Chronology of the halo globular cluster system formation

Maurizio Salaris* & Achim Weiss

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching, Germany

submitted to Astronomy & Astrophysics

Abstract. Using updated stellar models and isochrones we determine the age of 25 galactic halo clusters. The clusters are distributed into four groups of metallicity. We use a combination of two methods for obtaining either the absolute age of a template cluster within each group or relative ages for all other clusters of the same group relative to this one. This combination yields the most reliable results. We find that the oldest cluster group on average is 11.8 ± 0.9 Gyr or 12.3 ± 0.3 Gyr old, depending on whether we include Arp2 and Rup106. The average age of all clusters is about 10.5 Gyr. Questions concerning a common age for all clusters and a relation between metallicity and age are addressed. The cluster groups of lower metallicity appear to be almost coeval, but our results indicate that globally the sample has an age spread without a simple age-metallicity relation.

Key words: Galaxy: formation - Galaxy: halo - globular clusters: general — globular clusters: individual (M68, NGC6584, NGC3201, M5, M107, NGC6652) — stars: evolution

Send offprint requests to: A. Weiss (weiss@mpa-garching.mpg.de)

* *Present address:* Institut d'Estudis Espacials de Catalunya, 08034 Barcelona, Spain

1. Introduction

The age of galactic Globular Clusters (GCs) provides fundamental informations about the age of the universe and the formation history of the Galaxy. Recent improvements in the input physics needed for computing stellar evolutionary models have revived theoretical work on low-mass stars and GCs age determinations (Chaboyer & Kim 1995, Mazzitelli et al. 1995, D'Antona et al. 1997, Salaris et al. 1997). Salaris et al. (1997 - Paper I) have shown that the age of the supposedly oldest clusters – the most metal-poor ones – is around 12 Gyr. This age reduction with respect to earlier work (e.g. Chaboyer et al. 1992, Salaris et al. 1993) has been identified to be mainly due to the use of an improved equation of state that includes non-ideal gas effects (Rogers et al. 1996).

After this initial work, which was motivated by a possible "conflict over the age of the universe", the next step is to address the question of Galaxy formation. This means that one has to investigate many clusters and determine their ages, looking for correlations of age with cluster metallicity or galactocentric distance.

The position of the turn-off (TO) is the feature in the colour-magnitude-diagrams (CMD) of stellar clusters that is most sensitive to the age of the stellar population. The higher the cluster age, the less luminous and redder is the TO. Two differential quantities are suited as indicators that are independent of reddening and distance: the brightness difference in V magnitude between the TO and the horizontal branch (HB) at the RR Lyrae stars region, called the $\Delta(V)$ or vertical method (see, e.g., Sandage & Cacciari 1990; Stetson et al. 1996 for a review) and the $(B-V)$ colour difference between the TO and the base of the Red Giant Branch (RGB), called the $\Delta(B-V)$ or horizontal method (see, e.g., Chieffi & Straniero 1989, VandenBerg et al. 1990). In both cases the TO position is differentially determined with respect to a CMD branch (the HB or the RGB) whose location is virtually independent of age in the case of old stellar populations.

Direct absolute age determinations based on the vertical method lead to a large spread in ages, which seems to be correlated with metallicity (Chaboyer et al. 1996). However, the quality and diverseness of the data do not favor this method. For relative ages and age differences the horizontal method appears to be more reliable. This concept works best if all problems with theoretical effective temperatures (convection theory, atmospheres) and the conversion of theoretical quantities to observed colour and brightness are avoided, as is the case for clusters of similar metallicity. Due to these problems absolute ages are very difficult to obtain by this method.

A combination of both methods seems therefore to be promising for an accurate determination of absolute and relative ages. Clusters are inspected in groups of similar metallicity, and one or more suitable "template" clusters (with homogeneous and good photometry for both TO and RGB region) are chosen to determine an absolute age directly with the vertical method. Then, the horizontal method is used for a differential comparison with other clusters of the same group. This is the approach we have chosen (see also Paper I) and which is similar to the one by Richer et al. (1996). Our work differs from their analysis in that we use the vertical method for determining the absolute ages by virtue of theoretical isochrones and ZAHB models, while their absolute ages were obtained essentially from fitting Bergbusch & VandenBerg (1992) isochrones, without using explicitly theoretical HB models; moreover we use new and improved stellar models (see Paper I), taking into account the latest developments regarding stellar opacities and equation of state.

The questions we want to address are: (i) what is the absolute age of one or more template cluster in each metallicity group; (ii) how do $\Delta(B-V)$ differences between clusters within a group translate into age differences. This information is necessary for the more global problem of whether there exists an age spread between galactic clusters, and if so, whether it is correlated with metallicity. Assessing clearly the existence of an age spread among GCs and of an age-metallicity relation is fundamental for understanding the formation of our Galaxy. Very recently Chaboyer et al. (1996) found strong evidence in favour of a spread in the ages of galactic GCs and an age-metallicity relationship. On the contrary, Stetson et al. (1996) concluded that there is no evidence for a significant spread in ages among clusters of similar metallicity and that the case concerning age differences between metallicity groups remains unsettled, while Richer et al. (1996) found that the most metal-poor clusters may be slightly older than clusters of higher metallicities, but their results are neither inconsistent with a picture in which all clusters of all metallicities formed simultaneously. Between the most metal-rich clusters there appears to be a considerable age spread of ~ 2 Gyr (VandenBerg et al. 1990), and in addition a number of exceptional clusters were found in all investigations.

In the present paper we restrict ourselves to halo clusters - that means GCs with kinematic properties typical of the halo component of the Galaxy - and try to answer both the questions concerning the distribution of ages within individual metallicity groups and between groups. In Sect. 2 we will review our method used for determining absolute and relative cluster ages. Sect. 3 contains our results for a large group of halo clusters, which are compared with the results by Richer et al. (1996). In Sect. 4 the implications for the cluster age distribution are discussed, before a summary of our results follows in the final section.

2. Method

2.1. Stellar Models

As in Paper I we rely on theoretical models for all evolutionary phases involved; in particular we have computed stellar models from the MS up to the zero-age horizontal branch (ZAHB). The input physics employed in calculating the models is the same as in Paper I: for the opacities we used a combination of the latest OPAL opacities (Rogers & Iglesias 1992; Iglesias & Rogers 1996) and tables from D. Alexander (Alexander & Ferguson 1994; Alexander, private communication). The metal mixtures included α-element enhancement and were exactly the same for both opacity table sources. The equation of state consisted of the OPAL EOS (Rogers, Swenson & Iglesias 1996) with extensions for the lowest temperatures and degenerate helium cores taken respectively from Chieffi & Straniero (1989) and Straniero (1988).

Diffusion of helium and heavy elements is not included in the calculations. The effect of diffusion on the ages obtained from our models is discussed in the following section dedicated to the methods for determing absolute and relative ages.

We computed stellar models for the following compositions: (Z, Y) = (0.0002, 0.230), (0.0004, 0.230), (0.0008, 0.232), (0.001, 0.233), (0.002, 0.236), (0.004, 0.242). For $\triangle Y/\triangle Z$ we have taken a mean value of 3 (as in Bergbusch & VandenBerg 1992; Mazzitelli et al. 1995). The first two mixtures are those already used in Paper I. α-elements are always enhanced (f.e. [O/Fe] = +0.5); the total metal-abundance [M/H] is about 0.2-0.3 dex higher than [Fe/H].

Stellar models with masses between 0.7 and $1.0 M_\odot$ were evolved from the zero-age main sequence up to the RGB. The mixing length has been calibrated as explained in Paper I. Isochrones for different ages were computed from these evolutionary models. ZAHB models with varying envelope masses were calculated as described in Paper I.

Similarly, the conversion from theoretical effective temperature and luminosity to observable colour $(B - V)$ and visual magnitude V was done using the transformations of Buser & Kurucz (1978, 1992).

2.2. Globular Cluster groups

In this paper (as in Paper I) we have used both the vertical and the horizontal method for determining the distribution of the halo GCs ages, since one has to study many different clusters with different HB types and in many cases with photometries that do not cover at the same time the TO and the HB region. We have considered 25 halo clusters (see Table 1), which span a wide range of metallicities, galactocentric distances and HB type, divided into four groups according to their metallicity. The first group spans the range $-2.1 \leq$ [M/H] < -1.6 (metal poor clusters), the second $-1.6 \leq$ [M/H] < -1.3 (intermediate metal poor clusters), the third $-1.3 \leq$ [M/H] < -0.9 (intermediate metal rich clusters) and the fourth $-0.9 \leq$ [M/H] < -0.6 (metal rich clusters). The adopted [Fe/H] values come from Zinn (1985), and the global metallicity has been obtained considering an average $[\alpha/\mathrm{Fe}] = 0.3$ and [M/H] = [Fe/H] + 0.2 according to the discussion in Paper I. The metallicity difference among the clusters in each group is about a factor of 2. In the case of Rup106, Arp2 and Ter7, for which there are not data in Zinn (1985), we have considered the [Fe/H] estimates by Buonanno et al (1993, 1995a, 1995b) to which we have added the contribution of the α-elements [1], assuming that such an enrichment exists for these clusters as well.

In each group one cluster (or two clusters, as in the case of the second metallicity group) with suitable photometry for determining directly its absolute age by means of the vertical method is selected; this cluster is the "reference" one, and within each group the relative ages with respect to the reference cluster are determined by means of the horizontal method. In case of two reference clusters the age difference from the vertical method can be cross-checked with that derived by means of the horizontal one.

