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MASS FUNCTIONS FOR GLOBULAR CLUSTER MAIN SEQUENCES BASED ON CCD PHOTOMETRY AND STELLAR MODELS

ROBERT D. MCCLURE,[1,3] DON A. VANDENBERG,[1,4] GRAEME H. SMITH,[3] GREGORY G. FAHLMAN,[1,2,5]
HARVEY B. RICHER,[1,2,5] JAMES E. HESSER,[1,3] WILLIAM E. HARRIS,[1,6]
PETER B. STETSON,[3] AND R. A. BELL[1,7]
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ABSTRACT

Main-sequence luminosity functions constructed from CCD observations of globular clusters reveal a strong trend in slope with metal abundance. Theoretical luminosity functions constructed from VandenBerg and Bell's isochrones have been fitted to the observations and reveal a trend between x, the power-law index of the mass function, and metal abundance. The most metal-poor clusters require an index of about $x = 2.5$, whereas the most metal-rich clusters exhibit an index of $x \approx -0.5$. The luminosity functions for two sparse clusters, E3 and Pal 5, are distinct from those of the more massive clusters, in that they show a turndown which is possibly a result of mass loss or tidal disruption.

Subject headings: clusters: globular — luminosity function

I. INTRODUCTION

With the recent application of CCD detectors to observations of globular clusters, a significant advance has been made in the photometry of faint main-sequence stars. A number of pioneering photographic luminosity functions (LFs) have been obtained, for instance, by Sandage (1957), van den Bergh (1975), Sandage and Katem (1977), and Da Costa (1982). However, as these researchers were aware, photographic photometry in crowded regions can be seriously affected at the faint limit, and both color-magnitude diagrams and LFs can be degraded. A sample of globular clusters has now been studied with the new CCD technique, resulting in vastly improved color-magnitude diagrams. The main-sequence LFs derived from these data, when combined with stellar models, lead to a determination of the mass function, which is an important datum in directing our understanding of star formation during the early evolution of the Galaxy. We compare in this letter the available CCD data (either published or in preparation) on LFs for globular clusters. These data reveal the existence of important trends with other cluster parameters.

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

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

[3] Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics.

[4] Physics Department, University of Victoria.

[5] Department of Geophysics and Astronomy, University of British Columbia.

[6] Department of Physics, McMaster University.

[7] Astronomy Program, University of Maryland.

II. THE OBSERVATIONAL DATA

Although a growing number of papers reporting CCD photometry of globular clusters have provided much improved color-magnitude diagrams, there have been few deep LFs published to date. The determination of a reliable LF to faint limits on the main sequence is difficult primarily because of crowding. With the nonlinear photographic plate, it is impossible to detect and measure faint stars lying in the wings of brighter stars, and it is difficult to determine the correction factors needed to estimate the true numbers of faint stars. With the photometrically linear CCD device, the image shape can be accurately modeled and scaled to deconvolve overlapped images in a proper fashion, impossible with a nonlinear device. Nevertheless, construction of LFs is still a challenge that requires much more care and labor than does the construction of a color-magnitude diagram showing good principal sequences. The data for the present *Letter* have been gathered from papers by McClure *et al.* (1985), Fahlman, Richer, and VandenBerg (1985), Lupton and Gunn (1986), Penny and Dickens (1986), Richer and Fahlman (1986), and Smith *et al.* (1986), for the clusters E3, M13, M15, NGC 6752, and Pal 5, and from papers in preparation by various combinations of the present authors for 47 Tucanae, M4, M5, M15, and M68, based on data obtained with the CCD cameras at the Cerro Tololo 4 m telescope and the Canada-France-Hawaii 3.6 m telescope.

In all of these studies, the authors have been careful to determine the incompleteness at the faint limit of the photometry due to crowding effects, and the corrections to be applied due to contamination by background stars.[8] Though

[8] The latter effect is particularly important in the case of 47 Tuc which is superposed on the outer regions of the Small Magellanic Cloud. In this case the use of two-color data permits the effective separation of 47 Tuc stars from SMC stars, which form well-separated sequences in the color-magnitude diagram.

