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# A NEW SELF-CONSISTENCY CHECK ON THE AGES OF GLOBULAR CLUSTERS

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## ABSTRACT

We present a new method to compute stellar ages in globular clusters (GCs) that is 10 times more precise than the traditional isochrone-fitting procedure. The method relies on accurate stellar evolutionary tracks and on photometry for GCs complete down to the main sequence and is based on counting the numbers of stars in two different regions of the color-magnitude diagram: the red giant branch and the main sequence. We have applied this method to the globular cluster M68 and found an age of 16.4 ± 0.2 Gyr for $(m - M)_V = 15.3$. This new method reduces the error associated with the uncertainty in the distance modulus by a factor of 2, the error due to the choice of the value for the mixing-length parameter to almost zero, and the error due to the color-$T_{\rm eff}$ transformation to zero.

*Subject heading:* globular clusters: general

## 1. INTRODUCTION

Globular clusters (GCs) are among the oldest objects in the universe and also tracers of the collapse of the Galaxy, so they are very important cosmological probes of the age of the universe. The determination of the ages of GCs is still an open problem. GC ages have recently been reviewed by Chaboyer (1995). When all possible random and systematic errors are taken into account, an error of 5 Gyr is associated with any age determination using the main-sequence turnoff (MSTO) isochrone-fitting method. An alternative method has been proposed in order to cure some of the problems of the MSTO procedure (Jimenez et al. 1996b), yielding lower ages than the MSTO.

The main problem in the MSTO comes from the fact that the isochrone has to fit the position of the main-sequence turnoff, which is not a point on the color-magnitude diagram (CMD) but rather an extended region. The same is true for the alternative method developed by Iben & Renzini (1984).

In this Letter, we present a new method to determine ages of GCs that does not rely on fitting any particular morphological feature in the CMD and that allows us to reach a precision of 0.2 Gyr for a given distance modulus. The method is based on a careful computation of stellar evolutionary tracks and on counting stars in two different regions of the CMD, the red giant branch (RGB) and the main sequence, down to a magnitude where the sample is complete.

This Letter is organized as follows: In § 2, we describe the theoretical stellar evolution models used in this work. In § 3, we present the method and compute the age of M68. Section 4 contains a comparison with other methods. We finish with a summary and conclusions.

## 2. THEORETICAL STELLAR EVOLUTION MODELS

The set of stellar evolution models has been computed with the latest version of J. MacDonald's code (JMSTAR9). The code incorporates the latest advances in opacities and updated physics; it also uses the elegant technique developed by P. Eggleton to follow evolution up to the RGB tip. Tracks were computed for a range of masses from 0.50 to 1.00 $M_\odot$ with a mass interval of 0.001 $M_\odot$. This is achieved using an adaptive mesh grid with 3000 points. A complete description of the code, as well as a detailed list of the physics used in it, is given in Jimenez & MacDonald (1996).

The tracks were started from a contracting initial gas cloud in the Hayashi track and followed up to the RGB tip, where the helium core flash occurs. All evolutionary tracks were stopped at the helium core flash, which takes place under degenerate conditions. The mixing-length parameter was chosen from the fit to the RGB position (Jimenez et al. 1996b); for M68 we adopted a value of 1.38. The metallicity for all the tracks was $Z = 0.0002$, and $Y = 0.24$. The whole grid (which covers a range of masses from 120 to 0.01 $M_\odot$), with several metallicities and values of $Y$, will be made available shortly (Jimenez, Padoan, & MacDonald 1996a). Some of the tracks are plotted in Figure 1.

## 3. METHOD

Stars of different masses evolve at different speeds along the CMD—the more massive, the faster—with the effect that the number of stars inside a fixed-luminosity bin in the main sequence decreases as time increases. It seems natural to use this effect as a clock to measure the ages of the GCs, since it is as simple as counting stars in the CMD.