The virtues and weaknesses of both these techniques have been discussed extensively in many recent papers (VandenBerg et al. 1990, Salaris et al. 1993, Chaboyer et al. 1996). To summarize, the $\Delta(V)$ appears particularly suitable for the determination of the absolute clusters ages, since its independence of the treatment of convection and its weak sensitivity to metallicity. However, it can only be applied in the case of clusters with homogeneous photometry for both TO and HB, and with a well populated horizontal part of the HB. Clusters with only a blue, vertical HB are in principle excluded, because it is impossible to have observational estimates of the absolute HB luminosity in the

[1] Carretta & Gratton (1997) recently have recalibrated the Zinn & West (1984) [Fe/H] scale, that corresponds to the Zinn (1985) metallicity scale for almost all GCs in our sample. The new calibration is based on a homogeneous set of cluster [Fe/H] determinations from high resolution spectroscopical data; it provides [Fe/H] values for the clusters in our sample that are on average 0.20 dex higher than the ones we used. This simply corresponds to an almost constant shift of the [M/H] ranges adopted for our GCs groups, but the belonging to each single group does not change and similarly the absolute and relative ages we derive are only very marginally affected by the choice of this new scale (see the following section about the age determination).

RR Lyrae region or to constrain the age from the fit of theoretical ZAHB models. A further complication arises from the small number of reliable faint photometric standards with such blue colours (VandenBerg et al. 1990).

The $\Delta(B-V)$ can in principle be applied to each kind of GCs with sufficiently accurate photometry, since each GC shows a main-sequence TO and an RGB; it is also only weakly sensitive to metallicity, but obviously absolute ages depend primarily on the mixing length calibration and on the transformations from effective temperatures to colours. When all the problems related to the $T_{\rm eff}$ determination and the conversion to observed colours are minimized, as in the case of clusters with similar metallicities, the horizontal method turns out to be suitable for accurately determining the relative ages of clusters (VandenBerg et al. 1990, Stetson et al. 1996).

2.3. Absolute age determination

The advantage of using the vertical method for determining the absolute age of a cluster is therefore that it is largely independent of all uncertainties connected with the calculation of effective temperatures and their conversion to colours. It does not depend on the reddening and on the assumed distance modulus (the same holds, of course, also for the horizontal method), although the models yield a distance scale (by means of the comparison between observed and theoretical ZAHB level), which can be compared to independently determined values.

We have applied the vertical method as in Paper I; once the observational ZAHB luminosity is fixed, the ZAHB and the isochrones are shifted horizontally and vertically in order to match simultaneously the main-sequence (MS) ridge line and the observational ZAHB level. The age is then determined by matching the observed TO luminosity with the theoretical isochrones; the horizontal shift applied in order to match the observed MS corresponds to the cluster reddening $E(B-V)$, while the vertical shift necessary for fitting the observational ZAHB luminosity provides the apparent distance modulus $(m-M)_V$.

An important step in the vertical method is therefore to fix the zero-age level of the observed HB. In Paper I we selected two clusters (M68 and M15) with well-populated HBs and a sufficiently large number of RR Lyrae variables. With the mean brightness ($\langle V_{\rm RR}\rangle$) of the variables fixed, we derived the zero-age level using the relation by Carney et al. (1992):

$$V_{\rm ZAHB} = \langle V_{\rm RR}\rangle + 0.05[{\rm Fe/H}] + 0.20 \quad (1)$$

We have also demonstrated in Paper I (the reader is referred to this paper for a deeper discussion about the problem of the 'true' observational relation between RR Lyrae luminosities and metallicity) that (assuming a constant helium content of $Y=0.23$) our theoretical relation between ZAHB brightness (taken at $\log T_{\rm eff}=3.85$) and [Fe/H] together with Eq. 1 agrees nicely with that found empirically by Clementini et al. (1995) and also supports that of Walker (1992a - when translated into ZAHB luminosities according to Eq. 1). In the present paper we consider an initial helium abundance varying with Z, but the difference to the ZAHB luminosities obtained in Paper I is always less than 0.04 mag (reached at the highest metallicities considered). In Fig. 1 we show the final relation between ZAHB luminosity and [Fe/H] we now obtain from our stellar models; in the same figure the empirical relations (upper and lower limits according to the errors given by the authors) by Clementini et al. (1995 - when considering only ZAHB objects) and Walker (1992a) are also displayed. The agreement between the ZAHB theoretical models and both empirical determinations is evident.

For the present set of clusters it was not possible for all metallicity groups to find a cluster that fulfilled the requirements both with respect to the HB photometry and to the presence of a sufficient number of RR Lyr stars. Therefore, we developed a method to determine the observational ZAHB level when the HB is well populated. This can be applied each time the observational HB is populated in the horizontal part, even if there are no stars in the instability strip, or if there should be no photometry for the variable stars.

Theoretically all observed HB stars should be at least as bright as the ZAHB. Thus, the lower envelope (for well-populated HBs) to the observed HB provides a reasonable estimate for the ZAHB luminosity (Sandage 1990). In practice, however, photometric errors, field stars and other objects not belonging to the HB will spread out this lower limit and a more statistical approach is necessary. To this end we have looked into the brightness-distribution of HB stars in a few colour bins. For each colour bin count histograms for brightness bins were created; the brightness bins were typically 0.04-0.05 mag wide (depending on the HB population). From the histograms it is quite easy to determine the lower boundary of the HB distribution. Formally, we set the ZAHB level to the upper brightness of that bin, which shows a decrease in star counts by a factor ≥ 2 and where the brighter bins contain more than 90% of all candidate HB stars under consideration. This is illustrated in Fig. 2 for M5. For all the clusters to which we have applied the vertical method for age determination these two conditions were always fulfilled at the same luminosity bin. For M68 and M15, our method reproduces the ZAHB levels at the RR Lyrae instability strip as determined by Eq. 1 (Paper I) within 0.01 mag, i.e. within the binning error. In this paper we will adopt for M68 the ZAHB luminosity and the

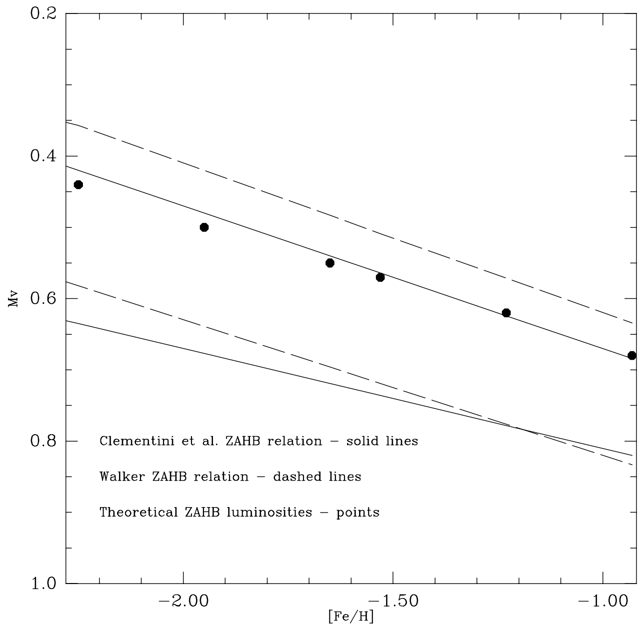

Fig. 1. Theoretical ZAHB luminosities as a function of [Fe/H]. Solid and dashed lines represent the upper and lower envelopes of the empirical determinations by Clementini et al. (1995) and Walker (1992a)

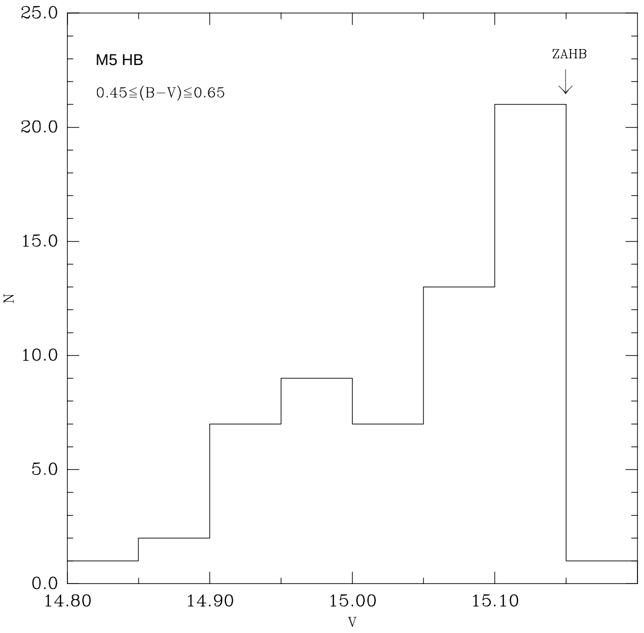

Fig. 2. Brightness distribution of M5 HB stars in the colour region $0.45 < (B-V) < 0.65$. The arrow marks the ZAHB level determined by both the total number of stars above this bin and by the decrease in the number of stars per bin

associated formal error (the width of the luminosity bin) determined with the new method; the resulting absolute age is the same as in Paper I, but the formal error associated to it results to be lower (see Table 1). Note that choosing the upper bin brightness possibly leads to an overestimate of the ZAHB brightness and consequently to ages slightly too high; the uncertainty, however, remains below $\approx$ 0.04-0.05 mag.

To check the influence of the chemical composition on our age estimates adopting the vertical method, we have shown in Paper I (but see also Salaris et al. 1994, Chaboyer 1995) that a variation of the metallicity by a factor of 2 or the use of an initial helium abundance Y different by 0.01 in the theoretical isochrones changes the derived ages by slightly less than 1 Gyr. When taking into account also helium and heavy elements diffusion in computing stellar models, contrary to our expectations expressed in Paper I, the GC ages derived by means of the vertical method are decreased by less than 1 Gyr, because of balancing effects on TO and ZAHB (Castellani et al. 1996).