TABLE 1

CLUSTER PARAMETERS

Cluster	[M/H][a]	c[a]	$\log T_r$[a]	r_{obs}[b]	x	References
47 Tuc..........	−0.75	2.08	7.870	49	−0.5	1, 2
E3	−0.96	0.78	8.803	< 1	...	3
M68.............	−1.85	1.63	8.400	8	2.0	4
Pal 5	−1.43	0.83	9.808	~ 1	...	5
M5	−1.60	1.83	8.223	21	1.5	6
M4	−1.09	1.53	7.839	4.5	−0.5	6
M13.............	−1.60	1.44	8.672	11	1.5	7, 8
NGC 6752	−1.64	1.59	7.789	18	1.5	9
M15.............	−2.06	2.54	7.133	95	2.5	2, 10

[a] From Webbink 1985.

[b] Radius of observations in units of core radius.

REFERENCES.—(1) Harris and Hesser 1985. (2) W. Harris and J. Hesser unpublished. (3) McClure *et al.* 1985. (4) R. McClure *et al.* unpublished. (5) Smith *et al.* 1986. (6) H. Richer and G. Fahlman unpublished. (7) Lupton and Gunn 1986. (8) Richer and Fahlman 1986. (9) Penny and Dickens 1986. (10) Fahlman, Richer, and VandenBerg 1985.

the effective area surveyed differs from cluster to cluster, most observations have been made at relatively large radial distances where faint-star photometry is most reliable (see Table 1). For many clusters, long exposures of comparison fields outside the cluster have been used to correct for field-star contamination. Even though the data have been analyzed with somewhat different procedures by each group, we feel that, for the first time, the corrections that must be applied to observed LFs *are sufficiently small and well known* that they are not affecting the conclusions that can be drawn regarding trends with other cluster parameters. The derived LFs upon which this letter is based are shown in Figure 1. The function for M13 is based on an average of that from Lupton and Gunn (1986), which has been converted to V magnitude from their g magnitude, and that from Richer and Fahlman (1986). The function for M4 is based on analysis of the CCD images of two fields discussed by Richer and Fahlman (1984).

The LFs have been normalized to 50 stars at absolute magnitudes, M_V, between 5.0 and 5.5 mag after correcting the V magnitudes for a distance modulus based on the level of the horizontal branch. The latter is assumed to be at $M_V = 0.6$ mag (0.85 was used for the metal-rich cluster 47 Tuc); although this may be of some dispute, the likely error involved is small enough not to affect the conclusions of the present study. The LFs in Figure 1 are displayed as curves whose thickness is a function of metal abundance (see Table 1). Note the increase in steepness among LFs of more metal-poor clusters.

The two clusters whose LFs turn down at the faint end, E3 and Pal 5, differ in one major way from all the others, in that they are sparse. The downturn at the faint end is possibly an effect of tidal disruption or significant mass loss (see § IV).

III. FITS WITH THEORETICAL MODELS

The theoretical isochrones of VandenBerg and Bell (1985) specify, among other things, the run of mass with luminosity for a given age. Hence, if a power-law mass spectrum of the form $\phi(m)\,dm = m^{-(1+x)}\,dm$ is assumed, where $\phi(m)\,dm$ is the number of stars with masses in the range m to $m + dm$, then theoretical LFs of the form Φ = number of stars per unit