In order to accurately predict the number of stars in a theoretical CMD, it is necessary to have a large number of evolutionary tracks in the range of masses observed in GCs (0.80–0.70 $M_\odot$ for M68). To achieve a precision of 0.2 Gyr, it is necessary to have one track every 0.001 $M_\odot$ (see § 4) and therefore a high number of grid points (2000 or more) in the

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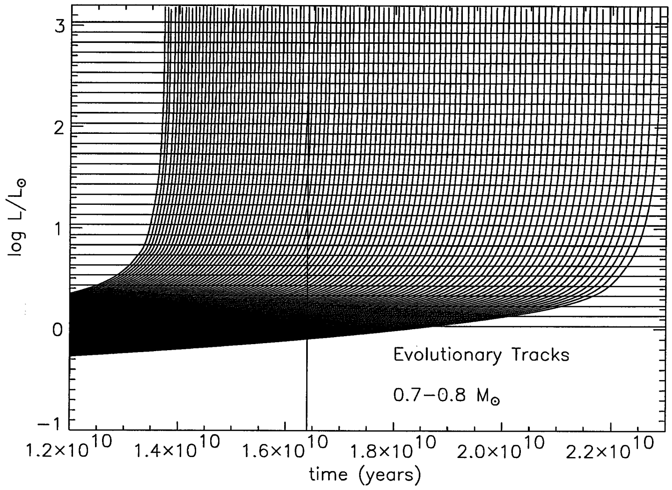

FIG. 1.—Evolutionary tracks for stars in the range of masses 0.7–0.8 $M_\odot$. The luminosity bins and the time are those used to compute the luminosity function shown in Fig. 2. The tracks are spaced by 0.001 $M_\odot$.

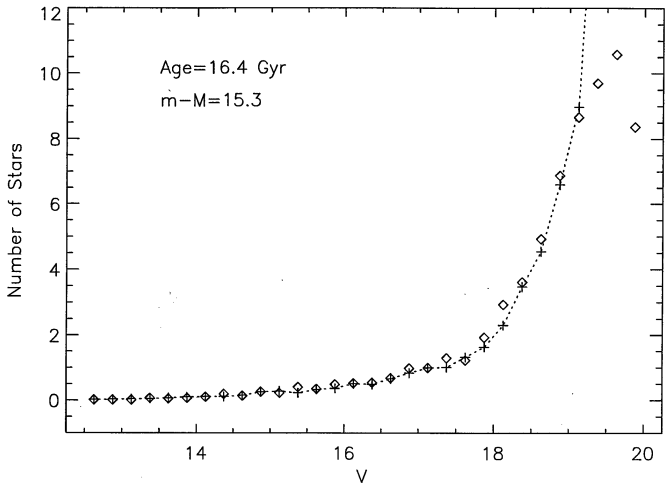

FIG. 2.—Theoretical luminosity function (*plus signs, dotted line*) for the estimated age of M68 compared with the observational luminosity function (*diamonds*). The observations are fitted remarkably well by the theory down to the magnitude $V = 19.0$. This indicates that the data are complete down to $V = 19$. The largest error bars for the observations are about the size of the diamonds.

adaptive mesh of the stellar evolution code. In addition, it is necessary to have *complete* photometry for the GC to a certain magnitude along the main sequence and very accurate photometry along the RGB to be able to distinguish asymptotic giant branch (AGB) stars from RGB stars.

To test our method, we have used photometric data for the GC M68. Very accurate photometry was obtained in several bands (*UBVRIJHK*; Jimenez et al. 1996b). This allowed us to clearly distinguish the AGB from the RGB. M68 has a very low metallicity ($Z = 0.0002$), and therefore it is representative of the oldest GCs in our Galaxy and its age is a constraint on the age of the universe.

The first step of the method consists of comparing the theoretical and observational luminosity functions for the main-sequence stars in order to determine to which magnitude the observational data are complete. The second step consists of sampling the luminosity function using only two luminosity bins, one for the RGB and the other for the main sequence, down to the luminosity at which the data are complete. Note, however, that in our application of the method to M68 we hardly include the top of the main sequence in the second bin since our data are complete only to $V = 19.0$.

### 3.1. *Theoretical Luminosity Function*

We first draw a set of evolutionary tracks (luminosity vs. time) for a given value of the metallicity and helium content (the mixing-length parameter was fixed at 1.38; see Jimenez et al. 1996b). We then choose an age, which is represented by a vertical line that intersects the tracks. Finally, we fix luminosity values, which are horizontal lines in the same time-luminosity diagram. The track that goes through the intersection between a given luminosity and the time gives the mass that corresponds to that luminosity at that time. The whole procedure is illustrated in Figure 1.

In this way, we can use stellar evolutionary tracks to determine the mass-luminosity ($M$-$L$) relation for stars of any mass and metallicity (Padoan & Jimenez 1996). The luminosity function is determined by using this $M$-$L$ relation and assuming a stellar initial mass function (IMF) (Padoan 1995).

