THE ASTROPHYSICAL JOURNAL, 359:L11–L14, 1990 August 10

LOW-LUMINOSITY STELLAR MASS FUNCTIONS IN GLOBULAR CLUSTERS

HARVEY B. RICHER[1] AND GREGORY G. FAHLMAN[1]
Department of Geophysics and Astronomy, University of British Columbia
ROBERTO BUONANNO[1]
Osservatorio Astronomico di Roma
AND
FLAVIO FUSI PECCI
Dipartimento di Astronomia, Università di Bologna
Received 1990 April 13; accepted 1990 May 21

ABSTRACT

New CCD photometry in selected fields in the globular clusters M13 and M71 is used to construct stellar luminosity and mass functions extending down the main sequence to at least 0.2 $M_{\odot}$. The luminosity function of M71 is rather flat from $M_I = 3.5$ through to $M_I = 7.5$ and displays a sharp increase fainter than this to the limit of the data at $M_I = 10$. The result for M13 is not significantly different from that obtained by Drukier *et al.*, with the luminosity function being very steep at the faint end. Comparing the mass functions for M13 and M71 to existing data for NGC 6397, we find that all three display a marked change in slope at about 0.4 $M_{\odot}$, with the slope becoming considerably steeper toward lower masses. The three systems span almost the full range of metallicity observed in the Galactic globular clusters, but no sign of a correlation between the slope of the mass function (at either high or low masses) and metallicity is seen. Both NGC 6397 and M71 appear to be in a more advanced stage of dynamical evolution than M13, and it is perhaps significant that the low-mass slope of the mass function is much steeper in M13. The implication of these results for the source of dark matter in the Galactic halo is discussed.

Subject headings: clusters: globular — dark matter — luminosity function

I. INTRODUCTION: OBSERVATIONS AND REDUCTIONS

Mass functions in globular clusters are important for the insight they provide into star formation in the early universe. However, the observed mass function is the initial mass function only if dynamical processes are unimportant. Of particular interest is the low-mass end of the mass function. Here, a sensitive test of stellar evolution theory is available through the boundary between hydrogen burning stars and brown dwarfs, expected to occur near 0.1 $M_{\odot}$ in a metal-poor cluster (D'Antona 1987). If current models are at all accurate, this will appear at an absolute *I* magnitude brighter than 12, a magnitude that is reachable from the ground for the nearest clusters (Fahlman *et al.* 1989). Further, if the halo mass function is similar to that found in globular clusters, then the low-mass end of the cluster mass function is also important for establishing the mass budget of the Galactic halo and thereby has obvious implications for the Galactic dark matter.

The major problem in accurately constructing the stellar mass function is the mass-luminosity relation. Unfortunately, the input physics into the models defining the mass-luminosity relation is complicated and uncertain for low-mass main-sequence stars (see Renzini and Fusi Pecci 1988). In particular, the main feature predicted by the models is the flattening of the mass-luminosity relation below about 0.5 $M_{\odot}$. The consequences of this are a steepening of the cluster main sequence and the luminosity function below this mass. Hence, the use of inadequate stellar models to derive the cluster mass function could result in large errors associated with the mass function slope. In this *Letter* we present new data on the cluster luminosity functions, construct mass functions from the available models, and draw some preliminary conclusions on the basis of the derived mass functions. We are mindful, however, of the pitfalls involved in this process.

The stars at the faint end of the stellar mass function are very red; consequently, there is considerable leverage to be gained by obtaining deep CCD images of the nearby globular clusters in the *I* band. The mass function of the metal-poor cluster NGC 6397, obtained from such data, has already been published (Fahlman *et al.* 1989). Here we report the results from similar observations of the intermediate metallicity cluster M13 and the metal-rich system M71.

Data for both of these clusters were obtained at the prime focus of CFHT using a double density RCA chip (640 × 1024 pixels) with each pixel's side subtending 0".205 on the sky. For M13, 11 frames, each of 1200 s exposure were obtained for both a cluster field and a blank field located about 52′ west of the center at same Galactic latitude as the cluster. The cluster field was situated about 11′ west of the center, just to the northwest of star A1 of Sandage (1970). A second field in M13 (six 1200 s exposures) was observed directly to the south of the first field with a slight overlap between the two. All the M13 frames have seeing better than 0".7 (FWHM). These fields were deliberately chosen far from the cluster center in order to investigate the stellar population at about half the cluster tidal radius. This means that few high-mass stars will be seen; only the faint end of the mass function can be observed. Because of the relatively poor statistics resulting from these distant fields, the mass function discussed below consists of data from both