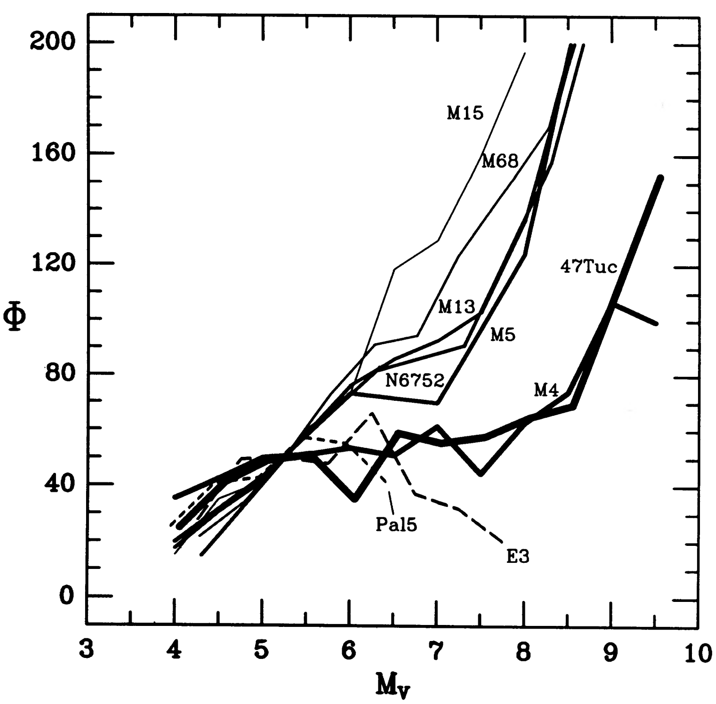

FIG. 1.—Observed luminosity functions for globular clusters observed with CCD detectors. Φ is the number of stars in a magnitude interval $\Delta M_V = 0.5$ mag. The thickness of the curves increases with the metal abundance as compiled by Webbink (1985). The observations for the two sparse clusters represented by dashed curves were obtained in the cluster centers and are almost certainly affected severely by dynamics.

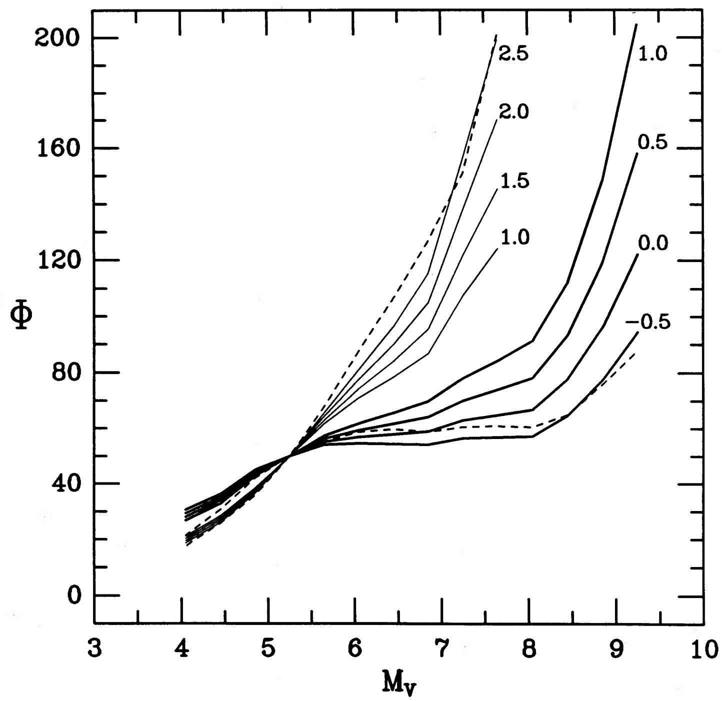

FIG. 2.—Theoretical luminosity functions (Φ defined as in Fig. 1) from the isochrones of VandenBerg and Bell (1985) for helium abundance $Y = 0.20$ and for metal abundances $Z = 0.0001$ ([M/H] $= -2.3$) (*light solid curves*) and $Z = 0.006$ ([M/H] $= -0.5$) (*heavy solid curves*). Values of x in the power-law mass spectrum are indicated. Luminosity functions for $Y = 0.30$ are shown, for the extremes of metal abundance and x, by the dashed curves.

magnitude interval [$= \phi(m)(dm/dM_V)$] can be calculated for comparison with the observations. (Since in several instances the observed data extend to fainter magnitudes than the VandenBerg and Bell isochrones, some additional lower mass models for each adopted composition were computed.) The value of x which best describes a given observational LF is determined by comparing the observed locus with those calculated for the appropriate metal abundance and a range in x. Figure 2 illustrates representative theoretical LFs for two heavy-element abundances, $Z = 0.0001$ and $Z = 0.006$ assuming, in each case, a helium content $Y = 0.20$ and the indicated values of x.[9] Dashed curves representing LFs for $Y = 0.30$ (for $Z = 0.0001$, $x = 2.5$, and for $Z = 0.006$, $x = -0.5$) show that varying helium abundance has little effect. An age of 16 Gyr was selected (e.g., see VandenBerg 1983); note, however, that by normalizing the models to have the same number of stars at $M_V = 5.25$, which is sufficiently faint that evolutionary effects are minimized, the additional uncertainty due to age is demonstrably small compared to the effects of varying x.