An example of a theoretical luminosity function is shown in Figure 2 for the range of masses 0.71–0.77 $M_\odot$ and for metallicity $Z = 0.0002$ with $Y = 0.24$. The observed luminosity function for M68, obtained excluding the AGB and horizontal-branch stars, is plotted for comparison.

In the case of our data for M68, the theoretical luminosity function is remarkably well fitted by the theory down to a magnitude of $V = 19$ (note the linear scale in the plot). The observational luminosity function deviates from the theoretical one only for magnitudes larger than $V = 19$. Therefore, we consider our data complete down to a magnitude of $V = 19$.

### 3.2. *Age of the Globular Cluster*

The second step of the method consists of sampling the luminosity function using only two luminosity bins, one for the RGB and the other for the main sequence down to the value at which the data are complete (see Fig. 3).

The number of stars that populate the luminosity bin in the main sequence is decreasing, as time increases, more rapidly than the number of stars in the RGB. Therefore, the ratio of these two numbers is a function of the age of the GC.

In Figure 4, we show the two-bin luminosity function for different ages and compare it with the observational value. For a distance modulus $(m - M)_V = 15.3$, the observations are best fitted by an age of 16.4 ± 0.2 Gyr.

The age determination depends on the assumed distance modulus. In Table 1, ages are given for different distance moduli. As expected, the cluster appears older when it is assumed to be closer (smaller distance modulus). Jimenez et al. (1996b) have determined the distance modulus with high precision by fitting the luminosity function of the RGB with theoretical luminosity functions (from stellar evolutionary tracks). Their result is $(m - M)_V = 15.3 \pm 0.1$. Therefore, our best estimate of the age of the globular cluster M68 is 16.4 ± 0.2 Gyr for the assumed distance modulus. If the uncertainty in the distance modulus is considered, the uncertainty in the age is ±1.5 Gyr.

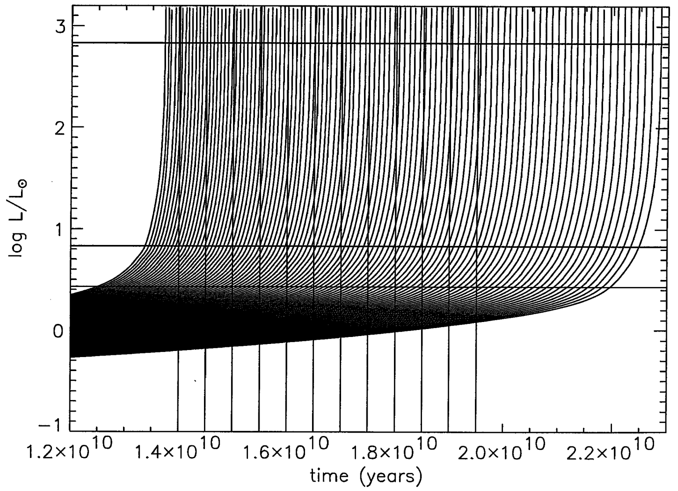

FIG. 3.—Luminosity bins used to determine the age of M68. The vertical lines are the different ages considered.

### 3.3. *Accuracy of the Method*

To estimate the error due to counting stars, we proceeded in the following way: Several frames of the same clusters taken during a period of 15 nights and under different seeing conditions were analyzed to count the total number of stars in the frame and the number of stars per luminosity bin. This allowed us to estimate the error that comes from crowding and choice of the point-spread function. For this purpose we used 20 frames. The difference in the total number of stars from frame to frame was not greater than 2%, and the same applied when the stars were counted in the bins used in the method. This corresponds to an error of 0.15 Gyr.

We have also checked the effect of the IMF on the age determination. In this Letter we use a power-law IMF with exponent 2.0 (the Salpeter value is 2.35). A steeper IMF, with exponent 3.0, affects the age only slightly in the sense of making the GC older by only 0.1 Gyr. Therefore we conclude that, for reasonable IMF slopes, the error related to the IMF is ~0.1 Gyr.

