors have been calculated by propagating 1 σ errors and assuming a binomial distribution for N_{XR} and a Poisson distribution for N_{tot}. The further ratio R_R/R_P between these two ratios can eventually be considered to be a first rough estimate of the impact (in terms of frequency of the LMXBs within an "isodensity" cluster sample) due to increasing metallicity from $\langle[\mathrm{Fe/H}]\rangle \sim -1.67$ (metal-poor group) to $\langle[\mathrm{Fe/H}]\rangle \sim -0.43$ (metal-rich group). Using again propagation of errors, the best estimate $(R_R/R_P)_{best} = 4.26 \pm 3.34$ is obtained. Very schematically, one gets that the formation of a LMXB in a metal-rich cluster would be ~ 4 times more probable than in a metal-poor one. Nevertheless, because of counting statistics on such a small sample, the permitted range of values for R_R/R_P turns out to span from a few hundredths to ~ 22, with a reasonable 3 σ upper limit of ~ 15. On the other hand, values equal or less than 1 are ruled out by a simple χ^2 test applied to the sample of clusters with $\log \rho_0 > 2$, in order to obtain a more robust statistical significance. The H_0 hypothesis that the probability of being XR is the same for the clusters more metal rich than [Fe/H] $= -1$ as for those poorer than this limit is rejected with a confidence level greater than 99.8%, therefore substantially excluding that $R_R/R_P \leq 1$.

This observational result [i.e., $(R_R/R_P)_{best} \sim 4$, with $1 < R_R/R_P \leq 15$] can then be compared with theoretical predictions.

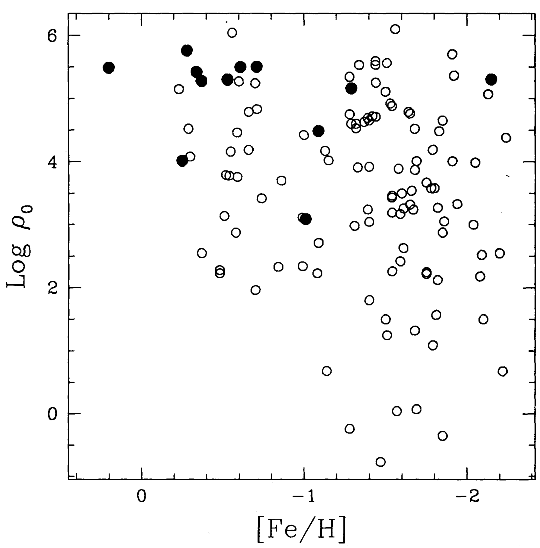

FIG. 5.—The distribution of the X-ray clusters (*filled dots*) and the non–X-ray globulars (*open dots*) in the Galaxy in a log-density–metallicity plane.

4.2.1. *Influence of the IMF*

Grindlay (1987, 1993) suggested that the metallicity dependence of the LMXB frequency comes via the possible dependence of the IMF slope on [Fe/H] as claimed by McClure et al. (1986). In synthesis, metal-rich clusters show a flatter mass function, are expected to produce more NSs and, as a consequence, they would have a larger rate of "right" binaries.

As stressed by Renzini & Fusi Pecci (1988) and by Richer et al. (1991), due to both observational and theoretical problems, the estimate of the "true" index of the IMF is particularly tricky and uncertain. However, one must rely upon the available data.

To quantify the effect of the claim on the two-body capture rate, we introduced the metallicity dependence of the IMF as proposed by McClure et al. (1986) and computed the expected number of NSs according to Hut et al. (1991). Following their assumptions, a 1.4 $M_\odot$ NS is originated from a star with $M > 8\, M_\odot$.

Assuming for the two metallicity groups the mean metallicities reported above, $N_{NS}^{M-R}/N_{NS}^{M-P} \sim 500$ is obtained. Since the expected rate of two-body captures is directly proportional to the number of NSs (Lee & Ostriker 1986), one would compute that the probability of having LMXBs in metal-rich clusters is ~ 500 times larger than in metal-poor ones (of course, at fixed density). Such a ratio is hardly compatible with the observed frequency even taking into account the many uncertainties involved in the various steps.

In a recent analysis, Piotto (1993) and Djorgovski, Piotto, & Capaccioli (1993) found a different dependence of IMF on the cluster intrinsic parameters. Adopting the monovariate relation (Djorgovski et al.'s eq. [3b])

$$\frac{\Delta x_0}{\Delta[\mathrm{Fe/H}]} = -1.6 ,$$

where x_0 is the slope of the global IMF, one can easily repeat the previous estimates getting $N_{NS}^{M-R}/N_{NS}^{M-P} \sim 500$ again, a value still incompatible with observations.

If one considers the global multivariate formula (Djorgovski et al.'s eq. [5]), taking into account also the claimed dependence of the IMF slope on R_{GC} and $|Z_{GP}|$, the result, leading to $N_{NS}^{M-R}/N_{NS}^{M-P} \sim 1000$, is even more inconsistent with the observed LMXB frequencies. Actually, the relation had to be extrapolated to a wider metallicity range and this could be partially responsible for the discrepancy.

However, a simple simulation shows that the assumption

$$\frac{\Delta x_0}{\Delta[\mathrm{Fe/H}]} = -0.4$$

yields $N_{NS}^{M-R}/N_{NS}^{M-P} \sim 4$, in good agreement with the observed R_R/R_P ratio. Considering the quoted uncertainties, this slope is constrained to be anyway ≥ -0.8.

