THE AGES AND DISTANCES OF GLOBULAR CLUSTERS WITH THE LUMINOSITY FUNCTION

METHOD: THE CASE OF M5 AND M55

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Received 1997 April 21; accepted 1997 December 23

ABSTRACT

We present new age and distance determinations for the Galactic globular clusters M55 and M5, using the luminosity function (LF) method of Padoan & Jimenez. Using the set of stellar tracks computed by Jimenez & MacDonald and taking into account a value of [\(\alpha/Fe\)] = 0.4, we find an age of 12.5 ± 1.0 Gyr for M55 and 10.6 ± 0.8 Gyr for M5. We also find \(m - M = 14.21 ± 0.08\) mag for M55, and \(m - M = 14.55 ± 0.10\) mag for M5, where the errors refer to the internal accuracy obtained from the method applied to the observed LFs of M5 and M55. These values of \(m - M\) agree with the ones obtained using the tip of the red giant branch and with the ones given by the subdwarf fitting method with Reid's new \textit{Hipparcos} results. If the accuracy of the LF method is further confirmed, it will mean that the period of the formation of the Galactic halo took place over a few Gyr and that halo globular clusters are not older than 14 Gyr.

Subject headings: globular clusters: individual (M5, M55) — stars: distances — stars: evolution

1. INTRODUCTION

An accurate determination of the ages and distances of globular clusters (GCs) is a constraint for the age of the universe and for the theory of galaxy formation. In particular, it is interesting to compute very accurate relative ages of the Galactic GCs to understand whether or not there is a significant spread in their values. Since GCs are potentially the best cosmological clock for measuring the age of the universe, it is important to develop alternative methods to the "standard" isochrone fitting method to unveil possible systematic errors. As an example, the distance scale proposed by Reid (1997) from the \textit{Hipparcos} set of nearby subdwarfs implies that the ages of the oldest GCs are to be shortened by about 3–4 Gyr (being previously about 16 Gyr), in agreement with the ages predicted with other novel techniques (e.g., Jimenez et al. 1996).

The use of the stellar luminosity function (LF) to compute ages of GCs was first proposed by Paczyński (1984). Later on, Padoan & Jimenez (1997) (hereafter PJ97) developed a method to determine the age and the distance of a GC simultaneously, using the LF. The method is described in detail in PJ97, where it is concluded, on the basis of artificial data, that an uncertainty of about 0.6 Gyr in the age and 0.06 mag in the distance modulus can be achieved if the number of stars, in 1 mag wide luminosity bins, is known with an uncertainty of 3%. The LF method provides an alternative and a self-consistency check (Sarajedini, Chaboyer, & Demarque 1997) on the ages of GCs. Furthermore, since the LF is insensitive to stellar parameters like mixing length, it allows assessment of ages obtained with traditional methods, like those based on the main-sequence turnover point. Also, the LF is more robustly predicted by stellar evolution theory (Paczynski 1984; Sarajedini, Chaboyer, & Demarque 1997).

In order to apply the LF method, it is necessary to obtain the complete LF of the globular cluster, from almost the tip of the red giant branch (RGB) down to the upper main sequence. It is important that the LF be complete, because the incompleteness corrections obtained from experiments with artificial stars introduce errors in the observed LF that cannot be appropriately dealt with. As a result, it may be necessary to exclude the central part of some GCs because of the incompleteness that results from image "crowding." Nevertheless, the LF method uses only the brightest stars in a GC, that is, the RGB and the upper main-sequence stars, for which the quality of the photometry can be excellent and the completeness can be close to 100%. Large samples of stars are necessary to lower the statistical errors. Nevertheless, the method can, in principle, be applied when the number of stars is low, because the uncertainty of the result is also well determined. In this paper we apply the LF method for the first time to real data: for the Galactic GCs M5 (Sandquist et al. 1996) and M55 (Desidera & Ortolani, private communication) to compute accurate ages and distance moduli. Since M55 is metal poor and M5 has intermediate metallicity, we can investigate the spread in ages (if any) in the formation of the GC system and its relation with the chemical composition. This first application of our LF method to real data shows that our previous theoretical predictions (PJ97) were correct.