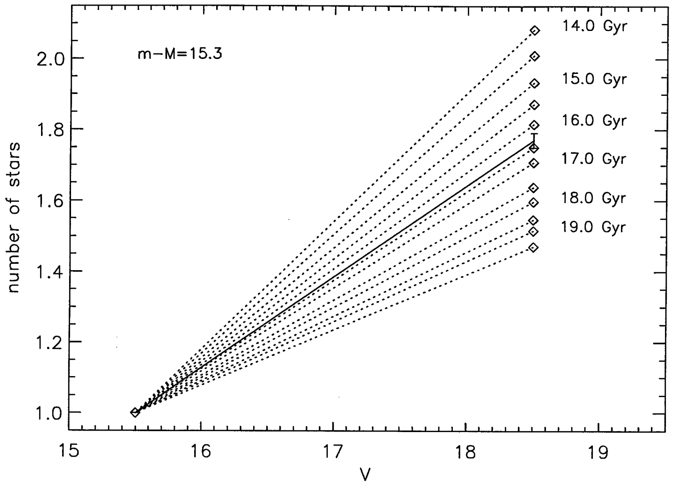

FIG. 4.—Two-bin luminosity function. The left bin contains the RGB stars; the right bin, the main-sequence stars down to $V = 19.0$. Diamonds connected by dotted lines are the theoretical two-bin luminosity functions for different ages spaced by 0.5 Gyr. The solid line is the observational value. We have plotted the 1% error bar due to the uncertainty in counting stars, which corresponds to an uncertainty of 0.2 Gyr in the age.

TABLE 1

AGE DETERMINATION FOR DIFFERENT DISTANCE MODULI

| $(m - M)_V$ | Age (Gyr) |
|---|---|
| 15.5 | 14.5 ± 0.2 |
| 15.4 | 15.0 ± 0.2 |
| 15.3 | 16.4 ± 0.2 |
| 15.2 | 17.5 ± 0.2 |
| 15.1 | 18.8 ± 0.2 |
| 15.0 | 20.0 ± 0.2 |

It is interesting to point out how stable the stellar evolution code is. Stellar tracks spaced by 0.001 $M_\odot$ are clearly defined in the time-luminosity diagram (see Fig. 1). We tried to understand how much the position of the tracks in such a diagram could change as a result of different initial conditions in the starting protostellar cloud and round-off errors in different computers. The results of computations with different initial conditions and with different machines has shown that the computed tracks are very stable, in the sense that they occupy the same position in the time-luminosity diagram with a precision such that two tracks spaced by only 0.0001 $M_\odot$ can be distinguished, when the stellar evolution code is run with 3000 mesh points. Therefore, the uncertainty in the theoretical determination of stellar masses does not affect the method at all.

As stated by Chaboyer (1995), the main uncertainty in the MSTO method is the choice of the value of the mixing-length parameter ($\alpha$). This gives uncertainties in the age as large as 10%. In our method, the value of $\alpha$ does not affect the age determination since we use only tracks in the time-luminosity diagram that look almost identical even for very different values of $\alpha$ (Jimenez et al. 1996b). Therefore, the mixing length parameter is not a source of error for us as it is in the MSTO method.

Another source of error in the MSTO is the transformation between color and $T_{\rm eff}$. Chaboyer (1995) gave an estimate of 5%. In our method the error due to this is zero since no color transformation is necessary to compute the luminosity function.

Finally, we comment briefly about how the uncertainty in the value of the distance modulus affects our age determination. Again, Chaboyer (1995) computed an error of 25% on the age due to uncertainties in the distance-modulus value for the MSTO. It can be seen from Table 1 that in our method that uncertainty has been reduced to 15%.

The total error in our age determination is estimated to be 0.2 Gyr, that is, the sum of the uncertainty in the number of stars per bin and in the IMF slope. In addition, an error of 1.5 Gyr should be added when the distance modulus is not known to better than 0.25 mag. It should be stressed that the same uncertainty (0.25 mag) yields, in our method, an uncertainty in the age of only 15%, but 25% in the MSTO.

In the case of the MSTO, if the distance modulus, $\alpha$, color-$T_{\rm eff}$ transformation, and chemical composition are fixed to a certain value, the uncertainty in the age is 10%, while it is only 2% in the present method.

## 4. DISCUSSION

The investigation of GCs' ages requires the discussion of two basic problems:

The determination of the stellar absolute luminosity from the observed stellar magnitudes, that is, the problem of measuring distances accurately;

The uncertainties in stellar evolution theory, which translate into uncertainties in the prediction of stellar ages.

A third problem arises in the age determination method based on isochrone fitting. Namely, this method presents the problem of fitting the position of the MSTO, which is not a point on the CMD but rather an extended region. In fact, the position of the MSTO is very sensitive to the assumed mixing-length parameter and color calibration. The same is true for the alternative method developed by Iben & Renzini (1984).

