STELLAR LUMINOSITY AND MASS FUNCTIONS OF GLOBULAR CLUSTERS[1]

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Abstract. HST makes it possible for the first time to study nearly the entire mass range of globular-cluster main sequences, from the turnoff down almost to the theoretical limit for hydrogen ignition. We present main-sequence luminosity functions (LFs) for four clusters that include stars with $\mathcal{M} < 0.15\mathcal{M}_\odot$ in all cases. We compare these and other LFs that have been obtained with HST for a total of five globulars to date. Two of the three clusters in the sample that have similar metallicities have nearly identical LFs, while the third is relatively deficient in low mass stars. Possible implications of this finding are briefly discussed. Inferred mass functions vary significantly depending on the mass–luminosity relations that are adopted.

1. Introduction

The *Hubble Space Telescope* (HST) allows photometry and counting of globular-cluster (GC) stars several magnitudes fainter than is possible with ground-based equipment. For the closest clusters, luminosity functions (LFs) and the resulting mass functions (MFs) can be extended down to $\sim 0.10\mathcal{M}_\odot$, or nearly the hydrogen-burning limit. The MFs of GC stars provide impor-

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tant observational inputs into a wide variety of astrophysical problems, including (1) the realistic dynamical modeling of individual clusters; (2) the role of dynamical evolution in modifying globular-cluster MFs; (3) the amount of mass contained in very-low-mass (VLM) and brown-dwarf stars in globulars and, by extension, in the halo; (4) globular-cluster formation and initial MFs.

The first extensive comparison of Galactic GC MFs was presented by Scalo (1986), but was still based on star counts on photographic plates. Due to the limitation in mass range and to the big uncertainties in the incompleteness at the low-mass end, Scalo concluded there was no compelling evidence for differences among GC MFs. This result was questioned in the same year by McClure *et al.* (1986), who presented the first set of LFs based on CCD photometry. From a sample of 7 GCs, they noted a strong dependence of the slope of the MF on the metal content, the steepness increasing with decreasing metallicity. In a subsequent comparison of 17 GCs, Piotto (1991) suggested that dynamical evolution could also be important. A detailed multivariate statistical analysis (Djorgovski, Piotto, & Capaccioli 1993) confirmed both these results, and showed that the MFs depend mainly on a cluster's position in the Galaxy, and only secondarily on metallicity: clusters closer to the Galactic plane and center have flatter MFs. (The secondary dependence on metallicity is in the same direction as originally suggested by McClure *et al.*) The main limitation of all these ground-based studies is the small mass range ($0.5 < \mathcal{M}/\mathcal{M}_\odot < 0.8$) and the fact that the MFs were approximated by power laws. In the same period, Richer *et al.* (1991) tried to push the study of MFs to significantly fainter magnitudes in 6 globulars. Their results suggested that the MFs of at least some globulars are so steep at the faint end that VLM stars make a significant contribution to the total cluster mass. Extending this finding to the halo MF, the authors suggested that VLM stars could contribute to the missing mass of the Galactic halo.

Here we present LFs measured with the HST/WFPC2 for four globular clusters: M30 (NGC 7099), M15 (NGC 7078), 47 Tuc (NGC 104), and NGC 6397. We compare our results to existing HST studies of the latter three of these GCs, to the HST study of ω Cen by Elson, Gilmore, & Santiago (1995), and to earlier ground-based studies. We discuss the main properties of the LFs for the clusters of our sample, and infer the corresponding MFs using the most recently calculated mass–luminosity relations.