Examination of Figure 2 shows clearly that a unique mass function is incapable of reproducing the observations for all clusters. While a steep mass spectrum is required to fit the data for the most metal-poor systems, it is apparent that for more metal-rich clusters, a much shallower mass spectrum is consistent with the flattening of the LFs below the turnoff ($M_V > 4.5$), as well as the turnup at faint magnitudes. The latter effect is a result of a pronounced decrease in sensitivity of luminosity to stellar mass on the lower main sequence at masses below 0.5–0.6 $\mathcal{M}_\odot$. This could have been predicted from examining Table 2 or Figure 3 of VandenBerg *et al.* (1983).

In Figure 3 we display as heavy curves the mean observed LFs for the three distinct regimes of metal abundance represented by (1) M15, (2) M5, M13, and NGC 6752, and (3) 47 Tuc. (Both the metal abundance and LF for M68 are intermediate between those for M15 and the clusters in group [2]). Superposed on the observational curves are the best-fit theoretical luminosity functions for the appropriate metallicities and the displayed values of x (in parentheses). VandenBerg and Bell's (1985) isochrones are computed for several widely differing [M/H] values, and we have selected abundances similar to those used by VandenBerg and Bell (1985), and Richer and Fahlman (1986) for isochrone fits to color-magnitude diagrams of 47 Tuc, M15, and M13. The dashed curves in Figure 3 represent luminosity functions with $x = 1.5$ for the extreme values of [M/H] indicated, to illustrate again that the observed spread in LFs cannot be reproduced with the same x value. For example, while a theoretical LF with $x = 1.5$ fits the [M/H] $= -1.3$ cluster observations quite well, it does not reproduce the metal-poor ([M/H] $= -2.3$) M15 data. Our derived values of x are listed in Table 1. From a consideration of the uncertainties in both the observations and theory, we estimate these to be accurate to ± 0.5.

The present results for 47 Tuc seem to be in accord with published analyses of dynamical data. In order to model the

[9]Note that the normalization is affected at a constant M_V, not a constant stellar mass, e.g., $M_V = 5.25$ corresponds to stellar masses of 0.74, 0.76, and 0.83 $\mathcal{M}_\odot$ for [M/H] $= -2.3$, -1.5, and -0.5 respectively.

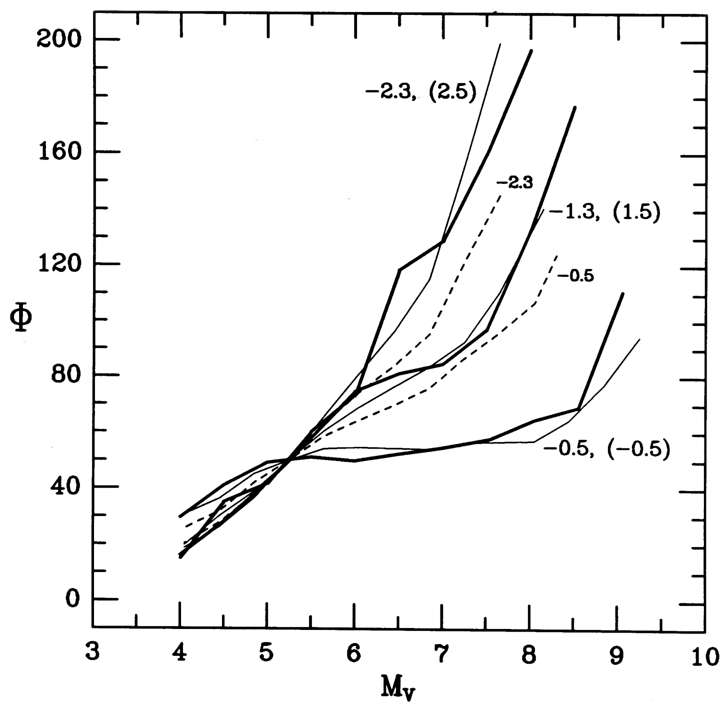

FIG. 3.—The heavy solid curves represent mean observed luminosity functions for (1) M15 (*upper curve*), (2) M5, M13, and NGC 6752 (*middle curve*), and (3) M4 and 47 Tuc (*lower curve*). The light solid curves represent "best-fit" theoretical luminosity functions for the appropriate [M/H] values and the x values shown (the latter in parentheses). The dashed curves represent additional luminosity functions for $x = 1.5$ and the values of [M/H] shown.

