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On the relative ages of galactic globular clusters

A new observable, a semi-empirical calibration and problems with the theoretical isochrones

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Abstract. A new procedure is described to derive homogeneous *relative* ages from the Color-Magnitude Diagrams (CMDs) of Galactic globular clusters (GGCs).

It is based on the use of a new observable, $\Delta V^{0.05}$, namely the difference in magnitude between an arbitrary point on the upper main sequence ($V_{+0.05}$ –the V magnitude of the MS-ridge, 0.05 mag redder than the Main Sequence (MS) Turn–off, (TO)) and the horizontal branch (HB).

The observational error associated to $\Delta V^{0.05}$ is substantially smaller than that of previous age-indicators, keeping the property of being strictly independent of distance and reddening and of being based on theoretical *luminosities* rather than on still uncertain theoretical *temperatures*. As an additional bonus, the theoretical models show that $\Delta V^{0.05}$ has a low dependence on metallicity. Moreover, the estimates of the *relative* age so obtained are also sufficiently invariant (to within $\sim \pm 1 Gyr$) with varying adopted models and transformations.

Since the difference in the color difference $\Delta(B-V)_{TO,RGB}$ (VandenBerg, Bolte and Stetson 1990 –VBS, Sarajedini and Demarque 1990 –SD) remains the most reliable technique to estimate relative cluster ages for clusters where the *horizontal* part of the HB is not adequately populated, we have used the differential ages obtained via the "vertical" $\Delta V^{0.05}$ parameter for a selected sample of clusters (with high quality CMDs, well populated HBs, trustworthy calibrations) to perform an *empirical* calibration of the "horizontal" observable in terms of [Fe/H] and age.

A direct comparison with the corresponding calibration derived from the theoretical models reveals the existence of clear-cut discrepancies, which call into question the model scaling with metallicity in the observational planes.

Starting from the *global* sample of considered clusters, we have thus evaluated, within a homogeneous procedure, *relative* ages for 33 GGCs having different metallicity, HB–morphologies, and galactocentric distances. These new estimates have also been compared with previous latest determinations (Chaboyer, Demarque and Sarajedini 1996, and Richer et al. 1996).

The distribution of the cluster ages with varying metallicity and galactocentric distance are briefly discussed: (a) there is no direct indication for any evident age-metallicity relationship; (b) there is some spread in age (still partially compatible with the errors), and the largest dispersion is found for intermediate metal-poor clusters; (c) older clusters populate both the inner and the outer regions of the Milky Way, while the younger globulars are present only in the outer regions, but the sample is far too poor to yield conclusive evidences.

Key words: stars: evolution – stars: horizontal-branch – stars: Population II – globular clusters: general

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1. Introduction

The main reason to measure the ages of GGCs is their intimate connection to the knowledge of timescales and processes of Galaxy formation and early evolution. Leaving aside the difficult issue of determining the *absolute* ages (the most important item concerning the cosmological impact, see Gratton et al. (1997) and VandenBerg, Stetson and Bolte (1996) for a complete review), there are several reasons to improve the reliability of the derived *relative* ages, at least.

First of all, if we start from the evidence (Zinn 1993, and references therein) that the halo and disk populations display distinctly different rotational properties (slowly rotating the former, rapidly rotating the latter) and we consider that GGCs at different galactocentric distances appear to show similar, though less significative, kinematical differences, it is fundamental to know the actual age differences as they set the basic timescale in the whole Galaxy formation process.

Second, in recent years, a growing group of "young" GGCs has been detected which (based on the Main Sequence TO properties) seem to be $\sim 3-5$Gyr younger than the bulk of GGCs having similar metallicities (see for references Buonanno et al. 1994, Fusi Pecci et al. 1995). These clusters (Pal 12, Ruprecht 106, Arp 2, Terzan 7, IC 4499)[1] are actually quite small and appear located on great circles in the sky suggesting possible connections to satellites of the Milky Way, like the Magellanic Clouds and the Sagittarius dwarf spheroidal (Sgr dSph), and it is thus under debate their possible peculiar origin somehow related to interactions between these satellites and the Galaxy (see for references and discussions Lin and Richer 1992, Buonanno et al. 1994, Ibata et al. 1994, Mateo et al. 1995, Sarajedini and Layden 1995, Fusi Pecci et al. 1995).