2. The Data Set

All the images were taken with the WFPC2 in parallel mode, at ~4.6 arcmin from the cluster centers. Filters and total exposure times are given

TABLE 1. **Data Set**

Cluster	$(m-M)_I$	[Fe/H]	Filter	Exp time [sec]	$M_{I,50\%}$	$\mathcal{M}_{lim}$ $[\mathcal{M}_\odot]$
NGC 6397	12.05	-1.9	F555W	14200	12.3	0.10
			F814W	18700		
NGC 7078	15.26	-2.2	F606W	6050	10.7	0.11
			F814W	6050		
NGC 7099	14.48	-2.1	F555W	15300	10.5	0.12
			F814W	8700		
47 Tuc	13.35	-0.7	F606W	1600	10.0	0.13
			F814W	2000		

in Table 1, together with metallicities and adopted distance moduli. The reduction procedures are described by Cool & King (1995) and Cool, Piotto, & King (1995). Instrumental magnitudes were transformed into the WFPC2 "ground" system following Holtzman *et al.* (1995). Here we present only LFs from the V_{555} and I_{814} photometry, which are very similar to Johnson standard V and I; the V_{606} filter is significantly different from Johnson V.

3. The Luminosity Functions

Particular attention has been devoted to determination of the completeness and to corrections for field-star contamination (see Piotto, Cool, & King 1995). The LFs presented here include only points for which the completeness was found to be $> 50\%$. With the exception of 47 Tuc, which has the most crowded images, the completeness drops below 80% only in the last $\simeq$1 mag of any of the LFs. The last two columns in Table 1 give the absolute I_{814} magnitude at which 50% completeness was reached, and the approximate corresponding mass. All the LFs have been obtained from color–magnitude diagrams (CMD), which allow the direct discrimination of cluster stars from background/foreground objects. Field-star contamination was significant only in the case of NGC 6397, which has the lowest Galactic latitude of the four clusters ($b = -12^\circ$). (Compare the NGC 6397 CMD [Fig. 1 in Cool, Piotto, & King] with that of M30 [Fig. 2 in King], both elsewhere in these proceedings.)

In Figure 1 we present the I_{814} LF for NGC 6397. The star numbers peak at $I_{814} \sim 20.5$ ($V_{555} \sim 22.2$), and then decline by a factor of 3 over the next three magnitudes. Also shown is the HST-based LF of Paresce, De Marchi, & Romaniello (1995). The two HST-based LFs span somewhat

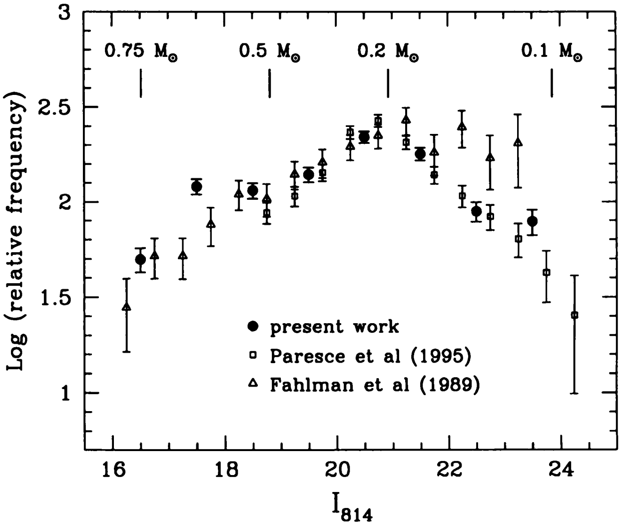

Figure 1. Two HST LFs for NGC 6397, along with the ground-based LF of Fahlman et al. (1989).

different magnitude ranges. Ours extends closer to the turnoff, owing to the inclusion of short exposures in our observing program, and ends with a bin at $I_{814} = 23$–24 ($V_{555} \simeq 25.3$–26.5), beyond which we consider the field-star corrections to be too uncertain to permit a reliable measurement of the LF (see the color–magnitude diagram in Fig. 1 of Cool, Piotto, & King elsewhere in this volume). Over the common range, the two HST-based LFs are in good agreement. Also shown is the ground-based I-band LF of Fahlman *et al.* (1989), which for $I_{814} \leq 21.5$ is in reasonable agreement with the HST-based LFs. At fainter magnitudes however, the ground-based LF rises significantly above both of the presumably more reliable HST-based LFs. Similar discrepancies between HST and ground-based results at the faint end of the LF were noted by Elson *et al.* (1995) for ω Cen.