observed run of velocity dispersion and light with radius, Da Costa and Freeman (1985) find that many more dark remnants are required than would be predicted from a Salpeter mass-function ($x = 1.35$). The flat mass-function derived from Figure 3 is consistent with the requirement of such an excess remnant population. In contrast, Gunn and Griffin (1979) and Lupton, Gunn, and Griffin (1985) from similar analyses of the metal-poor clusters M3, M13, and M92, find steep mass-functions having $x \approx 2$.

IV. DISCUSSION

The available data provide evidence for a strong trend between metal abundance and the power-law index of the present-day mass function. In any cluster the form of the present mass function depends on (1) the initial mass function, and (2) the process of internal dynamical relaxation which can lead to mass segregation within the cluster and the loss of the lowest mass stars. For example, mass segregation can cause an anomalously steep mass function to be observed beyond a few core radii with differences between the initial and apparent x values of ~ 1 being possible (C. Pryor, private communication; Lupton and Gunn 1986). The models, however, are quite uncertain, and it remains to be determined how effective dynamical relaxation is in the outer parts of a cluster. Observationally, the problem of measuring the effect of mass segregation is also a very difficult one and will require data in much more crowded (central) regions than are presented here. Lupton and Gunn (1986) could see no evidence of mass segregation in their M13 data obtained for this purpose over a range of ~ 6 to 14 core radii. When it is considered that a cluster's stellar content might also be modified by events such as passage through or close to the Galactic disk, it becomes apparent that a complete interpretation of the trend seen in Figure 3 will require considerable theoretical and observational effort. The lack of a correlation between x and the parameters c, $\log T_r$, and $r_{\rm obs}$ (concentration, relaxation time, and radius of observations relative to the core radius—see Table 1) suggests, however, that the observed strong dependence on metallicity reflects, at least in part, properties of the initial mass functions with which the clusters formed. *A priori*, no correlation between x and metallicity would be expected to result from dynamical processes. A deficiency in low-mass stars is seen in the cluster E3 and possibly also in Pal 5, as noted above. These clusters are, however, morphologically very distinct from the others in our sample, having low surface densities, low masses, and large core radii—properties which would in fact be consistent with these objects having lost a significant percentage of their initial mass (Smith 1985; Applegate 1986), either through stellar evolution (Smith *et al.* 1986), or possibly tidal disruption in the case of E3 (van den Bergh, Demers, and Kunkel 1980).

Should the trend seen in Figure 3 reflect a property of the initial mass function, then it may be argued that low metallicity favored the production of low-mass stars in globular clusters. However, another possibility is that systems with flat mass-functions, by virtue of having formed large numbers of massive stars, were able to chemically enrich themselves to a higher metal abundance than steep mass-function systems.

Whatever the interpretation, it is clear that the concept of a metal abundance–dependent mass function will have fundamental impact on such areas of research as globular-cluster formation in galactic halos and the chemical and dynamical evolution of galaxies.

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R. A. Bell: Astronomy Program, University of Maryland, College Park, MD 20742

Gregory G. Fahlman and Harvey B. Richer: Department of Geophysics and Astronomy, University of British Columbia, 2219 Main Mall, Vancouver, B.C. V6T 1W5, Canada

William E. Harris: Department of Physics, McMaster University, Hamilton, Ontario L8S 4M1, Canada

James E. Hesser, Robert D. McClure, Graeme H. Smith, and Peter B. Stetson: Dominion Astrophysical Observatory, 5071 West Saanich Road, Victoria, B.C. V8X 4M6, Canada

Don A. VandenBerg: Physics Department, University of Victoria, Box 1700, Victoria, B.C. V8W 2Y2, Canada