2.4. Relative age determination

In deriving the relative GC ages we have applied the horizontal method, following the procedure presented by VandenBerg et al. (1990). The ridge lines of two clusters are shifted horizontally in order to match their TO colours, and then vertically, to force coincidence between the main sequences at a position 0.05 mag redder than the TO. Differences in the RGB colour (fixed for example at a point 2.5 mag more luminous than the MS reference point) correspond to age differences derived from our new theoretical isochrones. As already discussed by VandenBerg et al. (1990), the precise point on the RGB is of little significance, since the RGBs run essentially parallel to one another. We have evaluated *mean* $\Delta(B-V)$ differences from the cluster fiducials by considering, when possible, a magnitude range along the RGB of typically 0.5-1.0 mag (depending on the extension of the fiducial line), starting approximately from the point 2.5 mag more luminous than the MS reference point. The formal error of the relative ages derived by means of this procedure, estimated from the uncertainty in measuring the shift in the position of the RGB with respect to the reference cluster is about 0.5 Gyr.

As for the reliability of the age scaling derived adopting the $\Delta(B-V)$ technique, the following points have to be mentioned:

i) a comparison of the $\Delta(B-V)$ scaling with respect to the age at fixed global metallicity, by adopting the oxygen-enhanced Bergbusch & VandenBerg (1992), the scaled-solar Straniero & Chieffi (1991) and our own isochrones shows a good agreement in spite of different codes, different effective temperature normalization and/or completely different input physics and heavy elements distribution used in the respective calculations. The relative ages obtained in the three cases differ by no more than 20%;

ii) the effect of a variation in the initial helium content is almost negligible. A variation of $\delta Y = \pm 0.01$ induces a change in the relative ages of only $\approx$ 0.15 Gyr.

iii) a variation in the global metallicity by a factor of 2 changes the relative ages by less than 0.5 Gyr;

iv) a global change of the mixing length parameter $\alpha_{\rm MLT}$ for each metallicity affects *absolute* ages derived by means of the horizontal method, but not relative ones. A variation of $\alpha_{\rm MLT}$ by ± 0.1 changes the relative ages by 0.10-0.15 Gyr (while changing the absolute ages obtained from the horizontal method by $\approx$ 1 Gyr);

v) the influence of the helium and heavy element diffusion on the relative ages obtained by means of the horizontal method is almost negligible (Cassisi 1996, private communication). A check at $Z = 0.0002$ shows that the relative ages determined with and without including diffusion agree within 10%;

vi) The scaling of $\Delta(B-V)$ with respect to the age is independent of the absolute age only for ages higher than a certain value (depending on the metallicity). Below this limit, which, for example, is around 11-12 Gyr at $Z = 0.0002$, the age differences depend on the absolute ages assumed for the reference clusters; it is therefore important to fix the absolute age of the reference cluster within each group by means of the vertical method.

3. Cluster ages – absolute and relative

In this section we will discuss separately the absolute and relative age determinations of the clusters within each of the four metallicity groups. All the selected clusters, their metallicity, HB type, galactocentric distance (R_{GC}), the derived ZAHB luminosity (and the associated error) for the reference clusters, relative and absolute ages (with their formal errors), are displayed in Table 1. The ZAHB luminosities are referred to the instability strip for M68, to the red boundary of the instability strip for NGC6584, NGC3201 and M5, which have a well developed HB but no homogeneus RR Lyrae photometry; in the case of NGC6171 and NGC6652 the ZAHB luminosity corresponds to its red HB. The HB types come from Chaboyer et al. (1996); an evaluation of the galactocentric distances (in Kpc) has been obtained by mainly adopting the clusters average HB luminosities given by Chaboyer et al. (1996; in the case of NGC6366 the average HB luminosity comes from Alonso et al. 1997, while for the "reference" clusters we have adopted the ZAHB luminosities given in Table 1), translating them into ZAHB luminosities by means of Eq. 1, deriving the apparent distance modulus by means of our ZAHB models, and then applying the following equation:

$$R_{GC} = ((R_{GC}^{\odot})^2 + d^2 - 2dR_{GC}^{\odot}cos(l)cos(b))^{0.5} \tag{2}$$

where b and l are the cluster galactic coordinates, $log(d) = (((m-M)_o + 5)/5) - 3$ (the reddening values come from Chaboyer et al. 1996 for the "non-reference" clusters, with the exception of NGC6366, whose reddening comes from Alonso et al. 1997; A_V=3.3E(B-V)) and the Sun's galactocentric distance is set to $R_{GC}^{\odot}$=8.0 Kpc.

A simple estimate of the formal error in the absolute age for the reference clusters is obtained as in Paper I, by statistically adding the formal uncertainties on the ZAHB level (displayed in Table 1) and on the TO luminosity (as derived from the original papers) in order to obtain the error in the observed $\Delta(V)$ value; this error is then transformed into an uncertainty in the age by using the theoretical isochrones. For the other clusters the formal error in the relative ages derived by means of the horizontal method (see the previous section) is statistically added to the error in the age of the corresponding reference cluster.

At this point we have to comment on the meaning of the formal errors given in Table 1. These errors have no true statistical meaning and therefore the results of the statistical analyses of Sect. 4 should be considered as being indicative and not rigorous. Chaboyer et al. (1996), who commented on this, have argued that the errors quoted by the observers correspond to 1.63σ, and since these errors referring to the HB or TO brightness are of a similar kind as those given in Table 1, our errors could be considered as corresponding to 1.63σ. However, we prefer to be more conservative and assume that they are of the order of 1σ. An argument being in favour of this is that according to Chaboyer et al. (1996) the average 1σ error for all their clusters is 0.083 mag – corresponding to ≈1 Gyr, which is a similar age uncertainty as we give in Table 1.

3.1. Metal-poor clusters: $-2.0 \leq$ [M/H] < -1.6

The clusters belonging to this group are M68 (Walker 1994), M15 (Durrell & Harris 1993), M92 (Stetson & Harris 1988), M30 (Richer et al. 1988), NGC6397 (Buonanno et al. 1989), NGC2298 (Janes & Heasley 1988), Rup106 (Buonanno et al. 1993) and Arp2 (Buonanno et al. 1995a).

The reference cluster is M68, and its age determined as in Paper I by means of the vertical method is 12.2±1.0 Gyr. The relative ages of the other clusters with respect to M68 have been derived by means of the horizontal method and are displayed in Table 1.

In Fig. 3 we show, as an example, the fiducial lines of NGC2298 and M92 registered to that of M68 as described in the previous section; the two dashed lines parallel to the RGB of M68 correspond to an age variation of ±1 Gyr with respect to the age of M68. When neglecting Rup106 and Arp2, this group results to be remarkably homogeneus in age (an occurrence already discussed by VandenBerg et al. 1990 and Straniero & Chieffi 1991), the maximum age difference with respect to M68 being ≈ 0.5 Gyr.

Rup106 and Arp2 have been included in this group following the metallicity determinations by Buonanno et al. (1993, 1995a), which are based on the characteristics of the observed cluster RGBs. The final value for [M/H] has been obtained by adding the contribution of the α-elements as for the other clusters. The main lines of Rup106, Arp2 and M68 are displayed in Fig. 4, shifted as before; Rup106 and Arp2 appear to be younger by ≈ 2 Gyr with respect to M68. This age difference is only half as large as that claimed by Buonanno et al. (1993, 1995) with respect to an 'average' metal-poor cluster, obtained by averaging the fiducial lines of M92 (Stetson & Harris 1988), M68 (McClure et al. 1987), NGC6397 (Buonanno et al. 1989), M15 (Fahlman et al. 1985) and M30 (Richer et al. 1988).

In this work we have compared Rup106 and Arp2 with the new M68 photometry by Walker (1994), and the differences in the average $\Delta(B-V)$ values of Rup106 and Arp2 with respect to M68 are, respectively, +0.041 mag and +0.030 mag, almost coincident with the values +0.041 mag and +0.028 mag found by Buonanno et al. (1993, 1995a).

Table 1. Halo Globular Clusters data. The columns display respectively: cluster name, global metallicity (incldg. α-enhancement), absolute age with the associated formal error, relative age with respect to the reference cluster, HB type, galactocentric distance (in kpc), estimated level of the observational ZAHB (only for reference clusters). The absolute age is obtained by means of the vertical method for the reference clusters and by adding the relative ages for all other clusters in the same group.

Name	[M/H]	Age	Rel. age	HB type	R_{GC}	V_{zahb}
		$-2.1 \leq$ [M/H] < -1.6				
NGC4590 (M68)	-1.90	12.2±1.0		0.44	10.2	15.72±0.04
NGC6341 (M92)	-2.04	11.8±1.1	-0.4	0.88	9.5	
NGC7099 (M30)	-2.03	12.7±1.1	0.5	0.88	7.3	
NGC7078 (M15)	-1.95	12.2±1.1	0.0	0.72	10.5	
NGC6397	-1.70	12.2±1.1	0.0	0.93	5.9	
NGC2298	-1.65	12.5±1.1	0.3	0.93	17.0	
Arp2	-1.65	10.6±1.1	-1.6	0.86	24.4	
Rup106	-1.65	10.1±1.1	-2.1	-0.82	18.7	
		$-1.6 \leq$ [M/H] < -1.3				
NGC6584	-1.34	11.0±1.1		-0.09	6.6	16.60±0.05
NGC3201	-1.36	10.5±1.2	-0.5	0.08	10.1	14.90±0.05
NGC1904 (M79)	-1.49	11.0±1.2	0.0	0.89	19.0	
NGC5272 (M3)	-1.46	11.0±1.2	0.0	0.08	11.9	
NGC6254 (M10)	-1.40	11.0±1.2	0.0	0.94	4.7	
NGC6752	-1.34	10.5±1.2	-0.5	1.00	5.2	
NGC7492	-1.31	11.0±1.2	0.0	0.90	24.8	
		$-1.3 \leq$ [M/H] < -0.9				
NGC5904 (M5)	-1.20	10.4±0.8		0.37	6.2	15.15±0.05
Pal5	-1.27	8.8±0.9	-1.6	-0.40	17.3	
NGC288	-1.20	9.3±0.9	-1.1	0.95	11.7	
NGC1851	-1.13	8.4±0.9	-2.0	-0.33	17.6	
NGC362	-1.07	9.2±0.9	-1.2	-0.87	9.2	
Pal12	-0.94	7.0±0.9	-4.0	-1.00	17.0	
		$-0.9 \leq$ [M/H] < -0.6				
NGC6171 (M107)	-0.79	11.0±1.1		-0.76	3.6	15.72±0.04
NGC6652	-0.69	8.0±1.2		-1.00	1.6	15.95±0.05
Ter7	-0.80	6.5±1.2	-4.5	-1.00	27.5	
NGC6366	-0.79	13.2±1.2	2.2	-1.00	4.9	