2. THE DATA

M5 is a massive globular cluster with an average metallicity of [\(Fe/H\)] = −1.17 ± 0.01, according to Sneden et al. (1992), and [\(Fe/H\)] = −1.4, according to Zinn & West (1984). Since it is a high Galactic latitude cluster (\(b = 46°8\)), it is not seriously affected by contamination and interstellar reddening. For the metallicity of this cluster we use [\(Fe/H\)] = −1.3 and adopt \(Y = 0.24\). The completeness of the LF is discussed in detail in Sandquist et al. (1996). Since the central region of M5 is very crowded, the LF there is already incomplete at magnitudes corresponding to the
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For this reason we did not use the central region of M5 and, therefore, used only 60% of the total number of stars observed by Sandquist et al. (1996).

M55 is among the metal-poor clusters. The main advantage of M55 is that it is not very concentrated, and it is relatively easy to resolve its core into stars and, thus, to obtain a complete LF in the magnitude bins used in this work. Because of its high Galactic latitude ($b = -23\degree$), interstellar reddening and contamination are not very large. Nevertheless, the reddening of M55 is not as well constrained as the reddening of M5, and some authors quote values as high as 0.14. We adopt a metallicity of $[\text{Fe/H}] = -1.9$ (Briley et al. 1993) and $Y = 0.24$. The LF was kindly provided to us by Desidera & Ortolani (private communication), who have performed extensive tests with artificial stars in order to check the completeness of the sample.

To use the LF method, we need first to identify the horizontal branch (HB) and asymptotic giant branch (AGB) stars and remove them. In the case of the data for M5 and M55, both the HB and the AGB are easy to distinguish from the RGB. Only a few stars between the AGB and the RGB cannot be clearly assigned to one region or the other, but their total number is less than 1% of the total number of stars in the RGB and therefore does not contribute significantly to the uncertainties in the final age and distance determination. In Figure 1 we show the color-magnitude diagrams of M5 and M55 containing all the stars that we used in the present work, after the subtraction of the AGB and HB stars. The color-magnitude diagram of M55 is almost as well defined as the one of M5, and the apparently larger scatter in the plot for M55, compared with the plot for M5, is mainly due to the smaller magnitude ranges. In this paper we use data in the $V$ and $I$ bands for M55 and in $V$, $B$, and $I$ for M5. A key issue in obtaining the LF of a stellar population is to apply accurate bolometric corrections (BCs), since theoretical stellar tracks give the total luminosity. To do so we have used the latest version of our stellar atmospheric models (Jimenez et al. 1998), which are based on the well-known MARCS atmospheric program (Gustafsson et al. 1975). The BCs we use are the following:

- $BC(I, M55) = -0.04 + 1.29(V-I) - 0.69(V-I)^2$,
- $BC(V, M55) = -0.04 + 0.29(V-I) - 0.69(V-I)^2$,
- $BC(V, M5) = -0.04 + 0.09(B-I) - 0.18(B-I)^2$,
- $BC(B, M5) = -0.14 - 0.28(B-I) - 0.19(B-I)^2$,
- $BC(I, M5) = -0.14 + 0.72(B-I) - 0.19(B-I)^2$. (1)

(1) They are consistent with one another in the sense that

![Fig. 1.—Upper panels: Color-magnitude diagrams for M5 (left) and M55 (right) containing all the stars, after the elimination of the AGB and HB stars, used in this work. Lower panels: Contour plots of $R(t, m-M)$ (see text), the residual between theoretical and observational counts for M5 (left) and M55 (right). The contour lines are closed around a minimum value of $R(t, m-M)$, which shows that the LF method can break the age-distance degeneracy. The numbers along the contour lines are the values of $100 \times R$ that are to be compared with the uncertainty in the observational stellar counts in percent. The dashed lines mark the $1 \sigma$ value around the most probable age and distance modulus.]
they give the same bolometric magnitude \( (m_{\text{bol}}) \) for a star observed in different bands. As a result, the GC LFs in different bands correspond to exactly the same LF in bolometric magnitudes, and one band or another can be used according to the quality of the photometry, for example. In our work we used all the bands available from the observations, but the results from different bands were indistinguishable. There is still an open debate among the scientific community on the accuracy of BCs. What this means is that theoretical models for stellar atmospheres are not yet converging (Gustafsson & Jørgensen 1996), and therefore their predictions are not consistent. Nevertheless, the effect of different values for the BCs in the LF method is easy to estimate, and one can then evaluate its effect in the age and distance modulus determination. For example, if our BCs had been overestimated by 0.08, it would translate into an increase in the age by 0.5 Gyr and a reduction in the distance modulus by 0.08.

