FAINT CCD PHOTOMETRY IN GLOBULAR CLUSTERS. II. COMPARISON OF THEORETICAL ISOCHRONES WITH THE GLOBULAR CLUSTERS M4 AND M15

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INTRODUCTION

Globular cluster work touches on virtually all branches of astronomical research. The age of the globular system (or any variations in age among individual clusters) has important cosmological implications as well as relating to the formation time of the halo of our galaxy. Star to star chemical inhomogeneity within a cluster may set important constraints on either mixing within the stars themselves or on the chemical inhomogeneity of the early universe. Metallicity variations among clusters may provide the clue to galaxy-wide enrichment processes, while the cluster color-magnitude diagrams themselves are a testing ground for virtually every facet of stellar evolution.

One important aspect of globular cluster research is photometry of individual stars within the cluster, but before it can provide the critical input needed to constrain some of the problems mentioned above, extremely high accuracy is required. This required accuracy is actually composed of 3 separate units, high precision (small internal scatter), no systematic errors, and deep enough so that a cluster turnoff and lower main sequence is well defined.

At the time this paper was written, a rather casual search of the literature indicated that 17 globular clusters had photometry available for stars below the main sequence turnoff. In most cases the scatter near the turnoffs and on the lower main sequences of these clusters exceeds $\delta(B-V) = 0.2$ magnitudes. This means that many of the most important cluster parameters are simply lost in the noise. Table 1 provides a graphic illustration of this; the entries coming from interpolation of VandenBerg's (1983) theoretical isochrones for a cluster of intermediate metallicity.

*Visiting Astronomer Cerro Tololo Interamerican Observatory which is operated by AURA, Inc., under NSF contract AST 74-04129.

A. Maeder and A. Renzini (eds.), Observational Tests of the Stellar Evolution Theory, 147–151.

https://doi.org/10.1017/S0074180900030734 Published online by Cambridge University Press

Table 1
Effect on Derived Cluster Parameters for
δ(B-V) = 0.2 Among Main Sequence Stars

Cluster Parameter	Minimum Detectable Star to Star Variation with δ(B-V) = 0.2
δ[Fe/H] among stars (δ Y = 0)	200%
δY among stars (δ[Fe/H] = 0)	300%
binary frequency in cluster	all knowledge lost
δage (uncertainty in derived age of cluster itself, assuming all other parameters perfectly known)	$\pm$ 6 x 10^9 years

Table 1 points out the need for the highest possible precision in the observations. With this in mind, we began a program of CCD observations of a number of globular clusters. The data discussed here was acquired at CTIO using the 4.0 meter telescope. We present results for two clusters of rather different metallicity: M4 and M15.

FUNDAMENTAL CLUSTER PARAMETERS

From our UBV CCD data of M4 and M15 we were able to derive: (1) the reddening to each cluster (from field stars in the cluster direction) and (2) an estimate of [Fe/H] for each cluster (from the ultraviolet excess of main sequence stars). (3) The distance moduli to the clusters were determined using the Sandage (1981, 1982) technique of assigning an absolute magnitude to the cluster RR Lyraes. We have taken account of the suggestion of Cox et al. (1983) that the zero-point in the Sandage recipe may be too faint. (4) The age of each cluster was derived from a comparison with the recent theoretical isochrones of VandenBerg (1983 a,b) which were superimposed (not fitted) to our cluster color-magnitude diagrams. (5) In all cases the helium abundance (Y) was assumed to be 0.2. Table 2 provides a summary of our derived parameters for M4 and M15.

Table 2
Fundamental Parameters for M4 and M15

Parameter	M4	M15
E(B-V)	0.37 $\pm$ .06	0.12 $\pm$ .04
[Fe/H]	-.93 $\pm$ .31	-2.07 $\pm$ .31
$(m-M)_V$	12.50 $\pm$ .15	15.25 $\pm$ .15
age	15($\pm$1) x 10^9 years	16.5($\pm$1) x 10^9 years

The error in the age listed in Table 2 is based solely on the scatter of the individual stars around the appropriate isochrone (see Figures 1(a) and (b)) and does not include possible errors in the reddening, [Fe/H], distance modulus, or Y.

COLOR-MAGNITUDE DIAGRAM AND ISOCHRONES

Figures 1(a) and (b) present our color-magnitude diagrams for each cluster and the appropriate VandenBerg isochrones (1983 a,b). No fitting of the isochrones was done to the data; we simply selected the VandenBerg isochrones which most closely matched our derived metallicity and shifted them so they had the same reddening and distance modulus as the cluster. The agreement is quite excellent, particularly for M4 where the data is of much higher quality than that for M15. Field stars were not removed from these diagrams. The straight line shown in the lower left hand corner of the M4 diagram is a theoretical cooling curve for 0.51 $M_{\odot}$ white dwarfs (Sweeney 1976). A number of promising cluster white dwarf candidates are clearly present.