Thirdly, even by restricting the sample to more "classic" GGCs, it is very important to study how the differential ages vary within the Milky Way with varying metallicity, galactocentric distances, etc. as this is crucial to a complete description of the chemical and dynamical history of the Galactic material.

As recently reviewed for instance in *The Formation of the Galactic Halo ...Inside and Out* (Morrison and Sarajedini, eds. 1996; see also VandenBerg, Stetson and Bolte 1996), a massive number of papers have dealt with the problem of GGC (relative) age determination using different methods. However, the uncertainties affecting the results are still too large to yield a truly satisfactory answer to most questions. In particular, for various reasons discussed below (a) it is almost impossible to make precise *differential* comparisons of the ages of a wide GGC sample, because even well settled procedures cannot be applied to clusters having different color–magnitude diagrams (CMD) morphologies, and (b) restricting the comparison to cluster-pairs, very discrepant results are frequently obtained. For instance, the two clusters NGC 288 and NGC 362, generally considered to be a pair of clusters having different ages by $\sim 3-7$ Gyr (Bolte 1989, Green & Norris 1990), have recently been re-analysed by Catelan and de Freitas Pacheco (1994) pointing out the difficulties to interpret the observed features just in terms of age-differences. Similar conclusions are obtained comparing this couple of cluster to NGC 2808 (Rood et al. 1993) and to NGC 1851 (Stetson et al. 1996), two clusters with clearly bimodal HB's.

The first traditional technique to estimate relative ages for cluster-pairs having the same metallicity, the ΔV_{HB}^{TO} method (Iben & Faulkner 1968), is in principle very robust essentially because the *clock*, i.e. the TO luminosity calibrated in terms of age by the theoretical models, is based on relatively "well known and properly checked" input physics (see Renzini & Fusi Pecci 1988, and references therein).

Nevertheless, when applied to the bulk of GGCs, the use of the observable ΔV_{HB}^{TO} –the magnitude difference between the TO-point and the horizontal branch (HB) at the corresponding color– suffers of two major disadvantages: (1) the apparent magnitude of the TO can hardly be measured to better than ~ 0.1mag even from high quality CMDs, mainly because the TO-region is almost vertical at the TO-point; (2) there are clusters (like M92, M13, NGC 6752, NGC 6397, 47 Tuc, NGC 6553 etc.) which present CMDs totally depopulated in the *horizontal* portion of the HB, making the estimate of the HB luminosity hardly better than an educated guess. Moreover, even if the HB is populated, one should properly take into account the (generally small) effects due to evolution off the Zero Age Horizontal Branch (ZAHB).

To reduce the impact of these two effects, we propose here to use a *new observable* measured on the CMD and to follow a *new semi-empirical approach* to derive the relative ages of GGCs. In particular, this new approach passes through an empirical calibration in metallicity of the the second traditional method for estimating cluster *relative* ages, i.e. the so-called $\Delta(B-V)_{TO,RGB}$-method (VBS, SD) which can yield accurate age comparisons only for clusters having strictly similar metal content.

[1] Another cluster has been recently found to be many Gyr younger than average, i.e. Pal 1 (Rosenberg et al. 1997). The large uncertainties in the determination of its metallicity prevented us from including Pal 1 in the adopted sample

2. A new observational age–parameter

2.1. Definitions

To overcome the first of the two problems listed above, we suggest a new method, hereafter called vertical method, based on the measure and calibration of a new CMD observable (see Fig. 1): $\Delta V^{0.05}$, the distance in magnitude between the HB at the color of the TO (like in the ΔV_{HB}^{TO} -method) and an arbitrary point on the upper main sequence, near the TO but where the main sequence has a non–vertical slope. For the precise location of this arbitrary point, we choose for simplicity to follow VBS and use $V_{0.05}$, the well–defined point on the main sequence which is 0.05 mag redder than the TO.