To produce theoretical LFs to be compared with the data, we have computed the effect of \( \alpha \)-nuclei enhancement in our solar-scaled tracks, using the approach by Chieffi, Straniero, & Salaris (1991). In this approach, \( \alpha \)-enhanced tracks can be well mimicked, using a higher metallicity in solar-scaled tracks, following \( Z = Z_0(0.63f_\alpha + 0.362) \), where \( Z_0 \) is the solar-scaled value of the metallicity, \( Z \) is the new value of the metallicity to be used, and \( f_\alpha \) is the enhancement factor. We use \( [\alpha/Fe] = 0.4 (f_\alpha = 2.51) \), which is well justified by spectroscopic observations of giants in GCs (e.g., Carney 1996; Minniti et al. 1996) and is valid for a metallicity range of \([Fe/H] = -1.2 \) to \(-2.0\).

3. THE LUMINOSITY FUNCTION METHOD

In our previous work (PJ97), we gave a detailed description of our LF method and discussed its theoretical foundations. In this section we summarize the main steps of the method and give the result of the optimization of the bins of the M5 and M55 LFs.

The LF method provides simultaneous, independent determinations of distance and age of a GC simply by counting the number of stars found inside specified luminosity bins. To determine the age and the distance of a GC, two independent constraints (i.e., the number of stars in two different bins) are needed from the LF. One more bin is needed for the normalization, and a fourth bin is useful to estimate the completeness of the data; it is not used in this work, however, since the completeness was previously estimated performing experiments with artificial stars.

We use the first bin (see Fig. 2 and Fig. 3) at the RGB to normalize the LF. This is fundamental in order to increase the sensitivity of the third bin to age, and it is also a good choice because the uncertainty of the photometry for the most luminous stars in the GC can be as low as 0.01 mag. This normalization is one of the reasons why our conclusions differ from those of Stetson (1991), although our theoretical results do not differ (see the discussion in next section). Since this first bin includes almost all the RGB, the position of the RGB bump is irrelevant, and the number of stars is sufficiently large to keep statistical errors at an acceptable level. The second bin, which is most sensitive to the distance modulus, is positioned between the base of the RGB and the subgiant branch (SGB) in order to contain the steepest section of the LF and, therefore, be sensitive to a translation in magnitude. The third bin contains the SGB, because this is the part of the LF that is most sensitive to age. The width of the second and third bins should be large enough to reduce the effect of photometric and statistical uncertainties in the stellar counts, but small enough to be sensitive to age and distance modulus variations. We found in PJ97 that a good compromise was the use of 1 mag wide bins, but this value can be slightly adjusted as a part of the optimization process.

The method requires a previous knowledge of the chemical composition of the GCs (i.e., the helium abundance and metal content). For the helium fraction we use the value derived by Pagel (1992), \( Y = 0.24 \). For the metal content (including \( \alpha \)-nuclei enhancement), we use the best spectroscopic measurements available. Since the metallicity of a GC can be determined more accurately using spectroscopy than by using features in the color-magnitude diagram or in the LF, we do not use the LF to determine the metallicity of the GC. It is important to notice that uncertainties in the metal content of the GC will affect the LF method. This is so because it will change both the shape of the LF and also the rate of stellar evolution.

We define \( M_{2,3}(t) \) as the absolute bolometric magnitude that separates the second from the third bin, whose optimal value depends on the age, \( t \), of the GC; \( m_{2,3} \) as the apparent bolometric magnitude.
olographic LF; as the number of stars in the $i$th observational bin; $n_{i,obs}$ as the normalized ratio $N_{i,obs}/N_{1,obs}$; and $n_{i,th}$ as the corresponding theoretical ratio; $m - M$ is the distance modulus. The main steps to apply the method are the following:

1. Determine the metallicity of the GCs: $Y$, $Z$, and $[\alpha/Fe]$ (spectroscopy).
2. Choose a theoretical grid of ages and distance moduli.
3. Choose, for every age, the binning in absolute bolometric magnitude, $M_{2,3}(t)$.
4. For every distance modulus $m - M$, determine the binning in apparent magnitude by $m_{2,3} = M_{2,3}(t) + (m - M)$; this makes it possible to determine $n_{2,obs}(t, m - M)$ and $n_{3,obs}(t, m - M)$.
5. The corresponding theoretical ratios, $n_{2,th} = n_{2,th}(t)$ and $n_{3,th} = n_{3,th}(t)$, depend on age alone.
6. Thus, for every combination of age and distance modulus, one can calculate the residual $R$, where $R^2(t, m - M) = [n_{2,obs}(t, m - M) - n_{2,th}(t)]^2 + [n_{3,obs}(t, m - M) - n_{3,th}(t)]^2$.
7. The age and the distance modulus are determined as the minimum in the contour plot of $R(t, m - M)$, and the contour lines measure the uncertainty.

If the set of bins is not optimal [a bad choice of $M_{2,3}(t)$; for example, if the bins are positioned in featureless portions of the LF], the contour plot of $R$ shows only open lines, which define a relation between age and the distance modulus but do not allow their simultaneous determination. Once the set of bins is optimized, the contour plot shows closed lines that define both the age and the distance modulus of the GC at the same time. If, for example, the lines become closed only for $R \leq 0.15$, the degeneracy age-distance modulus is broken only if stellar counts are available with uncertainty smaller than 15%. The optimization process of the LF binning seeks the optimum bins to obtain closed contours of $R$, that is, to identify the portions of the LF with optimum sensitivity to age and distance. The optimization process gave the following set of absolute bolometric magnitude bins for M5 and M55:

Bin 1(M5) = $[-2.09, 1.91] \times M_{bol}$
+ $(Age - 9.0 \ Gyr) \times 0.13M_{bol}$,
Bin 2(M5) = $[1.91, 2.71] \times M_{bol}$
+ $(Age - 9.0 \ Gyr) \times 0.13M_{bol}$,
Bin 3(M5) = $[2.71, 3.71] \times M_{bol}$
+ $(Age - 9.0 \ Gyr) \times 0.13M_{bol}$,
Bin 1(M55) = $[-2.22, 1.88] \times M_{bol}$
+ $(Age - 9.0 \ Gyr) \times 0.05M_{bol}$,
Bin 2(M55) = $[1.88, 2.58] \times M_{bol}$
+ $(Age - 9.0 \ Gyr) \times 0.05M_{bol}$,
Bin 3(M55) = $[2.58, 3.58] \times M_{bol}$
+ $(Age - 9.0 \ Gyr) \times 0.05M_{bol}$. (2)

The bins shift by $0.13M_{bol} \ Gyr^{-1}$ for M5 and by $0.05M_{bol} \ Gyr^{-1}$ for M55, because we want to keep the bins around the feature of the LF sensitive to age; this feature shifts in $M_{bol}$ with age by an amount that depends on the chemical composition.