The smaller age difference is due to the fact that the relative ages determined with the horizontal method depend on the absolute age of the template cluster for the age range we are dealing with (the same behaviour is found when considering, for example, the Straniero & Chieffi 1991 or the Bergbusch & Vandenberg 1992 isochrones). If an age of 16 Gyr were assumed for M68, we would obtain that Rup106 is younger then M68 by $\approx$4 Gyr, and that Arp2 is $\approx$1 Gyr older than Rup106, in good agreement with the results found by Buonanno et al (1995a).

For testing in a different way the reliability of the relative ages of Rup106 and Arp2 with respect to M68 as derived from the horizontal method, we have checked if the same age difference is consistently obtained adopting the vertical method (in a very similar way as in Buonanno et al. 1993). As displayed in Fig. 5, we have considered the Rup106 photometry (the Arp2 photometry shows only a very poorly populated blue HB), and we have shifted horizontally and vertically the CMD and ridge line in order to superimpose them on the HB and RGB of M68; note the almost coincident shapes of the RGBs, which indicate a very similar metallicity for these two clusters. The TO luminosities given by the observers are 21.05 mag for Rup106 and 19.05 mag for M68; the vertical shift applied to Rup106 is -2.2 mag, and the horizontal one is -0.17 mag. The difference in the TO luminosities gives the age difference from the vertical method. Shifted in this way, the TO of Rup106 differs by 0.2 mag (Rup106 TO being more luminous) with respect to the M68 TO, and correspondingly Rup106 is $\approx$ 1.7 Gyr younger than M68, in very good agreement with the value derived from the horizontal method.

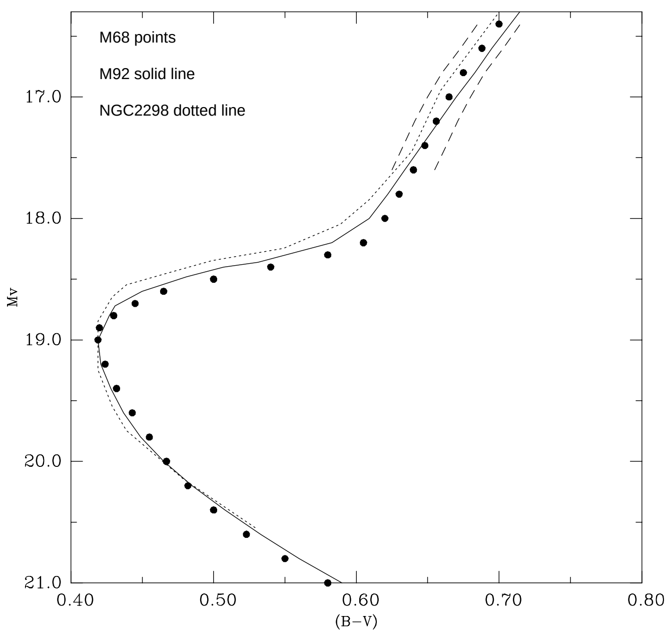

Fig. 3. Comparison of CMD ridge lines registered to that of M68 as explained in the text. The dashed lines on both sides of the M68 RGB indicate an age difference of ±1 Gyr with respect to this cluster

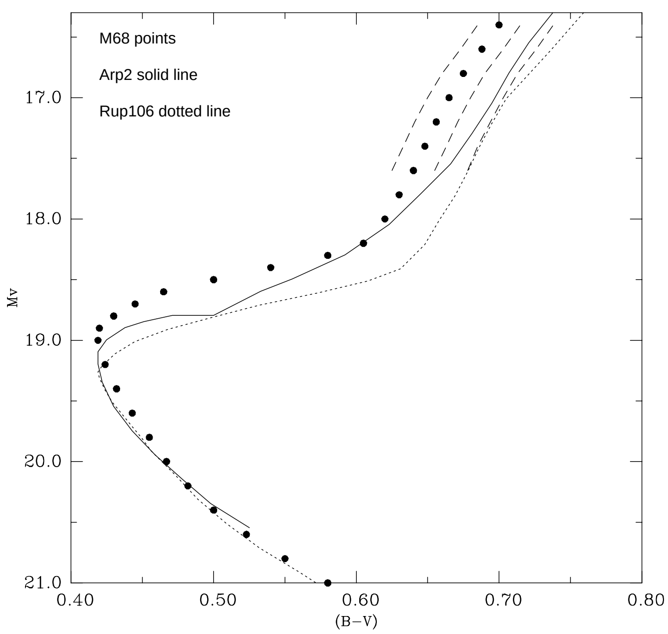

Fig. 4. As Fig 4, but for Rup106 and Arp2; in this case the dashed lines correspond to age differences of +1, -1 and -2 Gyr with respect to M68

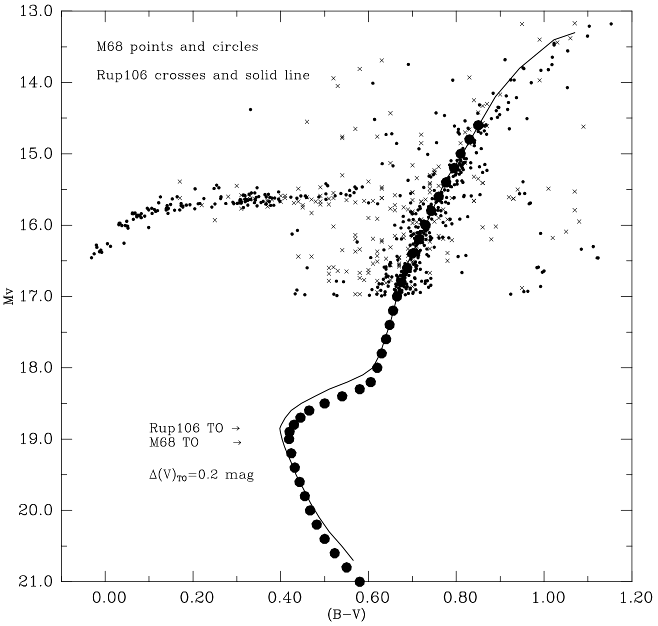

Fig. 5. Rup106 CMD and ridge line shifted in order to superimpose RGB and HB to the M68 ones. The cluster TO luminosities are indicated

3.2. Intermediate metal-poor clusters: $-1.6 \leq$ [M/H] < -1.3

In this metallicity range we have considered the following clusters: NGC6584 (Sarajedini & Forrester 1995), M3 (Ferraro et al. 1996), M79 (Ferraro et al. 1992), NGC6752 (VandenBerg et al. 1990), NGC7492 (Coté et al. 1991), M10 (Hurley et al. 1989) and NGC3201 (Covino & Ortolani 1997).

The reference cluster is NGC6584. From the vertical method, using a metallicity of $Z = 0.001$, we derive t=11.0±1.1 Gyr (see Fig. 6); we get an apparent distance modulus of $(m-M)_V = 16.01 \pm 0.05$ and a reddening of $E(B-V) = 0.13$, in agreement with previous estimates ranging between 0.07 and 0.15. By applying the horizontal method, we derive age differences not bigger than 0.5 Gyr for all clusters in the sample (see Table 1).

We can check the consistency of the horizontal age scaling with the absolute "vertical" age determination for another cluster with a well populated horizontal part of the HB, that is NGC3201 (Covino & Ortolani 1997). We get an age of 10.0 ± 1.6 Gyr from the vertical method ($(m-M)_V = 14.28 \pm 0.05$, $E(B-V) = 0.25$) adopting $Z = 0.001$ (see Fig. 7); this value is in good agreement with the age of NGC6584 obtained by means of the horizontal method (see Table 1 and Fig. 8).

In order to check the consistency of the absolute ages for the "non-reference" GCs obtained if we regroup the clusters in different metallicity bins, we have also derived the relative age of Rup106 with respect to NGC6584. These two clusters differ by ≈ 0.3 dex in [M/H], and in principle - following the criteria adopted in this work - could belong to one single metallicity group. Rup106 results to be -1.3 Gyr younger than NGC6584 by adopting the horizontal method; thus the derived absolute age is in this case 9.7 ± 1.2 Gyr, completely consistent with the value derived in the preceding subsection (see Table 1).

3.3. Intermediate metal-rich clusters: $-1.3 \leq$ [M/H] < -0.9

This group includes M5 (Sandquist et al. 1996), NGC1851 (Walker 1992b), NGC288 (Bolte 1992), NGC362 (VandenBerg et al. 1990), Pal12 (Stetson et al. 1989) and Pal5 (Smith et al. 1986).