[1] Visiting Astronomer, Canada-France-Hawaii Telescope which is operated by the National Research Council of Canada, the Centre National de la Recherche of France, and the University of Hawaii.

fields. For M71, a single cluster field was observed at about 3′ northwest of the cluster center. This is at about the cluster half-mass radius. Background contamination is very important for M71 as it lies at a low Galactic latitude, so two blank fields were used. One is located 65′ northwest of the cluster, while the other is just inside the western edge of the cluster tidal radius. The final M71 cluster frame was an average of ten 300 s exposures, the distant M71 blank field contained an average of seven 600 s exposures, and the field which is closer in five 600 s frames. Again, the seeing was superb on all these images, averaging about 0″.65.

Preprocessing of the data was accomplished using routines in IRAF. The frames were bias-corrected, trimmed, and flat-fielded using dome flats. A fringe frame was constructed from a median filtering of a large number of relatively uncrowded program frames. Residual fringing remaining in the images after defringing was well less than 1% of the sky level. The data were reduced using a version of DAOPHOT (Stetson 1987) modified at CFHT to run under the Unix operating system on a Sun workstation. Photometric calibration was achieved using NOAO consortium fields in M92 and NGC 4147 together with standards in SA 110 (Thompson and Searle 1988).

II. THE LUMINOSITY AND MASS FUNCTIONS

Luminosity functions for M13 and M71 were constructed by counting the stars in the cluster and background fields, correcting for incompleteness using the ADDSTAR routine in DAOPHOT, and subtracting the incompleteness corrected background counts from that in the respective cluster frames. These numbers are compiled in Table 1 where the subscript *c* refers to the cluster field and *b* is for the background. The observed counts are listed as *n*, the completeness corrections by *f*, and Φ represents the cluster luminosity function which is the difference between the cluster and background counts after both are corrected for incompleteness. The M13 counts were binned in ±0.5 mag intervals because of the small numbers involved. The statistical error is also indicated in Table 1. This error contains the uncertainty due to counting statistics as well as to the errors in the incompleteness corrections. The errors in the cluster and background fields were added in quadrature to obtain the final error estimate. In most cases, small geometrical corrections were applied to the counts to correct for slightly differing field sizes (due to the small shifts in position between each exposure); hence, Φ is not simply the differences between the cluster and background counts shown.

In order to convert the apparent *I* magnitudes to absolute magnitudes, we have adopted apparent distance moduli in *I* for M13 and M71 of 14.4 and 13.4, respectively. These were arrived at by using an apparent distance modulus in *V* of 14.4 and a reddening of 0.02 for M13 (Richer and Fahlman 1986), 13.7 and 0.28 respectively for M71 (Richer and Fahlman 1988), together with $A_I = 0.6A_V$ (Cohen *et al.* 1981). Small changes in these distance moduli do not affect the results discussed below.

The luminosity function for M71 is plotted in Figure 1. The major features are the rather flat section from $M_I = 3.5$ through to $M_I = 7.5$, and a sharp increase (by about a factor of 3) fainter than this to the limit of the data at $M_I = 10$. The sharp rise to low luminosities had been predicted earlier from an analysis of the star counts in M71 (Richer and Fahlman 1989). The M71 luminosity function bears a rather strong qualitative resemblance to that of the solar neighborhood (Stobie, Ishida, and Peacock 1989). The *I* band star counts for

TABLE 1

STAR COUNTS IN GLOBULAR CLUSTERS

A. M13

I^a	n_c^b	f_c^c	n_b	f_b	Φ^b
22.0....	138	1.00	42	1.00	48.5 ± 14
23.0....	325	1.09	76	1.00	183.4 ± 31
24.0....	426	1.69	159	1.15	318.9 ± 32
25.0....	848	...	331	...	...