4. RESULTS AND CONCLUSIONS

The contour plots of the values of $R$ are shown in Figure 1 for M5 and M55. The numbers along the contour lines are the corresponding values of $100 \times R$, that is, the residual between theoretical and observational counts expressed in percent. The contour lines are closed, and the position of the minimum of $R$ defines the age and the distance modulus of the cluster. These are $12.5 \pm 1.0 \ Gyr$ and $m - M = 14.21 \pm 0.08 \ mag$ for M55, $10.6 \pm 0.8 \ Gyr$ and $m - M = 14.55 \pm 0.10 \ mag$ for M5. The uncertainties in the age and the distance modulus are derived from the estimated uncertainty of 4% in the stellar counts for M55 and 6% for M5. The stellar counts are uncertain because of photometric errors and because of the statistical nature of the stellar initial mass function that is used to calculate the theoretical LF. It is worth mentioning that step 6 of §3 is used to compute the uncertainty in the derived age and distance modulus for a given set of theoretical LFs and metallicities, i.e., the error due to the stochastic nature of the number of stars in the LF. This gives the method a solid statistical base for assessing the errors involved in the binning process, since $R$ properly accounts for the error and provides the best-fitting values to the data. The contour plots in Figure 1 are obtained by sampling the plane (age, $m - M$) with 100 different ages and 100 different distance moduli. The stellar counts used to build the plots are listed in Table 1 for some ages and distance moduli. In the bottom panels of Table 1 we have listed the theoretical counts for the same ages to allow the comparison with the data. To facilitate the comparison, the counts are normalized so that the first bin always contains 100 stars. The precision in the result for M5 is strongly limited by the incompleteness of the LF in the central region of the cluster. A more precise result could be obtained if the LF was complete in the central region (down to the luminosity of the subgiants), because more stars could be used in that case. The distance moduli obtained with the LF agree well with the new distance scale established by using the subdwarf sample from Hipparcos (Reid 1997). In fact, we properly predicted the inferred new distances with the LF method (see Jimenez & Padoan 1997) before Hipparcos results were released. With this new distance scale, it is not surprising that ages of GCs obtained with the LF are consistent with the ones obtained by Reid (1997). In the case of M5, Sandquist et al. (1996) estimate an age of $11.5 \pm 1 \ Gyr$ for $[Fe/H] = -1.17$, and they state that the age would be $13.5 \ Gyr$ for $[Fe/H] = -1.4$. We use $[Fe/H] = -1.3$ and get an age of $10.6 \pm 0.8 \ Gyr$. They also estimate $m - M = 14.50 \pm 0.07 \ mag$ for $[Fe/H] = -1.17$ and $m - M = 14.41 \pm 0.07 \ mag$ for $[Fe/H] = -1.4$, using the subdwarf fitting of the main sequence. We get $m - M = 14.55 \pm 0.10 \ mag$ for $[Fe/H] = -1.3$. In PJ97 we estimated a variation of 0.02 mag in $m - M$ for a shift of 0.1 in metallicity; thus, we would predict $m - M = 14.53 \pm 0.10 \ mag$ for $[Fe/H] = -1.4$. Notice that in Jimenez & Padoan (1996) the value of the distance modulus for M68 was not determined with the present method; it was just a reasonable value assumed to determine the age. In this work, instead, we use the LF to determine both the age and the distance modulus at the same time, and the distance modulus agrees with the result of subdwarf fitting, using the Hipparcos sample.
It is important to notice that the LF method will be undermined and lose effectiveness if uncertainties in stellar evolution and chemical composition of the GC are large. In the previous paragraph, we have already mentioned the effect of uncertainties in the metallicity for M5. A similar uncertainty would occur for changes in \( Y \) and \([\alpha/\text{Fe}]\) (see also PJ97). In addition to this remains the question of whether or not theoretical LFs are well constrained and include all the relevant physical processes. A major effort has been made in the last year to model properly the structure and convective envelope of the stars, while the radiative core by treatment of convection because this concerns only uncertainties in the treatment of convection in the MSTO method is illustrated by Chaboyer et al. The LF is not affected (1995) and Mazzitelli (1995).

The uncertainty introduced by the treatment of convection in the MSTO method is illustrated by Chaboyer (1995) and by Mazzitelli et al. (1995). The LF is not affected by the treatment of convection because this concerns only the convective envelope of the stars, while the radiative core (where the luminosity is produced) is left unchanged. Furthermore, the MSTO method needs to know the distance in order to determine the age, and it is unable to break this degeneracy.

Stetson (1991) argues that the sensitivity of the luminosity function to the age is smaller than we find in the present work. He normalizes the LF on the turn-off, shifts the LF along magnitudes—assuming a total ignorance of the distance modulus—and finds that an uncertainty in stellar counts of 3% translates into an age uncertainty of 12% (using 1 mag wide bins). We find a similar result, as can be seen at the bottom of Table 1, where stellar counts from the theoretical LFs are listed for different ages. One can see an age variation of about 8% when stellar counts in the third bin vary by 3% (in the case of the theoretical LF used for M5) and an age variation of 17% for the case of M55.