In Figure 2 we compare the I_{814} and V_{555} HST LF with the ground-based I LF (Drukier *et al.* 1993), and V LF (Piotto, Ortolani, & Zoccali 1995) obtained at similar distance from the cluster center. The agreement is quite good, suggesting that while ground-based LFs should not be relied on at very faint magnitudes, they can be relied on at brighter magnitudes. This is important, as it means that the ground-based LFs can be usefully applied to extend the HST LFs to bright magnitudes (up to the turnoff), for which the use of HST would both be inefficient and unnecessary. In what

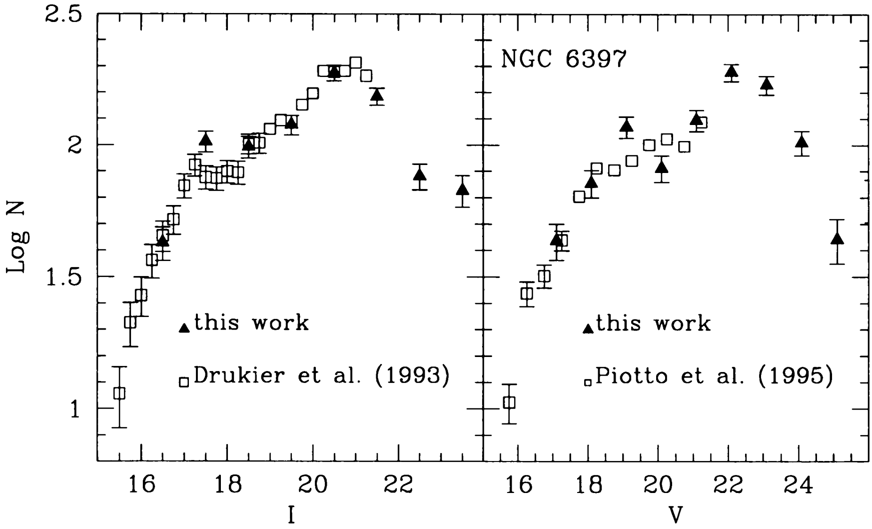

Figure 2. The I_{814} and V_{555} HST LFs for NGC 6397 are compared with the ground-based LFs by Drukier et al (1993) and Piotto et al (1995), obtained at similar distances from the cluster center. Where omitted, the error bars are smaller than the symbol size.

follows, the NGC 6397 HST LF, which is truncated at $M_{555} = 4.7$ ($M_{814} = 4$) due to the saturation of bright stars even in the short exposures, has been extended to the turnoff using the ground-based LFs shown in Fig. 2.

The I_{814} and V_{555} LFs for the three metal-poor clusters (NGC 6397, M15, and M30) are compared in the left and right panels of Figure 3. (M15 does not appear in the right panel, as the V data were taken with a different filter.) Vertical shifts were made to bring the LFs into alignment according to a least-squares algorithm, in the magnitude intervals $4.0 < M_{814} < 7.0$ and $4 < M_{555} < 7.0$. As shown by King elsewhere in this volume, the measured (local) LF of NGC 6397 closely resembles the cluster's global LF. As M30 and M15 are structurally very similar to NGC 6397, and the observations were similarly taken well outside of their cores, their observed LFs should also closely resemble the global LFs. What then makes these three clusters a particularly advantageous comparison is that their metal content is very similar (see Table 1, Col. 3), which implies that the mass–luminosity relations (MLR) for their stellar populations will also be very similar. Similarities or differences in their MFs can thus be discerned in a direct comparison of their observed LFs.