A similar approach to the same problem has been adopted by Chaboyer et al. (1996). They defined the observable $M_v(BTO)$ as a point which is brighter than the TO and 0.05 mag redder (i.e., at the base of the Sub Giant Branch). On the other hand, $V_{0.05}$ is a point 0.05 mag redder than the TO but dimmer than the TO itself (see Fig. 1). The philosophy at the base of both approaches is the same, but we prefer to use an observable which is defined in a portion of the Color-Magnitude Diagram populated by less evolved Main Sequence stars and, thus, presumably less sensitive to uncertainties in several parameters, like the mixing length, etc.

The age parameter $\Delta V^{0.05}$ defined here presents two main advantages:

1. It shares with ΔV_{HB}^{TO} the firm theoretical background and the independence of distance and reddening.
2. It offers an intrinsic higher accuracy in its practical measure from the observed CMDs.

On the other hand, we should recall that:

1. This new parameter cannot be applied to clusters having only blue HB stars, and the limitation discussed for the ΔV_{HB}^{TO} -method at point (2) above is still present. This does not allow us to apply the $\Delta V^{0.05}$ -method to the whole set of well observed clusters, but we present at Sect. 3 a procedure to partially overcome the problem.

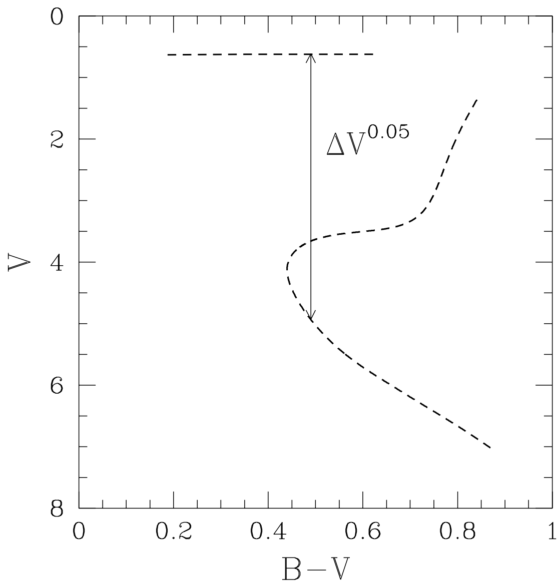

Fig. 1. Definition of the new CMD observable proposed as age–parameter (see Sect. 2.1)

2. Since the measure of the observable for the MS is not exactly the TO but rather a point shifted in color along the MS, actually one *contaminates* the observable V_{TO}, which in the models depends only on luminosities (and, in turn, on "safe" nuclear burning), with a "horizontal component" (due to the shift in color by 0.05 mag), which in the models depends on more uncertain quantities, like the mixing length, the color transformations, etc.

2.2. Dependence on the MS morphology

Since the reference point on the main sequence –$V_{0.05}$– has been selected using the TO *color*, we must study its dependence on the adopted theoretical isochrones. Together with the discussion presented in the following paragraph on the HB, this analysis is necessary to achieve a proper calibration in terms of age of the adopted observable as well as of any other "vertical" observable (like ΔV_{HB}^{TO}) used so far.

2.2.1. Properties of $V_{0.05}$ with varying the adopted models

Although it is commonly accepted that the most widely–used theoretical isochrones for Pop II stars produce substantially the same TO luminosity, it is nevertheless well known that they actually differ when compared in detail, especially after applying transformations into the observational plane.