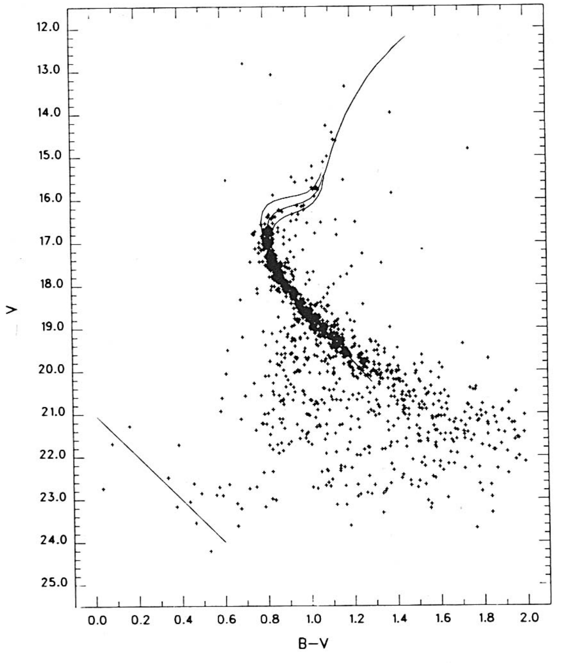

Figure 1 (a). Observed color-magnitude diagram of M4. The isochrones shown are from VandenBerg (1983 a,b) for [Fe/H] = -1.0, Y = .20, α = 1.5 (1.6 for giant branch) and ages 12, 15 and 18 billion years. The isochrones were shifted in order to represent a cluster with $(m-M)_V$ = 12.50 and E(B-V) = 0.37. The straight line in the lower left hand corner of the diagram is a cooling curve for 0.51 $M_{\odot}$ white dwarfs (Sweeney 1976).

https://doi.org/10.1017/S0074180900030734 Published online by Cambridge University Press

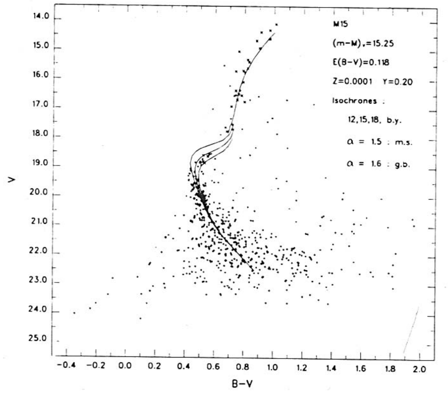

Figure 1 (b). Observed color-magnitude diagram of M15. The x's are data taken from Sandage (1970) to illustrate the giant branch. The isochrones shown are from VandenBerg (1983 a,b) for [Fe/H] = -2.30, Y = .20, α = 1.5 (α = 1.6 for the giant branch) and ages 12, 15 and 18 billion years. The isochrones were shifted in order to represent a cluster with $(m-M)_V$ = 15.25 and E(B-V) = 0.118.

SUMMARY

Our CCD observations of M4 and M15 have provided precise and deep photometry for individual stars in these clusters. A comparison between our derived color-magnitude diagram and the theoretical isochrones of VandenBerg (1983 a,b) have shown that these new isochrones provide a very faithful representation of the observational data. To within an error of ± 1 billion years, the ages of M4 and M15 are respectively 15 x 10^9 and 16.5 x 10^9 years.

Further details concerning these observations can be found in Richer and Fahlman (1984) and Fahlman and Richer (1984).

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DISCUSSION

Demarque: Your beautiful results emphasize once more the importance of determining reliable metallicities for the globular clusters, if one wants to derive reliable ages for them.

McClure: If all the stars, which scatter widely in the fainter part of the CM diagram of M4, are counted in the luminosity function, does the luminosity function then turn over or not?

Richer: The direct answer to your question is no, for the following reasons. (1) Firstly, the errors in the photometry at V = 20 are about 0.03 magnitudes while they are about 0.20 at V = 24.0. These error estimates come from two tests: (a) We measured about 100 stars on each of the 6 V frames and 4 B frames and looked at the scatter in the observed values. (b) We also introduced stars of known magnitude into the frames and measured them. Both of them gave consistent results. The errors are thus too small to be able to move the stars that upper to scatter away from the main sequence back to the main sequence.
(2) There are, of course, field stars on the frames. In particular the stars seen to the blue of the M4 main sequence are contributed mainly from the nuclear bulge of the galaxy as M4 is seen projected against the bulge. The numbers and magnitudes of the stars seen are moderately consistent with current models of the bulge.

Penny: The accuracy of the age estimates is improved if one looks at the shape of the CMD locus from the turn-off to the SGB. I would estimate from the CMDs in my poster paper that they only permit a range of ±20 % in age, even when errors in the metallicity are allowed for.

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