The broad features of the three I_{814} LFs are similar. Each rises steadily to a peak near $M_{814} \simeq 8.5$–9.0, then bends over and drops significantly to the limit of the observations. But when the LFs are overlaid and lined up in the range $M_{814} = 4.0$–7.0 (left panel), it becomes clear that while the LFs

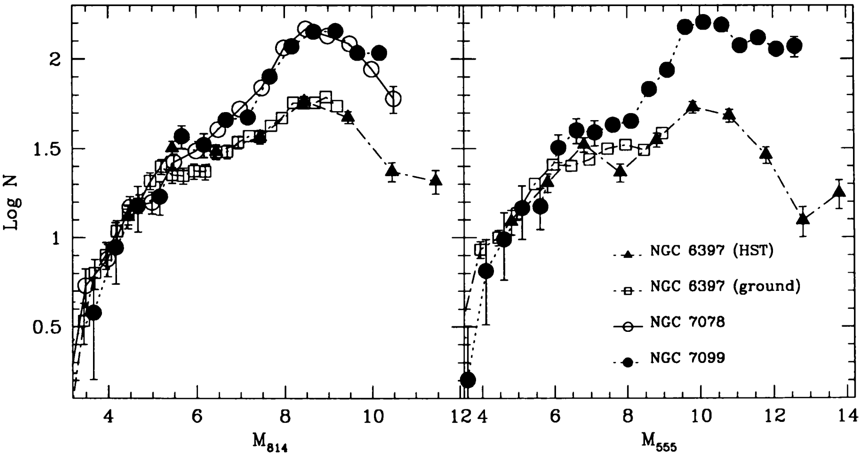

Figure 3. I_{814} (*left panel*) and V_{555} (*right panel*) LFs for the three metal-poor clusters, converted to absolute magnitudes. The LF for NGC 6397 has been extended to bright magnitudes (up to the TO), using ground-based LFs (*cf.* Fig. 2). Where omitted, the error bars are equal to or smaller than the symbol size.

of M30 and M15 are indeed very similar, NGC 6397 is markedly deficient in faint stars. A similar conclusion is reached by comparing the V_{555} LF of NGC 6397 with that of M30 (right panel). The differences are statistically highly significant, being many times the uncertainties in the single points of the LFs.

Interestingly, the difference between NGC 6397 and the near-twin LFs of M30 and M15 becomes apparent only when the LFs are compared over a wide range of magnitudes. De Marchi and Paresce (1995a) analyzed the same M15 data set that we have analyzed, and obtained an LF that is quite similar to ours. However, when they compared their M15 LF to that of Paresce *et al.* (1995) for NGC 6397, the two appeared indistinguishable. The resolution of this apparent contradiction between our respective results is that their comparison was limited to magnitudes in the interval $M_{814} \simeq$ 6.5–10. The brighter magnitudes included in our NGC 6397 measurements allow a more stringent comparison, from M_{814} = 4.5–10.5. The relative paucity of faint stars in NGC 6397 then becomes unmistakable, and is further confirmed by the extension of the NGC 6397 LFs to even brighter magnitudes using ground-based data.

The similarity of the LFs of M15 and M30 over a span of more than 6 magnitudes is striking. It implies that their MFs are very similar in the range of approximately $0.12 < \mathcal{M}/\mathcal{M}_\odot < 0.8$. It would appear that either these two clusters were born with similar MFs and have changed little since, or that they were born similar and have changed similarly. A scenario in which they were born different and have evolved to become the same seems too contrived. In view of this similarity, it is natural to ask why NGC 6397, which has a similar metallicity and similar morphology (all three are post-core-collapse clusters), should have so many fewer low-mass stars. As further discussed by King elsewhere in these proceedings, the deficiency may be the result of tidal shocks, to which NGC 6397 is quite vulnerable, given its low-inclination orbit and small perigalacticon. Even without this dynamical explanation, the difference between these clusters is in qualitative agreement with the correlations between MF slopes and Galactic position identified by Djorgovski *et al.* (1993).

In Figure 4 we show the I_{814} LF for 47 Tuc. The LFs of the metal-poor clusters from Fig. 3 are shown as lines, and the triangles represent the LF obtained by Elson *et al.* (1995) for ω Cen. The LFs have been aligned using a least-squares algorithm in the magnitude interval $5.0 < M_{814} < 7.0$. The 47 Tuc LF peaks at $M_{814} \sim 9$, at somewhat fainter magnitudes than the three metal-poor clusters, and then turns over. It agrees well with the LF obtained by De Marchi & Paresce (1995b) for a different field in 47 Tuc at a similar distance from the cluster center. Omega Cen is the only cluster of the five for which no drop-off has been detected to the limit of the existing HST observations.