The reference cluster is M5; by applying the vertical method to the recent photometric data by Sandquist et al. (1996), we get an age of 10.4 ± 0.8 Gyr (see Fig. 9) and $E(B-V) = 0.05$, $(m-M)_V = 14.53 \pm 0.05$. If we compute the real distance modulus, by adopting $A_V = 3.3E(B-V)$, we get $(m-M)_0 = 14.37 \pm 0.05$, a value that perfectly

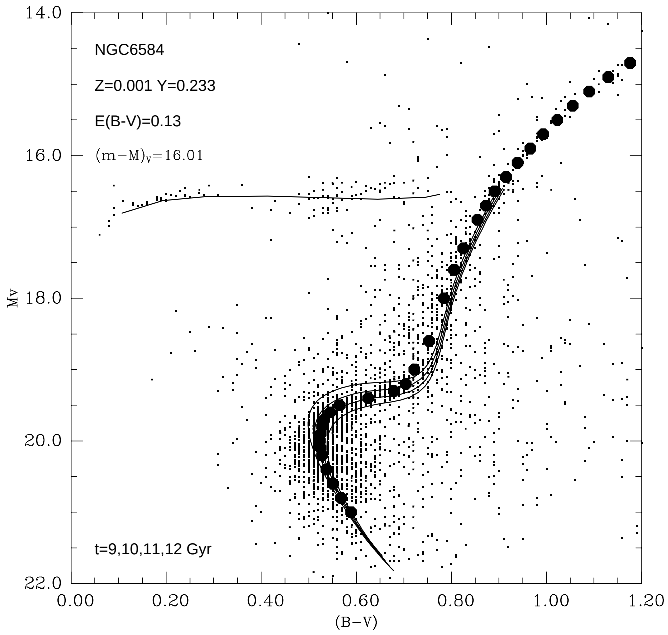

Fig. 6. Isochrones for ages between 9 and 12 Gyr and ZAHB theoretical models compared to the CMD and the ridge line of NGC6584 (Sarajedini & Forrester 1995)

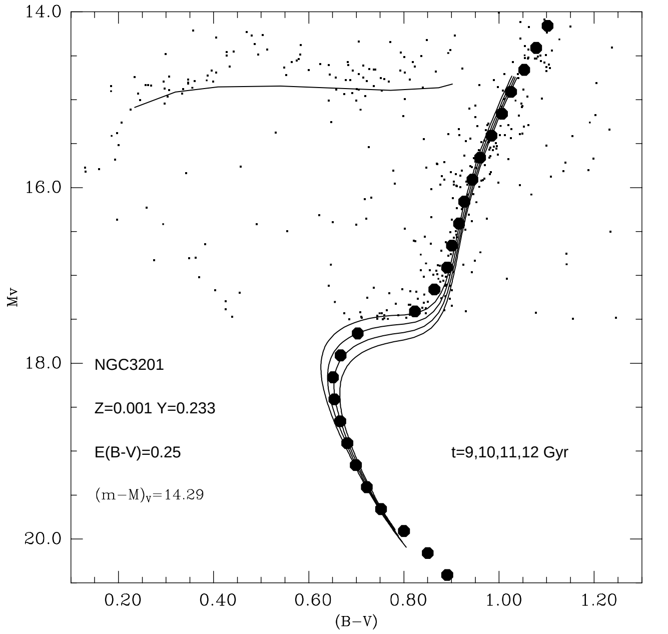

Fig. 7. Isochrones for ages between 9 and 12 Gyr and ZAHB theoretical models compared to the CMD and ridge line of NGC3201 (Covino & Ortolani 1997). For sake of clarity, only the ridge line is displayed for the cluster MS

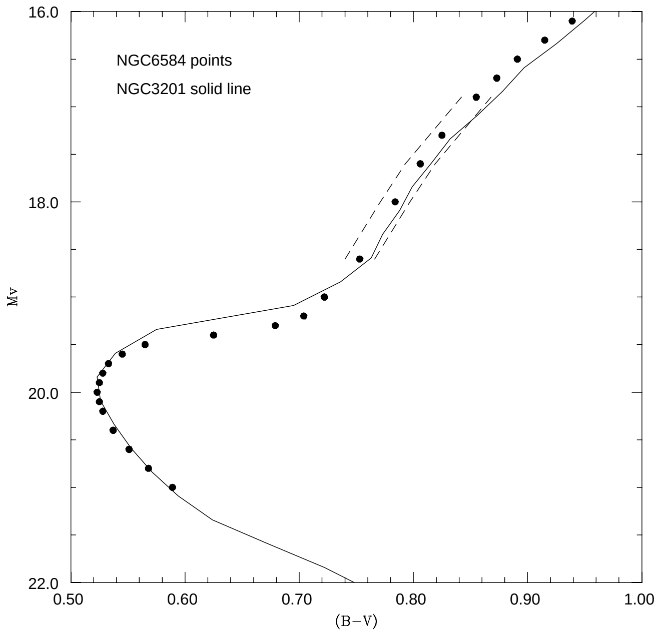

Fig. 8. The CMD ridge line of NGC3201 registered to that of NGC6584 as explained in the text. The dashed lines on both sides of the NGC6584 RGB indicate an age difference of +1 and -1 Gyr with respect to NGC6584

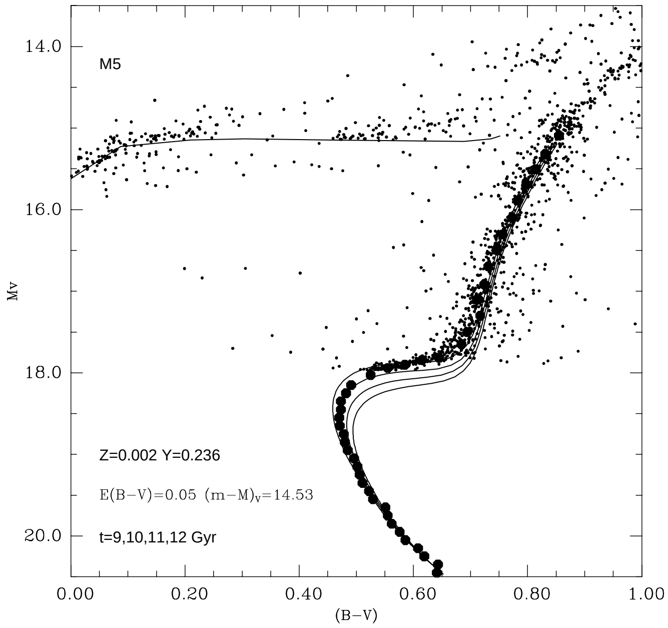

Fig. 9. Isochrones for ages between 9 and 12 Gyr and ZAHB theoretical models compared to the CMD and ridge line of M5 (Sandquist et al. 1996). Only the ridge line is displayed for the cluster MS, and along the RGB, at luminosities lower than the HB, only a subsample of stars is shown

agrees with the value of 14.37 ± 0.18 found by Storm et al. (1994) from the Baade Wesselink method for two cluster RR Lyrae stars.

The relative ages with respect to M5 are displayed in Table 1. All the other clusters result to be significantly younger, the youngest one being Pal12. In particular, when taking into account the recent photometric study by Bolte (1992) about NGC288, we find that NGC288 and NGC362 are practically coeval (see Fig. 10). This confirms the qualitative result by Stetson et al. (1996), who found (by using essentially the vertical method) that NGC1851, NGC362 and NGC288 should have the same age, thus giving a very strong evidence against the age as the second parameter. Our result is in agreement with their investigation; by using the horizontal method, the three clusters result to be coeval within less than 1 Gyr (Fig. 10)).

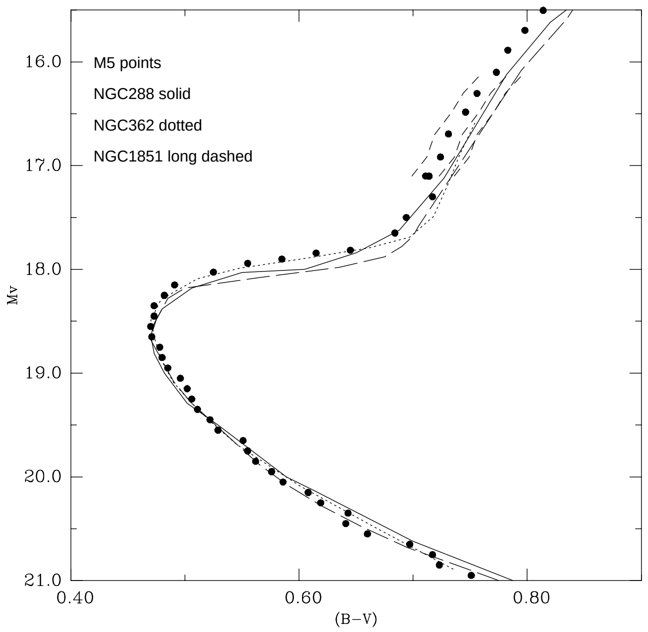

Fig. 10. Comparison of CMD ridge lines. The dashed lines on both sides of the M5 RGB indicate an age difference of +1, -1 and -2 Gyr with respect to the reference cluster M5

3.4. Metal-rich clusters: $-0.9 \leq [\mathrm{M/H}] < -0.6$

M107 (Ferraro et al. 1991), NGC6652 (Ortolani et al. 1994), NGC6366 (Alonso et al. 1997) and Ter7 (Buonanno et al. 1995b) are the four clusters considered in this group. The reference cluster is NGC6171; by employing isochrones for $Z = 0.004$ we get from the vertical method an age of 11.0 ± 1.1 Gyr, together with $E(B-V) = 0.38$ and $(m-M)_V = 15.02 \pm 0.04$ (see Fig. 11). The reddening we derive agrees with previous estimates, ranging between 0.30 and 0.48.