B. M71

I^a	n_c	f_c	n_b^a	f_b^c	Φ
14.25....	8	1.00	0	1.00	8 ± 2.8
14.75....	14	1.00	7	1.00	10.8 ± 4.0
15.25....	25	1.00	25	1.00	13.6 ± 6.0
15.75....	27	1.00	34	1.00	11.5 ± 6.2
16.25....	31	1.00	64	1.00	1.9 ± 7.4
16.75....	81	1.00	82	1.00	43.7 ± 10.2
17.25....	135	1.00	138	1.00	72.2 ± 13.7
17.75....	170	1.00	176	1.00	89.9 ± 15.3
18.25....	205	1.03	226	1.05	103.7 ± 19.1
18.75....	230	1.03	281	1.05	103.2 ± 20.4
19.25....	253	1.06	352	1.05	100.9 ± 23.0
19.75....	284	1.11	436	1.05	107.8 ± 29.2
20.25....	310	1.14	520	1.05	106.2 ± 32.5
20.75....	322	1.20	585	1.05	106.9 ± 37.8
21.25....	441	1.27	691	1.08	221.9 ± 45.9
21.75....	477	1.41	788	1.11	274.7 ± 59.9
22.25....	545	1.64	835	1.19	441.9 ± 72.7
22.75....	455	1.80	910	1.36	237.2 ± 79.8
23.25....	290	3.92	683	2.23	442.5 ± 150.1
23.75....	205	...	413	...	...
24.25....	107	...	203	...	...

[a] Counts are in bins ±0.5 mag wide for M13, ±0.25 mag wide for M71.

[b] Numbers are the sum in the two fields observed.

[c] Numbers are the average incompleteness corrections in the two fields.

M13 are not shown, but they were used to construct the mass function discussed below. The results are not significantly different from those obtained by Drukier *et al.* (1988).

To convert the luminosity functions into mass functions, mass-luminosity relations in *I* appropriate to each cluster

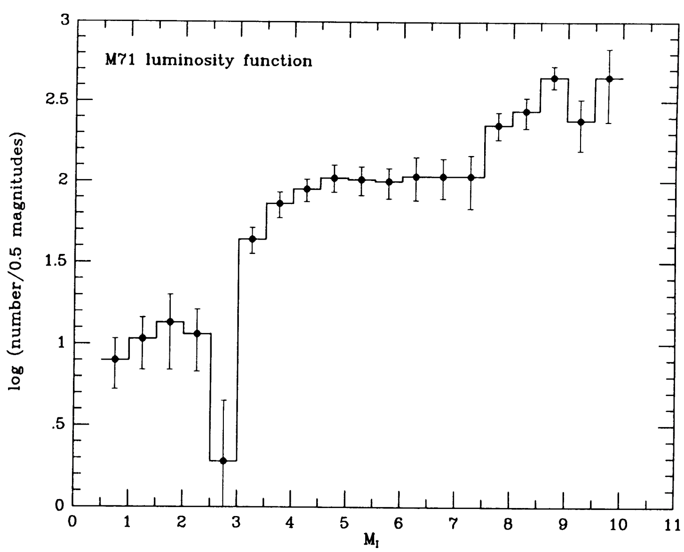

FIG. 1.—The *I* band luminosity function for a single field in M71. The assumed distance modulus in *I* is 13.4 mag.

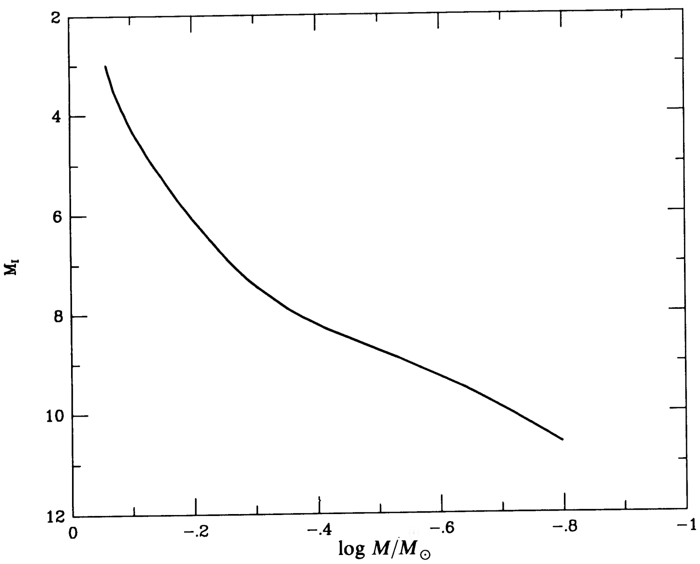

FIG. 2.—The derived M_I-mass relation for stars in metal-rich ([Fe/H] = −0.7) globular clusters.

metallicity are required. A relation for the metallicity appropriate to M13 was discussed in Fahlman *et al.* (1989) and is used here. For the metal-rich cluster M71, new models extending to 0.15 $M_\odot$ were kindly made available to us by Don VandenBerg. These models ([Fe/H] = −0.65, [O/Fe] = 0.3, $Y = 0.24$) were for ages in the range of 12–16 Gyr (we used those for 14 Gyr), and provided us with M_V, mass, and M_{bol}. To obtain M_I we adopted the relation $BC = -1.31(V-I) + 1.05$ from Gilmore and Reid (1984), and converted the model absolute V magnitudes to M_I. The above relation is rather insensitive to metallicity effects (see Gilmore and Reid 1984) and should be particularly appropriate for the metal-rich stars in M71. The resulting M_I-mass relation for metal-rich globular clusters is shown in Figure 2.