Leaving out a complete comparison which is beyond the present purposes, in order to understand how these subtle differences may play a rôle in the estimate of relative ages, we report in Fig. 2 the comparison of three of the latest theoretical isochrone sets kindly made available to us in machine-readable form by the authors.

In particular, we have compared the latest models computed by VandenBerg (1996–VdB96) and by Straniero and Chieffi (1996–SC96), which are based on the recent input physics and opacities and on the traditional mixing length approach to deal with convection, and those presented by D'Antona, Caloi & Mazzitelli (1997–DCM97) who have used the Canuto and Mazzitelli (1991, 1992) treatment for the convective layers.

For euristic purposes we adopted the same set of the Kurucz (1993–K93) transformations from the theoretical plane into the observational one, in order to separate the effects of the models from those of the transformations. Fig. 2 reveals that the models are substantially coincident in the TO region for the two metallicities and ages considered, while they are progressively more discrepant going towards redder colors, both along the MS and the base of the RGB. Note that the discrepancy in color for the faint MS ($M_V \sim +6$) is of the order of 0.04 mag in the worst case, while the base of the giant branches differs by about 0.1 mag for the two extreme cases (DCM97 and SC96).

In Fig. 3 (panels a, b) we compare, from the theoretical point of view, the behaviour of $V_{0.05}$ and V_{TO} as a function of metallicity and age with varying the isochrone-sets, but adopting the same color-transformations.

What matters in Fig. 3 is the dependence of the two observables, $V_{0.05}$ and V_{TO} , on the adopted model. Inspection of the plots reveals that while V_{TO} is substantially stable under this aspect, different models produces differences in $V_{0.05}$ that can reach 0.2 mag for the extreme cases. In other words, the calibration of $V_{0.05}$ in terms of age presents an indetermination of about 2 Gyr due to disagreements of the theoretical models. This drawback however, disappointing as it may be, is only a piece of a more general picture of indeterminacies which affect the calibration of many observables, including V_{TO} , as one passes from the theoretical to the observational CMD (see Sect. 2.2.2)

2.2.2. Properties of $V_{0.05}$ with varying the adopted transformations

Turning to the comparison of the same isochrone-set (SC96) but using different transformations, we examined three sets of transformations from the theoretical to the observational plane: K93, Buser and Kurucz (1992–BK92) and VandenBerg (1992–VDB92). The normalization has been achieved, imposing that $M_{V\odot}$=4.82 for all the three trasformations.

The effect of adopting different theoretical–to–observational plane transformations is displayed in fig. 4. The isochrones by SC96 transformed following K93, BK92 and VDB92 are plotted for two ages and two metallicities. Sizeable variations of the colors, the color-differencies, and also of the luminosities are clearly evident.

Fig. 4 shows that this choice actually matters. In fact, the effect of changing color-transformations is almost more important than the use of different original isochrones. In particular, all the panels of Fig. 4 show a clear difference in the color zero–point, but also a more evident discrepancy in the color–differential quantities ($\Delta_{RGB-TO}^{(B-V)}$, for example).

Moreover, also in the V–magnitudes scale, the three transformations give different values for V_{TO} and $V_{0.05}$. This disturbing evidence is further confirmed by the plots shown in Fig. 5, where