Since ω Cen and 47 Tuc are intermediate and metal-rich clusters, respectively, the MLRs appropriate for their stellar populations will be different from each other and from the metal-poor clusters. In addition, a non-trivial correction of the observed LFs may be required to convert to global LFs for these clusters. For both these reasons, it is inadvisable to draw any conclusions from the LF comparison in Fig. 4. The dynamical modeling required to convert the local LFs to global ones is under way, and will be presented elsewhere.

4. The Mass Functions

If the results of star counts are to be used in modeling globular clusters, and if clusters with differing metallicities are to be compared, we must transform the observed LFs to MFs. This transformation requires an appropriate MLR, and it is particularly sensitive to the latter, as the transformation depends on its derivative. Unfortunately, the MLRs for low-mass ($\mathcal{M} < 0.5\mathcal{M}_{\odot}$) stars are quite uncertain: there are still serious difficulties in both the calculation of the stellar structure (critically dependent on the difficult evaluation of both the opacity and the equation of state for a cool gas) and in the treatment of their atmospheres (Alexander *et al.* 1995).

Several MLRs for low-mass stars now exist in the literature, some of which have appeared quite recently. Consensus has yet to be reached, ow-

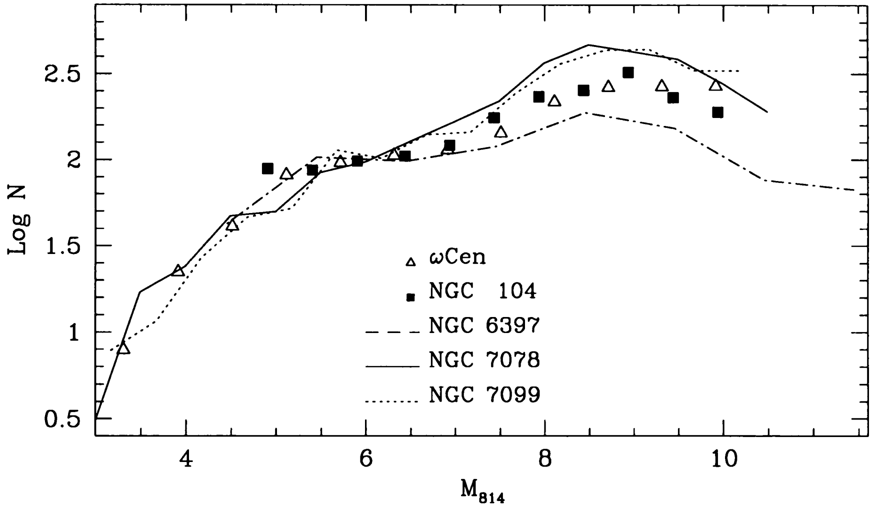

Figure 4. M_{814} LFs for the 5 clusters in the sample discussed in this paper.