In Figure 3 we present the globular cluster mass functions for the two clusters discussed here together with the mass function for NGC 6397 (Fahlman *et al.* 1989). The plot shown for M13 contains three sources of data: (1) triangular points from Richer and Fahlman (1988), (2) filled circles from Drukier *et al.* (1988), and (3) open circles representing the new I data. New mass functions were recalculated from the visual luminosity functions presented in the previous M13 papers so that a consistent mass-luminosity relation was used. The data from the three studies were scaled so that each contained the same number of stars in the region of overlap.

These three clusters span almost the full range in metallicity of the known globular clusters, so any correlations between the morphology of the mass function and abundance should be apparent if mass segregation effects are unimportant or can be accounted for (McClure *et al.* 1986). All the mass functions exhibit a qualitatively similar shape; a sharp increase in slope for masses less than about 0.4 $M_\odot$. This break in slope is much more apparent for M71 and NGC 6397. Both of these clusters exhibit a density cusp in their cores which is the usual diagnostic of a postcollapse cluster. For NGC 6397, Djorgovski and King (1986) found that the luminosity profile in the cluster core could not be fitted with a King model but required a power-law slope near the center. In M71, Fahlman and Richer (1990) find a shallow-sloped power-law deviation from a King model in the cluster core. Further, the slope at the low-mass end of the mass function for these two systems is significantly shallower than it is for M13. All the mass functions below 0.4 $M_\odot$ are reasonably well fitted by a power-law with index x defined by $n(M) \propto M^{-(1+x)}$, where $n(M)$ is the number of stars per unit mass. The values of x below 0.4 $M_\odot$ are indicated for each cluster in Figure 3 with the errors in these values 0.4 for both M13 and M71 and 0.1 for NGC 6397. In none of the clusters is there any evidence for a flattening of the slope toward the lowest masses even though all the mass functions extend to at least 0.2 $M_\odot$. The mass function slopes for the two dynamically old systems are much shallower than that for M13, and it is

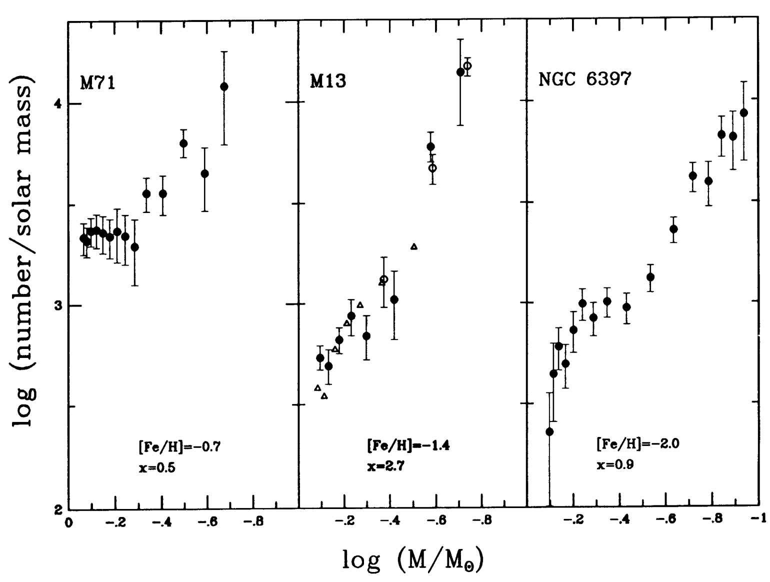

FIG. 3.—Mass functions for three globular clusters. The cluster metallicities as well as the mass function slopes for masses less than 0.4 $M_\odot$ are indicated. The function for M13 contains data from three independant studies. The error bars reflect the uncertainties in the luminosity functions only; the mass-luminosity relations are assumed to be error-free.

tempting to ascribe the difference to dynamical evolution. The more dynamically evolved clusters may have lost a much greater fraction of their low-mass stars through evaporation, thus flattening the low-mass end of their mass functions (Lee, Fahlman, and Richer 1990). A larger sample of pre- and post-collapse systems will have to be investigated before this possibility is confirmed. If correct, it may suggest that initially all clusters contained a large component of low-mass stars, extending (at least) to within a few hundredths of a solar mass of that of brown dwarfs.