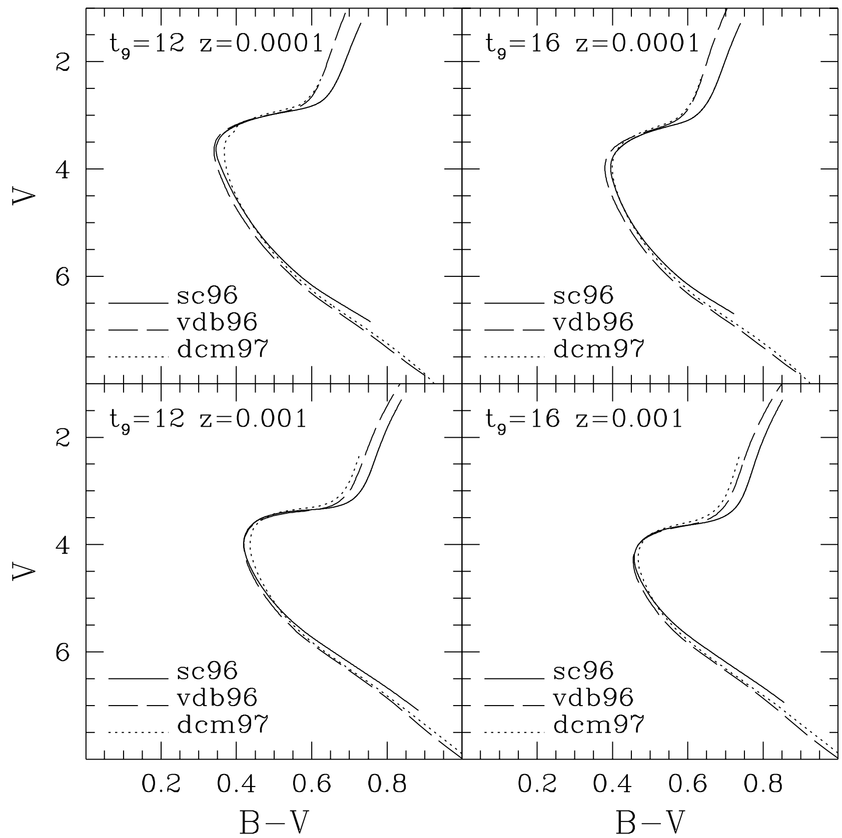

Fig. 2. Three recent sets of isochrones (Straniero and Chieffi 1996–SC96, D'Antona et al. 1997–DCM97, and VandenBerg 1996–VDB96) are compared for two values of age and metallicity. The transformations to the observational plane by Kurucz (1993) are used in all the cases. The relevant features of the CMD show very similar luminosities while the colors differ noticeably

the values obtained for $V_{0.05}$ and V_{TO} from the SC96 models are compared with varying metallicity, after applying the three different transformations, *i.e.* K93, BK92 and VDB92.

In particular, it is disappointing to note that with changing transformations, the trend of both V_{TO} and $V_{0.05}$ tends to diverge at the metal poor end, which, as well known, has the major cosmological impact. Furthermore, it is evident from Fig. 5 that the effect of the adoption of different trasformations is slightly greater on $V_{0.05}$ than on V_{TO} . As said in Sect. 1, the adoption of an observable different from the "pure" V_{TO} can have significant advantages from an observational point of view, but it presents some drawbacks in terms of theoretical calibration.

2.3. Dependence on the HB properties

Since the calibration of ΔV_{HB}^{TO} and $\Delta V^{0.05}$ rests on the theoretical models, the main point is to use sets of models as homogeneous as possible to avoid spurious differential effects introduced by variations in the input physics and in the treatments adopted in the computations. This means that it is better to adopt MS and HB models computed by the same authors, if available, and to apply the same set of color transformations.

However, it is also well known that for the specific case of the HB, there is still room for a residual discrepancy between the models and the observational data concerning the precise dependence of the absolute magnitude of the HB, –M_V^{HB} –, on metallicity, –[Fe/H] . In particular, if we assume a linear relationship between M_V^{HB} and [Fe/H] (see for references Chaboyer, Demarque & Sarajedini 1996), the slope can vary from about 0.15 (the standard theoretical models) up to 0.35 (Sandage 1982, 1993). Moreover, the zero-point is uncertain at the 0.2 mag level, but since we are mostly interested in the *relative* ages, this item is not so important here.