The method developed in the present work is also affected by the uncertainties in the estimated distance of the globular cluster and in the stellar evolution theory. Nevertheless, it improves considerably on the previous ones (by a factor of 10) because it does not rely on fitting any particular morphological feature in the CMD and does not depend at all on the mixing-length parameter and color calibration. In fact, it has been shown in this Letter that an uncertainty of only 0.2 Gyr is achieved, for a given distance modulus, just by counting stars on the CMD, as long as the stellar counts are stopped at a magnitude at which the data are known to be complete.

As far as the stellar evolution theory is concerned, there are two most important uncertainties:

Enhancement of $\alpha$-elements in GCs (Pagel & Tautvaisiene 1995), the handling of which in stellar evolution theory is still an open problem (VandenBerg 1992; Salaris, Chieffi, & Straniero 1993);

Helium settling in the radiative core, which can reduce the amount of H and therefore shorten stellar ages.

The stellar evolution models used in this work do not include any of these effects. A simple, solar-scaled composition has been used, and no He diffusion has been taken into account. Nevertheless, these uncertainties do not invalidate our procedure. If $\alpha$-elements and He diffusion significantly affect the stellar ages, our method would yield an age estimate for the globular cluster that was shortened by 20%–30%, that is, an age in agreement with previous works (Chaboyer, Sarajedini, & Demarque 1992; Jimenez et al. 1996b).

All errors quoted are internal errors. The reader should bear in mind that systematic errors from stellar evolution modeling are still an open possibility. In particular, the possibility of systematic errors in the RGB modeling is larger than in the main-sequence models. It is also important to note that the method depends on the timescale set by the evolutionary rate near the main sequence.

TABLE 2

COMPARISON OF ERRORS

| QUANTITY | ERROR MSTO | ERROR This Work |
|---|---|---|
| Distance modulus | 25% | 15% |
| Mixing length | 10 | 0 |
| Color-$T_{\rm eff}$ | 5 | 0 |
| He diffusion | 7 | 7 |
| $\alpha$-elements | 10 | 10 |

NOTE.—Values of the errors associated with different uncertainties when computing GC ages. The MSTO and our method are compared. Note how the influences of these uncertainties in our method are smaller than in the MSTO. An accuracy in the age determination of 5% can be achieved with our method.

## 5. SUMMARY AND CONCLUSIONS

We have developed a new method to determine the ages of GCs. Using theoretical evolutionary tracks, we have predicted the relative number of stars on the main sequence and on the RGB as a function of age and distance modulus.

The dependence of the age on the distance modulus is 2 times smaller than what is found using the traditional isochrone-fitting method, but the accuracy of the age determination for a given distance modulus is 10 times higher because the present method is based just on counting stars in different luminosity bins and therefore does not have troubles with fitting the morphology of the MSTO (mixing-length parameter and color calibration). In Table 2, we show a comparison of the errors involved in computing GC ages using the MSTO and our method.

We have applied this method to the old halo GC M68 and found an age of 16.4 ± 0.2 Gyr, if the distance modulus $(m - M)_V = 15.3$ determined by Jimenez et al. (1996b) is used. This value is in good agreement with previous age determinations found by Chaboyer et al. (1992), using isochrone fitting, and Jimenez et al. (1996b), using the horizontal-branch morphology technique.

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## REFERENCES

Chaboyer, B. 1995, ApJ, 444, L9
Chaboyer, B., Sarajedini, A., & Demarque, P. 1992, ApJ, 394, 515
Iben, I., & Renzini, A. 1984, Phys. Rep., 105, 329
Jimenez, R., & MacDonald, J. 1996, MNRAS, submitted
Jimenez, R., Padoan, P., & MacDonald, J. 1996a, in preparation
Jimenez, R., Thejll, P., Jørgensen, U., MacDonald, J., & Pagel, B. 1996b, MNRAS, in press
Padoan, P. 1995, MNRAS, 277, 377
Padoan, P., & Jimenez, R. 1996, in preparation
Pagel, B. E. J., & Tautvaisiene, G. 1995, MNRAS, 276, 505
Salaris, M., Chieffi, A., & Straniero, O. 1993, ApJ, 414, 580
VandenBerg, D. A. 1992, ApJ, 391, 685