### Table 1

| Age (Gyr) | Bin 1 | Bin 2 | Bin 3 |
|----------|-------|-------|-------|
| \( m - M = 14.12 \) |
| 12.0      | 100.0 | 67.6  | 420.5 |
| 12.2      | 100.0 | 67.2  | 420.6 |
| 12.4      | 100.0 | 68.5  | 424.3 |
| 12.6      | 100.0 | 69.2  | 431.9 |
| 12.8      | 100.0 | 69.9  | 432.8 |
| 13.0      | 100.0 | 70.5  | 439.6 |
| \( m - M = 14.22 \) |
| 12.0      | 100.0 | 74.0  | 447.4 |
| 12.2      | 100.0 | 74.8  | 450.0 |
| 12.4      | 100.0 | 75.8  | 449.9 |
| 12.6      | 100.0 | 77.0  | 454.7 |
| 12.8      | 100.0 | 78.6  | 456.0 |
| 13.0      | 100.0 | 78.3  | 456.8 |
| \( m - M = 14.32 \) |
| 12.0      | 100.0 | 83.2  | 462.8 |
| 12.2      | 100.0 | 83.5  | 463.5 |
| 12.4      | 100.0 | 85.0  | 466.5 |
| 12.6      | 100.0 | 87.0  | 470.3 |
| 12.8      | 100.0 | 89.5  | 472.7 |
| 13.0      | 100.0 | 90.1  | 476.5 |

**Note:** Used to make the contour plots of Figure 1 for some values of age and distance modulus.

### Table 2

| Age (Gyr) | Bin 1 | Bin 2 | Bin 3 |
|----------|-------|-------|-------|
| \( m - M = 14.45 \) |
| 10.0      | 100.0 | 79.6  | 567.7 |
| 10.2      | 100.0 | 80.6  | 578.1 |
| 10.4      | 100.0 | 78.0  | 586.9 |
| 10.6      | 100.0 | 75.0  | 592.3 |
| 10.8      | 100.0 | 76.6  | 607.6 |
| 11.0      | 100.0 | 79.9  | 621.4 |
| \( m - M = 14.55 \) |
| 10.0      | 100.0 | 75.7  | 605.9 |
| 10.2      | 100.0 | 79.5  | 619.5 |
| 10.4      | 100.0 | 80.0  | 627.6 |
| 10.6      | 100.0 | 80.9  | 639.4 |
| 10.8      | 100.0 | 81.8  | 651.1 |
| 11.0      | 100.0 | 87.4  | 655.0 |
| \( m - M = 14.65 \) |
| 10.0      | 100.0 | 82.1  | 651.5 |
| 10.2      | 100.0 | 87.0  | 655.6 |
| 10.4      | 100.0 | 88.8  | 660.6 |
| 10.6      | 100.0 | 96.5  | 673.3 |
| 10.8      | 100.0 | 105.8 | 680.1 |
| 11.0      | 100.0 | 108.9 | 673.2 |

**Note:** Used to make the contour plots of Figure 1 for some values of age and distance modulus.
counts in the second bin are almost unaffected by age, which means that we have shifted the bins with age in a way similar to how Stetson shifts the LF along magnitudes, which is equivalent to assuming ignorance of the distance. The age sensitivity of the counts depends on the metallicity and on the age of the theoretical LF and therefore can be different in different cases. Nevertheless, such sensitivity does not measure the sensitivity of our LF method. In fact, our method consists in comparing counts in the observed LF with counts in the theoretical LF in order to determine at the same time the age and the distance of the cluster. In this way, once the two LFs are compared to determine the age, we are not ignorant about the distance, and the sensitivity to age variation is therefore larger. Moreover, we normalize the LF on the RGB, which is convenient to increase the age difference in the subgiant region instead of normalizing it on the turn-off as Stetson does. The reason why it is possible to perform a two-dimensional minimization process (and, therefore, to extract the age while also determining the distance modulus) is the fact that the third bin is most sensitive to a shift in the age, while the second is most sensitive to a shift in magnitude (distance). In Figure 2 of P197 we demonstrated that the second bin is almost insensitive to age, while the third is age sensitive. This can be seen also from Table 1 (bottom panels) that the stellar counts in the second bin of the theoretical LFs are not sensitive to age, contrary to the counts in the third bin. Nevertheless, the counts in the second bin are strongly affected by a variation in the distance modulus (as can be seen in Table 1) from the observational counts. In order to be sure that our method is not affected by unusual features in the theoretical LFs, we have compared our theoretical LFs with the Yale LFs and found no appreciable difference.