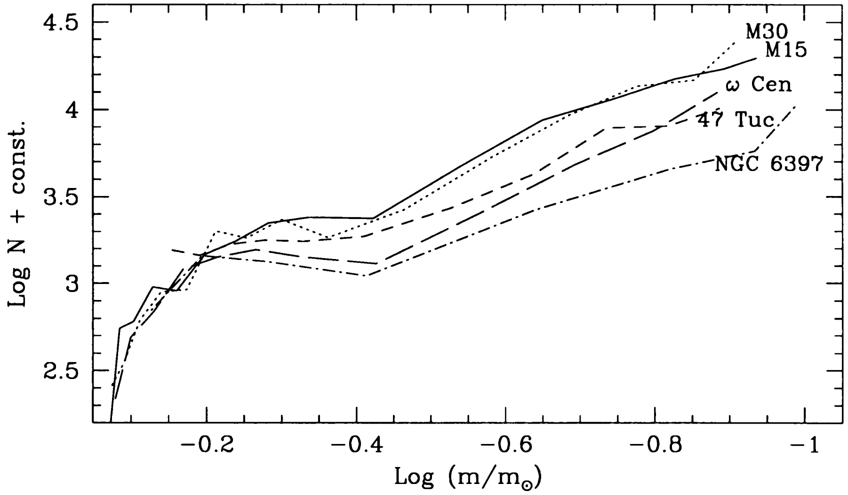

Figure 5. MFs derived from the LFs in Fig. 4, using the mass-luminosity relations of D'Antona & Mazzitelli (1995), which yield the steepest slopes at very low masses.

ing in part to a paucity of observational constraints. These MLRs differ from one another in ways that potentially can have a significant impact on the MFs derived from them. In particular, differences in the MLR slopes for very-low-mass stars are sufficient to produce significant differences in the slopes of the resulting MFs. In an effort to determine how large these variations can be, we have experimented with several of the available MLRs:

Baraffe *et al.* (1995), Bergbusch & VandenBerg (1992), D'Antona & Mazzitelli (1995), and Fahlman *et al.* (1989), as well as a set of models specifically calculated for the metallicity of these clusters by the Teramo group (Alexander *et al.* 1995).

In Figure 5 we show the MFs extracted from the I_{814} LFs of Fig. 4, using the MLRs of D'Antona & Mazzitelli (1995). Similar results were obtained by converting the V_{555} LF to mass. This set of MFs represents one extreme, since these MLRs have the steepest (and most rapidly steepening) slope of any of the MLRs we tried, and thus produce the steepest MFs. All the resulting MFs rise steadily at the low-mass end. In the interval $0.1 < \mathcal{M}/\mathcal{M}_\odot < 0.4$ the MFs can reasonably well be represented by power laws with slopes in the range $x = 0.6$–1.0 (where for the Salpeter law $x = 1.35$). The best fits to the MFs for NGC 6397 ($x = 0.6$) and ω Cen ($x = 0.9$) are both shallower than the MFs slopes found for these clusters in the ground-based study of Richer *et al.* (1991). None of the MFs obtained using D'Antona and Mazzitelli's (1995) MLR has a slope exceeding $x = 1.0$, though M30 and M15 approach this limiting case, which would correspond to a marginally divergent cluster mass *if* the MF slopes can be extrapolated into the brown dwarf regime.

At the other extreme are the MFs we obtain by using the MLRs of Alexander *et al.* (1995), which have a shallower slope for very-low-mass stars. With these MLRs, the MFs have slopes in the range $x = -0.1$ (NGC 6397) to $x = 0.7$ (M30), though the MFs deviate from power laws more than in the previous case. There is a tendency for the MFs to flatten out beyond $\log(\mathcal{M}/\mathcal{M}_\odot) = -0.8$ when these MLRs are used. In no case do we find evidence for a decline in the MF following the flattening.

5. Conclusions

With HST, main-sequence LFs can be readily measured from the turnoff down to less than 0.2 $\mathcal{M}_\odot$ in a large number of clusters, allowing for much more detailed comparisons of cluster LFs and MFs than have previously been possible. In the closest clusters, observations have already reached nearly to the hydrogen-burning limit, and future observations should reach even farther. While a sample of five clusters is too small to draw any broad conclusions, the initial results of comparisons between clusters with similar metallicities are intriguing, and provide support for the view that clusters may be born with similar MFs, which can then be altered by interactions with the Galaxy. As the sample of clusters observed with HST increases, much more will be learned about the various factors influencing cluster MFs.

The new capacity afforded by HST in the study of globular clusters will provide important new constraints on increasingly detailed dynamical modeling of globulars, which will interact with computations such as those we have admired at this meeting. At the same time, it is clearer than ever that the information contained in the observational data will be fully exploited only when the inner and outer workings of very-low-mass stars are more thoroughly understood.

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