By applying the horizontal method for getting the relative ages with respect to M107 (see Fig. 12), we find a large age spread within this group: NGC6366 is ≈ 2 Gyr older than M107, while Ter7 is ≈ 4.5 Gyr younger than M107. This is the largest age spread among all the clusters considered in this study. However some caution has to be taken when considering NGC6366, since this cluster (see Harris 1993 and Alonso et al. 1997) is affected by differential reddening; the determination of its relative age with respect to NGC6171 could therefore be less accurate even if the cluster appears undoubtedly to be an "old" Halo GC (see also the discussion in Alonso et al. 1997).

As for NGC6652, the cluster ridge line (not provided in the paper by Ortolani et al. 1994) has been derived according to the procedure described by Bartelmann et al. (1997 - Bartelmann, private communication), and the resulting TO luminosity is in very good agreement with the value V_{TO}=19.20±0.15 given by Ortolani et al. (1994). The cluster RGB shows a big dispersion in color and the ridge line for this CMD region is not well defined; therefore

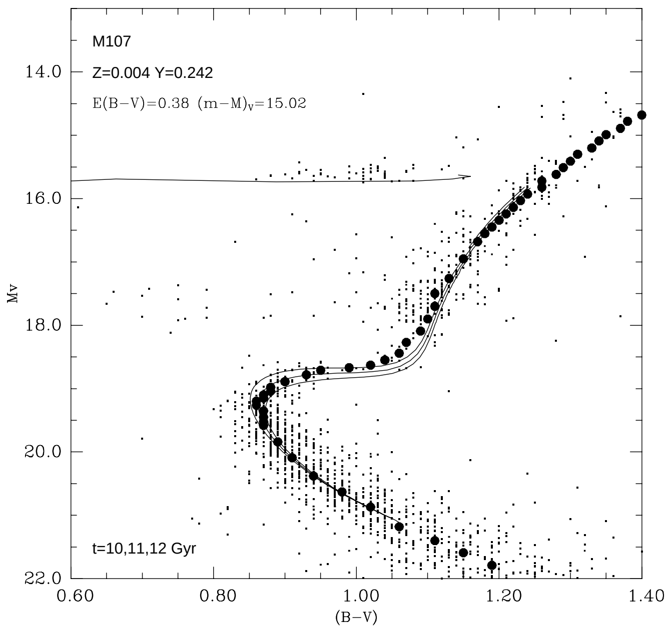

Fig. 11. Isochrones for ages between 10 and 12 Gyr and ZAHB theoretical models compared to the CMD and ridge line of M107 (Ferraro et al. 1991)

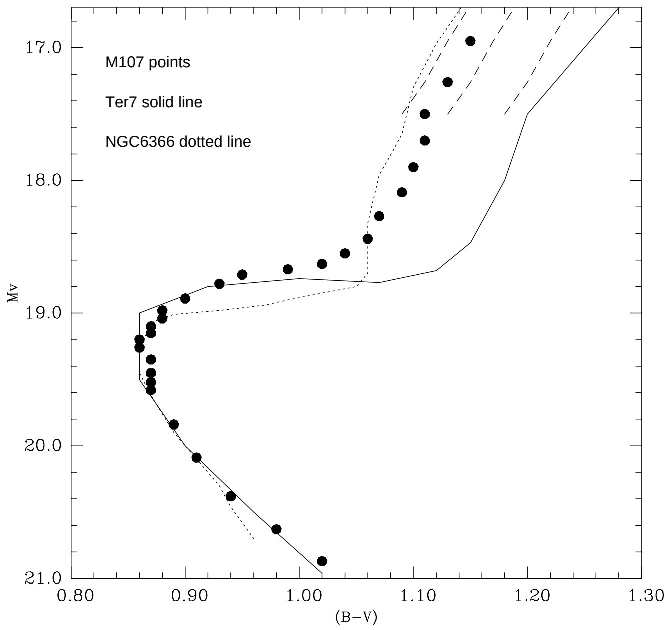

Fig. 12. Comparison of CMD ridge lines. The dashed lines on both sides of the M107 RGB indicate an age difference of +2, -2 and -4 Gyr with respect to this cluster

we have considered the ridge line only until the subgiant branch and the cluster age has been directly derived by using the vertical method. By using isochrones for Z=0.004 we get an age of 8.0±1.2 Gyr, E(B-V)=0.23, $(m-M)_V$=15.23 (see Fig. 13).

To check qualitatively the consistency between the NGC6652 absolute age and its relative age with respect to M107 derived by means of the horizontal method, the M107 ridge line registered to the NGC6652 one is shown in Fig. 14. Taking into account that the M107 age is ≈11 Gyr, an age difference by ≈3 Gyr as obtained by means of the vertical method is consistent with the relative ages obtained by applying the horizontal method.

3.5. Comparison with previous results

The results about the GCs ages displayed in Table 1 can be directly compared with the results from the work by Richer et al. (1996). Their approach has already been discussed in Sect. 1; they also arranged the clusters into four groups, according to the cluster [Fe/H]-content; the metallicity range of each group is very similar to our choice, and the metallicities adopted for each cluster are similar (also if not coincident, and in the case of Rup106 and Arp2 substantially higher) to the values we adopted. As for the absolute ages, we find that our values are systematically lower by ≈ 4 Gyr, due basically to the more updated stellar models used.

The relative ages among the metal-poor GCs in common with their work are in agreement with their results within the formal errors associated with the determination of the relative ages (≈ 0.5 Gyr).

When considering the second group (intermediate metal poor clusters), we have in common with their analysis M3, NGC6752, NGC1904 and NGC7492, which are coeval within 0.5 Gyr. Richer et al. (1996) find the same result for the first 4 cluster, while they obtain an age for NGC7492 that is 1.7 Gyr higher. This is surprising, since we are using the same source of photometric data for example for NGC6752 and NGC7492. The reason for this difference could be due to a point on the ridge line of NGC7492 that is clearly discrepant and it is almost 2.5 mag brighter than the point on the main sequence used for registering all clusters to the reference one. If only this point is considered for determining the relative age, one indeed obtains the result that NGC7492 is around 1.7 Gyr older than NGC6752.

In this second metallicity group Richer et al. (1996) also include Arp2 and Rup106. They find that Rup106 is younger by 1 Gyr with respect to Arp2, and by 4 Gyr with respect for example to NGC6752. We also determined the relative age of Rup106 with respect to clusters of the second group (see previous section), and the result is that it is younger by only ≈ 1.3 Gyr with respect to them. As previously discussed, this result is due to the dependence of the relative ages obtained by the horizontal method on the absolute age of the reference clusters, for ages lower than a certain value depending on the assumed metallicity.

The intermediate metal rich clusters in common with Richer et al. (1996) are M5, NGC288, NGC362, NGC1851 and Pal12. The substantial difference with their work is that we find NGC1851, NGC288 and NGC362 to be coeval within 1 Gyr (in agreement with the result by Stetson et al. 1996 obtained by the vertical method). This seems to be due to the use of the new Bolte (1992) photometry for NGC288. Had we used the NGC288 ridge line from Buonanno et al. (1989), we would have obtained an age difference by ≈2 Gyr with respect to NGC362 (NGC288 being older), in agreement with the results by Richer et al. (1996). Another difference is that we have adopted the very recent M5 photometry by Sandquist et al. (1996), that displays also a well-populated HB, and we find that M5 is older than NGC362 and NGC1851, while Richer et al. find these three clusters to be coeval; this difference again is due to the different data used. If we use the old data for M5 by Richer & Fahlman (1987, as in Richer et al. 1996), the results again agree with Richer et al. (1996).

Among the metal-rich cluster there is only Ter7 in common with the work by Richer et al. (1996); they consider 3 other clusters belonging to the disk GC system, for which there are indications that the original helium content could be substantially higher than $Y = 0.23$ (see Alonso et al. 1997 and references therein).

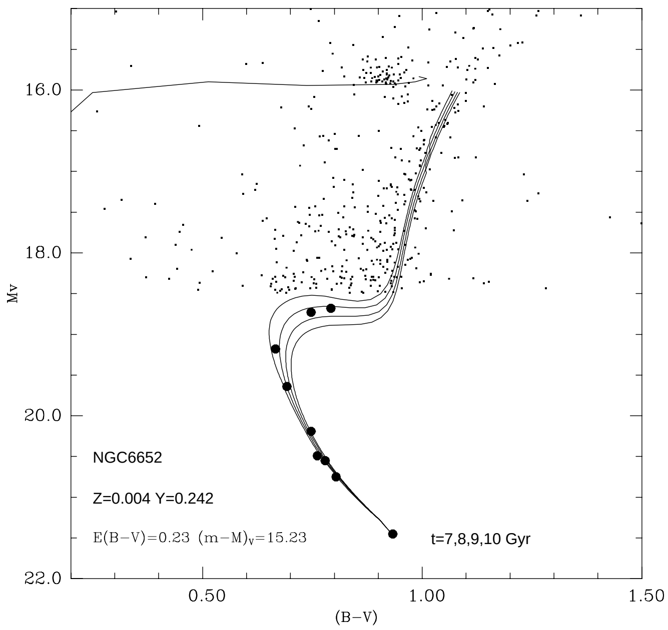

Fig. 13. Isochrones for ages between 7 and 10 Gyr and ZAHB theoretical models compared to the CMD and ridge line of NGC6652 (Ortolani et al. 1994). Only the ridge line is displayed for the cluster MS

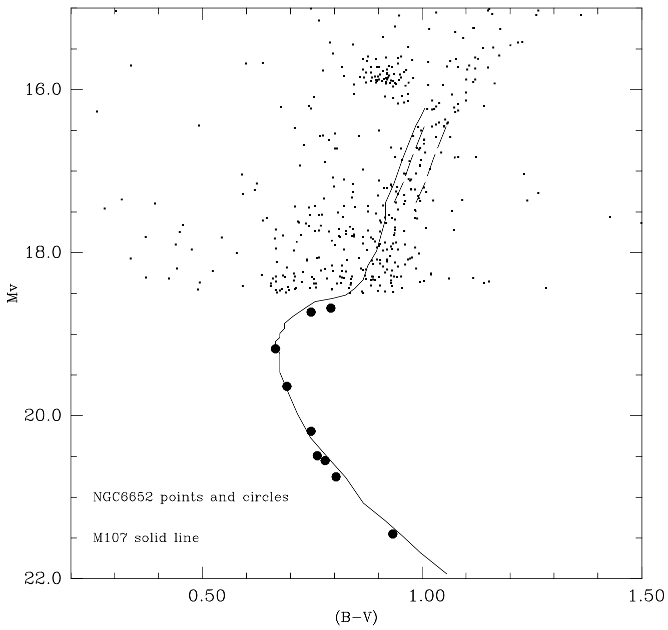

Fig. 14. Relative age of NGC6652 with respect to M107 derived from the horizontal method. The dashed lines on the right side of the M107 RGB indicate an age difference of -2 and -4 Gyr with respect to this cluster

4. Discussion

The results displayed in Table 1 can be used for checking for the existence of an age spread and an age-metallicity relation for halo clusters, as well as for testing the hypothesis that the so-called "second parameter", responsible for the HB morphology of galactic GCs, is age.