In synthesis, if this last metallicity-dependence for the IMF will be confirmed and if the adopted formulae to compute the NS numbers are correct, the suggestion put forward by Grindlay (1987, 1993) is thus a plausible explanation for the increasing incidence of LMXBs with increasing cluster metallicity. Moreover, one could also draw some other interesting considerations.

First, turning the problem around, one could use the evidence that the adoption of a steep dependence of the IMF slope on metallicity is hardly compatible with the observed frequency of LMXBs in Galactic globular clusters to conclude that such a dependence is much shallower than the one proposed earlier (McClure et al. 1986).

Second, since this flatter dependence by itself cannot account for the observed IMF slope variation, this result, in turn, may support the whole interpretative scenario proposed by Djorgovski et al. (1993) and Stiavelli, Piotto, & Capaccioli (1992).

In fact, these authors claim that the detected dependence of the IMF slope $-x_{0}$- on the galactic location can be accounted for considering the effects of the interactions between clusters and Galactic disk. In their view, all globular clusters are born with quite similar IMFs and the detected differences in the present mass functions (PMF) are due to the subsequent dynamical evolution which actually steepens the observed slope. The number of NSs is presumably determined by the original IMF, and not by the PMF, resulting after the dynamical interactions affecting mostly the cluster low-mass members. The consistency obtained between (*a*) the observed ratio of LMXBs with varying metal content and (*b*) the number ratio predicted adopting a slope concerning just the metallicity dependence equal to -0.4 could imply that this is the correct value to use to describe the intrinsic dependence of the IMF on metallicity.

4.2.2. *A "Natural" Effect*

Besides considering the effects induced by possible differences in the IMFs, we suggest here that there is a *natural* factor enhancing the probability of the two-body tidal capture (and, in turn, the rate of LMXB production) in high-metallicity clusters. This *new* factor comes from the stellar evolution theory itself.

In fact, the rate of tidal capture (Γ) as described by Lee & Ostriker (1986) depends, at fixed cluster density, on radius (R) and mass (M) of the capturing star, and precisely:

$$\Gamma \sim R^{2-\alpha} M^{\alpha} , \quad (1)$$

where $\alpha = 1.07$, a value appropriate for the case under consideration.

Following standard stellar models (VandenBerg & Bell 1985), stars with higher metal content have wider radii and higher masses than metal-poor ones. On the basis of those models, for a similar metallicity range, and of the above equation (1), thus

$$\frac{\Gamma_{M-\mathrm{rich}}}{\Gamma_{M-\mathrm{poor}}} \sim 2.2 .$$

This means that the *natural* contribution is at least as important as that of the IMF.

Furthermore, since for fixed binary separation and masses of the two components, metal-rich stars would more easily fill the Roche lobe, as their radii are larger, there is an additional "evolutionary" reason to favor a higher incidence of LMXBs in metal-rich clusters.

5. SUMMARY AND CONCLUSIONS

Adopting appropriately selected samples of XR and nXR clusters in the Galaxy and M31, it has been shown that

1. The XR clusters (with $L_X > 10^{36}$ ergs s^{-1}), commonly believed to contain the so-called low mass X-ray binaries, are in both galaxies in general denser than nXR globulars, as expected on the basis of current LMXB models. Furthermore, both XR cluster samples in the Galaxy and M31 are shown to be significantly metal richer than the corresponding nXR ones.

2. Within this framework and based on the accurate testing of the multivariate formula of Djorgovski et al. (1993, their eq. [5]), the apparent larger frequency of X-ray clusters at low R_{GC} and $|Z_{GP}|$ is simply a by-product of the primary dependencies on density and metallicity.

In order to test possible mechanisms through which metallicity can act as a critical parameter in increasing the LMXBs frequency at a fixed cluster density, we adopted a framework where LMXBs in GCs are formed via two main mechanisms: (1) two-body tidal captures form bound systems including a neutron star, in high-density GCs, heavily depleted of primordial binaries, and (2) LMXBs form via (2 + 1) encounters in low-density clusters, where primordial binaries are presumably still present.

The larger observed incidence of LMXBs in metal-rich clusters can be explained by the predicted increase of available NSs (Grindlay 1987, 1993), but the slope of the metallicity dependence of the IMF is constrained to be $\Delta x_0/\Delta[\mathrm{Fe/H}] > -0.8$ to preserve compatibility with data.

Second, there is also a *natural* factor enhancing the probability of the two-body tidal capture (and, in turn, the rate of LMXB production) in high-metallicity clusters which it is suggested to come from the stellar evolution theory itself.

From the rough computations made, this new effect could by itself explain the observed ratio of 4 between their incidences of XR clusters in the metal-rich and the metal-poor groups determined above. However, there is no reason to exclude that both mechanisms proposed so far to explain the dependence of the LMXB frequency on metallicity can be at work.

Finally, it may be interesting to note that the metallicity-dependence of the IMF slope, if real, would be efficient in enhancing the frequency of LMXBs independent of the actual mechanism adopted to form the LMXBs as it would directly increase the number of available NSs. On the contrary, the "natural" enhancement suggested here is *framework-dependent* as it would be most efficient in the two-body tidal captures. On the other hand, unless the evolutionary models are grossily in error, it must be surely present and the rate of captures should always increase with increasing metallicity of the star interacting with the NS.

In conclusion, the present results and suggestions represent an additional item in a scenario (see, i.e., Fusi Pecci et al. 1992, 1993c, d; Djorgovski & Piotto 1992; Ferraro et al. 1993) where global cluster dynamical effects and evolutionary properties of individual stars interfere to yield special objects or features which may be typical of very crowded systems.

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