III. DISCUSSION

The conclusions from this work are as follows.

1. In three globular clusters covering almost the entire range in metal abundance of the known systems, the mass functions show a break in slope at about 0.4 $M_\odot$, with the slopes becoming much steeper toward lower masses. We have some concern that this break occurs near where the mass-luminosity relation also shows a slope change, so that this result depends on the adequacy of the theoretical model used.

2. There is no correlation between the mass function slopes (either before or after the break) and the cluster metal abundance.

3. The mass function slopes are significantly flatter in the two clusters which are dynamically old, suggesting that dynamical evolution has played an important part in modifying the presently observed mass functions. Specifically regarding this point, the half-mass relaxation times[2] ($t_{\rm rh}$) for NGC 6397 and M71 are 2.95×10^8 and 2.24×10^8 yr, respectively, while it is 2.54×10^9 yr for M13. Since these clusters have a similar chronological age, it follows that M13 is about an order of magnitude younger dynamically than the other two clusters. Lee, Fahlman, and Richer (1990) have shown that clusters dissolve on a time scale of about $100t_{\rm rh}$ and that the late stages of dynamical evolution are characterized by significant changes in the cluster mass functions. Both NGC 6397 and M71 may be in these late phases. M13, on the other hand, might be expected to display an observed mass function which is still close to its IMF.

4. For none of the systems is there any indication of a turnover in the mass function even though they all extend to at least 0.2 $M_\odot$ and in the best case to 0.12 $M_\odot$. This limiting mass (for NGC 6397) is within a few hundredths of a solar mass of that of brown dwarfs. Since there is presently no identifiable mechanism for terminating star formation at the hydrogen-burning limit, we may surmise that brown dwarfs formed and possibly are still present in those clusters that are dynamically able to contain them.

We have attempted to derive the global parameters for M13 by constructing King-Michie models for the cluster (Gunn and Griffin 1979) and constraining these with the mass function slope seen in our field, together with the velocity dispersion curve and luminosity profile given in Lupton, Gunn, and Griffin (1986). While a rather wide range of models can be made consistent with the data, they all have similar features (cf. Lupton, Gunn, and Griffin 1987). The global mass function index must be steep. In fact, a value near that seen in our field ($x = 2.7$) seems close to the value required. Global values for the ratio of the mass to the visual light near 6 can be obtained for models containing a major proportion of their mass in brown dwarfs. The precise value of the mass-to-light ratio depends primarily on the adopted low-mass cutoff and to a lesser extent on the other model parameters. Models for M13 with very large mass-to-light ratios (> 10) could not be made consistent with the present data, but it should be remembered that M13 may have lost many of its low-mass stars in the course of its dynamical evolution. Nevertheless, the derived mass-to-light ratio is certainly within the range of that seen in normal spiral galaxies (Rubin 1986). Consequently, a halo population with a mass function similar to that inferred in M13, that is with a slope of $x = 2.7$, and a lower mass cutoff in the range of a few hundredths of a solar mass, could well explain the Galaxy's dark matter.

[2] The quoted half-mass relaxation times were obtained from the formula given by Spitzer and Hart (1971). The total cluster mass is obtained by applying a mass-to-light ratio of 1.6 to the visual luminosity, and the mean stellar mass is assumed to be 0.7 $M_\odot$. The half-mass radius is obtained from single-mass King models and the concentration parameters tabulated by Webbink (1985). Thus the quoted numbers are only indicative and useful primarily for comparison among different clusters.

The authors are indebted to CFHT for assignments of telescope time in support of this project. Special thanks are due to Don VandenBerg for providing his grid of oxygen-enhanced model atmospheres in advance of publication. H. B. R. and G. G. F. are supported by grants from the Natural Sciences and Engineering Research Council of Canada.

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ROBERTO BUONANNO: Osservatorio Astronomico di Roma, Viale del Parco Mellini 84, I-00136 Rome, Italy

GREGORY FAHLMAN and HARVEY RICHER: Department of Geophysics and Astronomy, University of British Columbia, 2219 Main Mall, Vancouver, B.C., Canada V6T 1W5

FLAVIO FUSI PECCI: Departimento di Astronomia, Università di Bologna, via Zamboni 33, I-40126 Bologna, Italy