As for the second parameter problem, the recent work by Chaboyer et al. (1996) confirms the conclusion, that it is age indeed, but the analyses by Richer et al. (1996) and Stetson et al. (1996) reach a negative conclusion. Checking Table 1, it is evident that the cluster pairs Rup106-Arp2 and NGC288-NGC362 are constituted by GCs with almost the same metallicity and ages, but completely different HB morphologies. We support therefore the conclusion that HB morphology must, at least in part, be due to causes other than only metallicity and age.

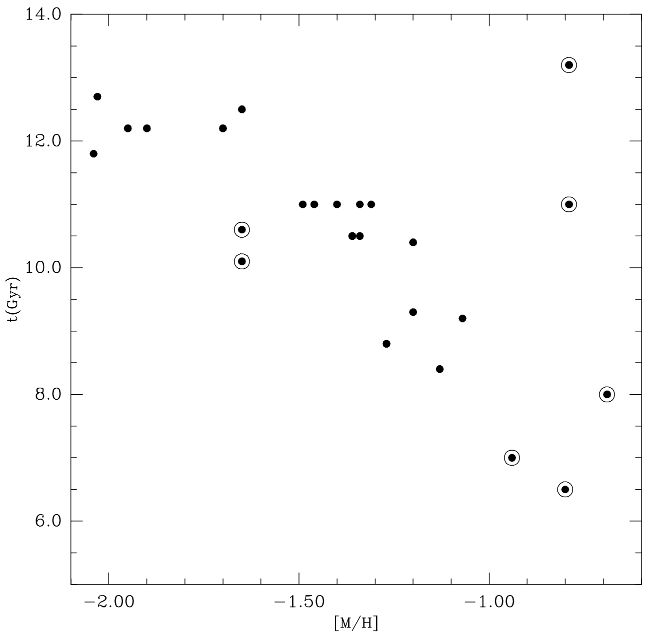

Fig. 15. Age (in Gyr) of the 25 clusters in our GCs sample as a function of their [M/H]. The clusters with the circled dots (Rup106, Arp2, Ter7, Pal12, NGC6366, M107, NGC6652) are those excluded from the analysis is some cases (see text). The error on the individual ages (of order ±1 Gyr) can be found in Table 1, while the error on [M/H] is typically of the order of 0.20 dex

As for the cluster age distribution, we find that if we take into account all 25 GCs considered in our investigation (see Table 1, Fig. 15, Fig. 16), we obtain an average age of $\langle t \rangle$ = 10.5 Gyr, with a standard deviation σ=1.7 Gyr. However, as discussed in the previous section, the relative age of NGC6366 with respect to M107 is uncertain, due to the differential reddening that affects this cluster, and therefore we will not consider NGC6366 in the following analysis; without NGC6366 (24 clusters), $\langle t \rangle$ = 10.4 Gyr and σ=1.7 Gyr, very close to the results for the complete sample. For the first three metallicity groups the average ages and the dispersions are, in the order of increasing metallicity, $\langle t \rangle$ = 11.8, 10.9, 8.9 Gyr and σ = 0.9, 0.2, 1.1 Gyr. In the most metal-rich group we have only three clusters, which give $\langle t \rangle$=8.5 Gyr. The rather large variance for the low-metallicity group results from the two clusters Arp2 and Rup106. If we omit these clusters (see below), we obtain $\langle t \rangle$ = 12.3 and σ = 0.3.

To quantify how much of the age range among the clusters could be due to errors and whether a real intrinsic age range exists, we have performed the same statistical test used by Chaboyer et al. (1996). We have calculated an "expected" distribution for the assumption of no intrinsic age range by randomly generating 10000 ages using a Gaussian distribution. The mean of the distribution was given by the mean age of the clusters (10.5 Gyr) , and the σ by the error on the individual age determinations. This is repeated for all clusters considered, so that the final distribution contains 240000 points. The F-test (Press et al. 1992) has been then applied in order to determine if this

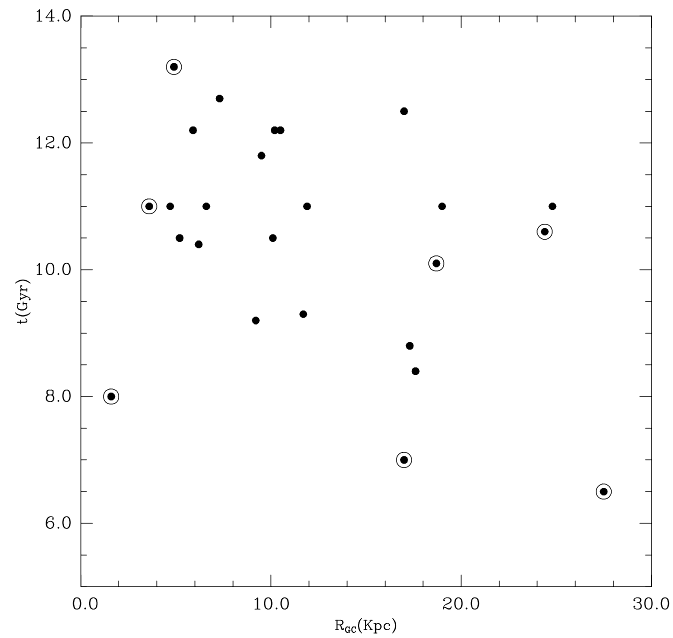

Fig. 16. As in the previous figure, but in this case the age is displayed as a function of the cluster galactocentric distance (in kpc)

"expected" distribution has the same variance as the age distribution obtained in our analysis. As in Chaboyer et al. (1996) we state that an age range exists if the probability that the two distributions have the same variance is smaller than 5%.

By performing this analysis, the F-test rejects the possibility that the clusters are coeval with a confidence level higher than 99.99%. The size of the true age range (σ_{range}) can be estimated according to $\sigma_{range} = (\sigma^2_{obs} - \sigma^2_{exp})^{0.5}$, where σ_{obs} is the sigma of the actual data, and σ_{exp} is the sigma of the expected distribution (Chaboyer et al. 1996); we obtain σ_{range}=1.4 Gyr.

As for an age-metallicity relation, a formal linear fit to the data yields

$$t = (-3.50 \pm 0.57)[\mathrm{M/H}] + (5.51 \pm 0.81). \quad (3)$$

The linear Pearson correlation coefficient is -0.80, implying that the confidence level for a linear correlation between age and [M/H] is not high. The correlation coefficient for the relation age-$R_{\rm GC}$ is even lower than in the previous case (-0.33). A visual inspection of Fig. 16 confirms that there is only an indication that the youngest clusters, with the exception of NGC6652, seem to be located in the outer Halo.

To summarize, when considering all the clusters in our sample (except NGC6366), we find an age spread among the GCs (σ_{range}=1.4 Gyr), but no statistically compelling evidence for either an age-metallicity or an age-R_{GC} relation. There is however an indication that the more metal-poor clusters are on average older then the clusters of higher metallicities, and that the age spread within each metallicity bin tends to be higher for increasing metallicities. Our analysis based on new stellar models therefore confirms the results of Richer et al. (1996) in this respect.

In the last years Lin & Richer (1992) and Buonanno et al. (1994) suggested that Pal12, Rup106, Arp2 and Ter7 (that appear to be younger than other clusters of approximately the same metallicity) could have been captured by the Milky Way from a companion galaxy, and therefore represent later infall events. In this case they could not be indicative of the Halo formation phase. This argument is based mainly on the fact that these four clusters appear to lie along a single great circle passing through the northern tip of the Magellanic Stream, thus suggesting a common orbit that could be the result of an accretion event from a companion galaxy. Although it is clear that proper motion studies are necessary for a definitive answer, the argument is reinforced by the fact that Ter7 and Arp2 lie very close to the Sagittarius Dwarf Galaxy (but see also the discussion in Chaboyer et al. 1996), which is currently being tidally disrupted and absorbed by the Milky Way.