The absolute ages, determined in this work for M55 and M5, seem to indicate that the oldest GCs are not older than 14 Gyr. However, some uncertainties in stellar evolution theory do affect the LF (see Renzini & Fusi Pecci 1988; Bolte 1994) and the absolute age determination. On the other hand, the LF method is a very powerful tool for investigating relative ages, since most uncertainties of stellar evolution theories are in that case avoided. From the comparison of the ages of M5 and M55, we can conclude that M55 is probably older than M5 and, therefore, that the metallicity of GCs decreases with increasing age.

Most methods for determining the age and the distance modulus of GCs share two common problems: some degree of dependence of age on the distance modulus (or vice versa) and a somewhat fuzzy procedure for estimating the uncertainty of the final result. Our LF method, instead, gives constraints for both age and the distance modulus independently and estimates both most probable values and uncertainties in a straightforward way. On the basis of the present work, we think that very high quality data from GCs, together with the LF method, may shed new light on the problems of the age of the oldest stars in the universe and of the formation of the Galaxy.

We are grateful to S. Desidera and S. Ortolani for providing us with unpublished data of M55, to E. Sandquist for providing us with his data on M5, and to the referee (Jim Hesser) for his useful comments that greatly improved this paper. P. P.’s work has been supported by the Danish National Research Foundation through its establishment of the Theoretical Astrophysics Center. P. P. is grateful to the staff at the Royal Observatory Edinburgh, where part of this work was done.

REFERENCES

Bolte, M. 1994, ApJ, 431, 220
Briley, M. M., Smith, G. H., Hesser, J. E., & Bell, R. A. 1993, ApJ, 306, 142
Carney, B. W. 1996, PASP, 108, 877
Chaboyer, B. 1995, ApJ, 444, 29
Chaboyer, B., Demarque, P., & Sarajedini, A. 1996, ApJ, 459, 558
Chieffi, A., Straniero, O., & Salaris, M. 1991, in ASP Conf. Ser. 13, The Formation and Evolution of Star Clusters, ed. K. Janes (San Francisco: ASP), 219
Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, Å. 1975, A&A, 42, 407
Gustafsson, B., & Jorgensen, U. 1996, A&A Rev., 6, 19
Jimenez, R., Dunlop, J., Peacock, J., MacDonald, J., & Jorgensen, U. 1998, MNRAS submitted
Jimenez, R., & Padoan, P. 1996, ApJ, 463, L17
Jimenez, R., & Padoan, P. 1997, preprint (astro-ph/9701141)
Jimenez, R., Thieill, P., Jorgensen, U. G., MacDonald, J., & Pagel, B. 1996, MNRAS, 282, 926
Jorgensen, U. G. 1991, A&A, 246, 118
Kurucz, R. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2km/s Grid (Cambridge: SAO)

Mazzitelli, I., D’Antona, F., Caloi, V. 1995, A&A, 302, 382
Minniti, D., Pettersen, R. C., Geisler, D., & Claria, J. J. 1996, ApJ, 470, 953
Nordlund, A., & Stein, R. F. 1996, Proc. 32d Li`ege Colloq., Convection: Significance for Stellar Structure and Evolution, ed. A. Noels, D. Frapoint-Cro, M. Gabriel, N. Grevesse, & P. Demarque (Li`ege: Inst. d’Astrophys.), 75
Paczynski, B. 1984, ApJ, 284, 670
Padoan, P. & Jimenez, R. 1997, ApJ, 475, 580
Pagel, B. E. J. 1992, in Observational and Physical Cosmology, ed. P. Sanchez et al. (Cambridge: Cambridge Univ. Press) 117
Reid, N. 1997, AJ, 114, 161
Renzini, A., & Fusi Pecci, F. 1988, ARA&A, 26, 199
Sandquist, E. L., Bolte, M., Stetson, P. B., & Hesser, J. E. 1996, ApJ, 470, 910
Sarajedini, A., Chaboyer, B., & Demarque, P. 1997, preprint (astro-ph/9710245)
Sneden, C., Kraft, R. P., Prosser, C. F., & Langer, G. E. 1992, AJ, 104, 2121
Stetson, P. B. 1991, in ASP Conf. Ser. 93, The Formation and Evolution of Star Clusters, ed. R. Zinn (San Francisco: ASP), 88
Zinn, R., & West, M. J. 1984, ApJS, 55, 45