If this is the case, the previous statistical analysis should be performed excluding these 4 objects from our halo GCs sample. Furthermore, from Fig. 15 it is evident that there are only two clusters of the metal-rich group left – M107 and NGC6652 (at respectively 11 and 8 Gyr). In the following we will in brackets give results also for the case when M107 and NGC6652 are not taken in account as well, and therefore the highest metallicity clusters are disregarded completely. The average age of the remaining 20 (18) clusters is then $\langle t \rangle = 10.7$ (10.9) Gyr (σ=1.4 (1.3) Gyr), which is a slightly older, but a lot narrower distribution; the correlation coefficient between age and metallicity is -0.80 (-0.85), which is the same as for the complete sample; the formal linear regression gives $t = (-2.93 \pm 0.52)[\mathrm{M/H}] + (6.58 \pm 0.76)$, and the F-test reveals that the possibility that the clusters in the sample are coeval can be rejected with a lower confidence level of ≈96% (88%) (the derived formal σ_{range} is equal to 0.9 (0.8) Gyr, slightly more than half of σ_{range} for the complete sample). We therefore conclude that, once excluded Pal12, Rup106, Arp2 and Ter7 (suspected to be accreted during merging events and therefore not belonging to the "primordial" galactic GC population), the genuine halo clusters formed within $\approx 2-3$ Gyr.

For the sample consisting of only 18 clusters, we find that the parabolic fit

$$t = -6.67 - 19.72[\mathrm{M/H}] - 5.12[\mathrm{M/H}]^2 \tag{4}$$

describes our results quite well with a correlation coefficient of 0.91, but for this subsample the F-test does not permit to completely reject the hypothesis of coeval GCs.

5. Summary

Our results can therefore be summarized as follows:

1. We have determined the ages of a sample of 25 halo clusters by use of updated stellar models that take into account all recent improvements in stellar input physics data.
2. The method for obtaining ages is a combination of the $\Delta(V)$-method for suitable clusters and the $\Delta(B-V)$-method for all clusters of a similar metallicity. The clusters are grouped into four of such groups.
3. Our results, summarized in Table 1, confirm that GCs are $\approx 12 \pm 1$ Gyr old or younger, as we already claimed in Paper I for a subset of three metal-poor clusters. The lower ages as compared to previous investigations are due to our new stellar physics input and our purely theoretical approach for the HB luminosities.
4. Since age differences depend on absolute age, we obtain smaller age differences at any given $\Delta(B-V)$. Therefore our sample becomes more homogeneous even if we use the same original data as in previous papers. This applies, e.g., for Rup106 and Arp2 w.r.t. M68.
5. Several cross checks (e.g. for Rup106) result in consistent ages.
6. NGC6366 is the oldest cluster of our sample with 13.2 ± 1.2 Gyr, but the photometry for this cluster might be affected by differential reddening, such that we tend to exclude it. The next oldest cluster is M30 with 12.7 ± 1.1.
7. We confirm earlier results that the metal-poor clusters form a very coeval group and that the more metal-rich groups show a larger age spread.
8. For the whole sample, which has not been selected on any specific grounds except that the photometry should be useful for isochrone comparisons, we obtain a mean age of 10.5 ± 1.7 Gyr (1σ-error) and can reject the assumption that all clusters are coeval. A linear correlation between metallicity and age is not confirmed.
9. For samples with all "peculiar" and metal-rich clusters excluded, the mean age becomes better defined (10.9 ± 1.3 Gyr). The age range of a large sample of clusters with the same average age and individual errors as ours would be only 0.9 Gyr (1σ range). Whether or not the assumption of a common age can be rejected savely, depends critically on the inclusion of individual clusters such as M107 and NGC6652. Clearly, the sample size is too small for any reliable conclusions.
10. There is no evidence for any correlation between age and galactocentric distance.
11. Known counter-examples against the hypothesis that age is the second parameter affecting HB morphology are confirmed. NGC288 and NGC362 have the same age. This result does not agree with Richer et al. (1996), and is due to new photometric data of NGC288, but it is in agreement with the results by Stetson et al. (1996).
12. Other differences with respect to Richer et al. (1996) can be explained in terms of our new models, lower absolute ages, or different original data.

To conclude we confirm and substantiate the results of Richer et al. (1996) in large parts, although differences for individual clusters exist, and we determine significantly lower ages for all cluster. According to both investigations the more metal-poor GCs all formed within 1 Gyr and throughout the whole halo. The more metal-rich systems possibly formed another Gyr later and over a somewhat longer timescale. The cluster population is contaminated by a few clusters not fitting into this simple picture. Consistent and high-quality photometric data for a large sample of clusters is needed to confirm our results.

Acknowledgements. We are grateful to Drs. Alexander and Rogers for computing special opacity tables for our purposes, E.L. Sandquist for providing us with his excellent M5 photometry before publication. S. Covino and S. Ortolani are acknowledged for providing us with their NGC3201 photometry. It is a pleasure to thank M. Bartelmann, J. Guerrero and A. Piersimoni for helpful discussions.

References

Alonso A., Salaris M., Martinez-Roger C., Straniero O., Arribas S., 1997, A&A in press
Alexander D.R., Ferguson J.W., 1994, ApJ 437,879
Bartelmann M., Weiss A., Salaris M., 1997, in preparation
Bergbusch P.A., VandenBerg D.A., 1992, ApJS 81, 163
Bolte M., 1992, ApJS 82, 145
Buonanno R., Corsi C.E., Fusi Pecci 1989, A&A 216, 80
Buonanno R., Corsi C.E., Fusi Pecci F., Richer H.B., Fahlman G.G., 1993, AJ 105, 184
Buonanno R., Corsi C.E., Fusi Pecci F., Richer H.B., Fahlman G.G., 1994, ApJ 430, L121
Buonanno R., Corsi C.E., Fusi Pecci F., Richer H.B., Fahlman G.G., 1995a, AJ 109, 650
Buonanno R., Corsi C.E., Pulone L., Fusi Pecci F., Richer H.B., Fahlman G.G., 1995b, AJ 109, 663
Buser R., Kurucz R.L., 1978, A&A 70, 555
Buser R., Kurucz, R.L., 1992, A&A 264, 557
Carretta E., Gratton R.G., 1997, A&AS 121, 95
Carney B.W., Storm J., Jones R.V., 1992, ApJ 386, 663
Castellani V., Ciacio F., Degl'Innocenti S., Fiorentini G., 1996, A&A in press
Chaboyer B., 1995, ApJ 444, L9
Chaboyer B., Kim Y.-C., 1995, ApJ 454, 767
Chaboyer B., Demarque P., Sarajedini A., 1996, ApJ 459, 558
Chaboyer B., Sarajedini A., Demarque P., 1992, ApJ 394, 515
Chieffi A., Straniero O., 1989, ApJS 71, 47
Clementini G., Carretta E., Gratton R., Merighi R., Mould J.R., McCarthy J.K., 1995, AJ 110, 2319
Coté P., Richer H.B., Fahlman G.G., 1991, AJ 102, 1358
Covino S., Ortolani S., 1997, A&A 318, 40
D'Antona F., Caloi V., Mazzitelli I., 1997, ApJ, in press
Durrel P.R., Harris W.E., 1993, AJ 105, 1420
Ferraro F.R., Clementini G., Fusi Pecci F., Buonanno, R., 1991, MNRAS 252, 357
Ferraro F.R., Clementini G., Fusi Pecci F., Sortino R., Buonanno, R. 1996, MNRAS 256, 391
Ferraro F.R. et al. 1996, A&AS submitted
Harris H.C., 1993, AJ 106, 604
Hurley D.J.C., Richer H.B., Fahlman, G.G., 1989, AJ 98, 2124
Iglesias C.A., Rogers F.J., 1996, ApJ 464, 943
Lin D.N.C., Rucher H.B., 1992, ApJ 388, L57
Mazzitelli I., D'Antona F., Caloi, V., 1995, A&A 302, 382
McClure R.D., VandenBerg D.A., Bell R.A., Hesser J.E., Stetson P.B., 1987, AJ 93, 1144
Ortolani S., Bica E., Barbuy B., 1994, A&A 286, 444
Press W.H., Teukolsky S.A., Vetterling W.T., Flannery B.P., 1992, Numerical Recipes (2d ed.; Cambridge: Cambridge Univ. Press)
Richer H.B., Fahlman G.G., 1987, ApJ 316, 189
Richer H.B., Fahlman G.G., VandenBerg D.A., 1988, ApJ 329, 187
Richer H.B., et al., 1996, ApJ 463, 602
Rogers F.J., Iglesias C.A., 1992, ApJS 79, 507
Rogers F.J., Swenson F.J., Iglesias C.A., 1996, ApJ 456, 902
Salaris M., Chieffi A., Straniero O., 1993, ApJ 414, 580
Salaris M, Degl'Innocenti, S., Weiss, A., 1997, ApJ in press
Salaris M., Straniero O., Chieffi A., 1994, MemSAIt 65, 693
Sandage A., 1990, ApJ 350, 603
Sandage A., Cacciari C., 1990, ApJ 350, 645
Sandquist E.L., Bolte M., Stetson P.B., Hesser J.E., 1996, ApJ 470, 910
Sarajedini A., Forrester W.L., 1995, AJ 109, 1112
Smith G.H., McClure R.D., Stetson, P.B., Hesser J.E., Bell R.A., 1986, AJ 91, 842
Stetson P.B., Harris W.E., 1988, AJ 96, 909
Stetson P.B., VandenBerg D.A., Bolte M., Hesser J.E., Smith G.H., 1989, AJ 97, 1360
Stetson P.B., VandenBerg D.A., Bolte M., 1996, PASP 108, 560
Storm J., Carney B.W., Latham D.W., 1994, A&A 290, 443

Straniero O., 1988, A&AS 76, 157
Straniero O., Chieffi A., 1991, ApJS 76, 525
VandenBerg D.A., Bolte M., Stetson P.B., 1990, AJ 100, 445
Walker A.R., 1992a, ApJ 390, L81
Walker A.R., 1992b, PASP 104, 1063
Walker A.R., 1994, AJ 108, 555
Zinn R., 1985, ApJ 293, 424
Zinn R., West M.J., 1984, ApJS 55, 45

This article was processed by the author using a modified version of the Springer-Verlag LaTeX A&A style file *L-AA* version 3.