In order to show the size of the effects due to significantly different choices, we have reported in Fig. 6 (panel a) the M_V^{HB} vs. [Fe/H] relationship recently obtained by SC96, by DCM97 and by VdB96 transformed to the observational plane adopting K93 as already done for the corresponding MS. As can be seen, the three theoretical loci are quite different. The mean slope goes from 0.18 to 0.26 for SC96 and DCM97, respectively, and covers almost the whole range of the observational estimates quoted above.

On the other hand, also the use of different color transformations makes a difference, as noted for the MS. As can be seen from Fig. 6b, where the ZAHB tracks computed by SC96 have been transformed using the quoted relationships, the differences in luminosities are quite sizeable. This reinforces the note that the use of different models and even of different transformations from the theoretical to the observational plane strongly affects the calibration of differential age observables like ΔV_{HB}^{TO} and $\Delta V^{0.05}$.

In synthesis, we can conclude that in the definition of the "constant-age loci" in the plane ΔV_{HB}^{TO} or $\Delta V^{0.05}$ *vs* [Fe/H] , the choice of the dependence of the HB luminosity M_V^{HB} on the metal–content [Fe/H] plays a crucial rôle.

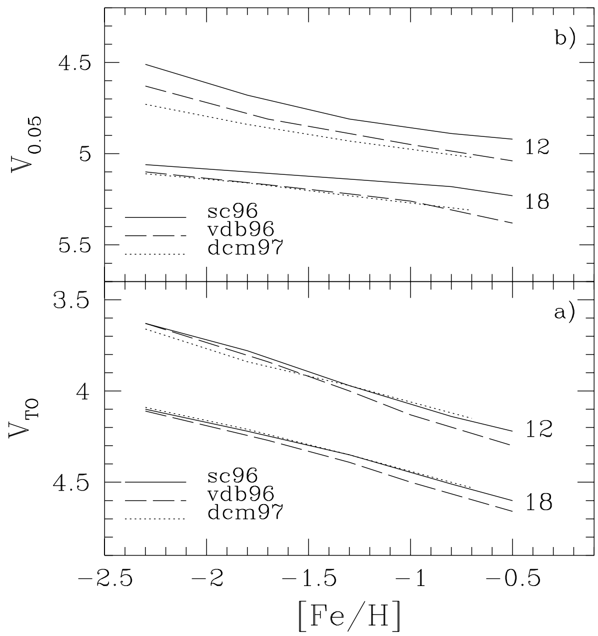

Fig. 3a and b. The luminosity of the MS–TO point (panel **a**) and of the MS–point 0.05 mag redder than (B-V)$_{TO}$ (panel **b**) as derived from the three isochrone–sets, are compared as a function of metallicity. The apparent better agreement for V$_{TO}$ is mainly due to a zero–point difference in V$_{0.05}$

The effect of choosing one of the very different slopes shown in Fig. 6a seems to induce insurmountable difficulties in the use of such a calibration (which is indeed present in any age-calibration somehow resting on the HBs). However, there are two important items to consider:

1. The recent determinations of the slope Δ M$_V^{HB}$/ Δ [Fe/H] from various methods (RR-Lyrae pulsational properties, Baade–Wesselink studies of individuul RR–Lyrae stars, HB studies of the M31 globular clusters with HST, etc.) seem to converge towards a mean value of about 0.20 or smaller (see for references Chaboyer, Demarque & Sarajedini 1996), which is very close to the mean slope of the standard theoretical HB models.
2. Since we aim here at studying just the *relative* ages, we propose a *differential* use of the $\Delta V^{0.05}$ parameter (which is, by the way, already a differential quantity, so as to yield a double differential method). This choice eliminates the problem of the inaccurate knowledge of the zero-point of the M_V^{HB} *vs* [Fe/H] relationship.

2.4. The $\Delta V^{0.05}$ vs. age calibrations

Once that a self-consistent set of isochrones has been adopted, the choice of the M_V^{HB} *vs* [Fe/H] relationships allows us to draw plots of the resulting isochrones in the $\Delta V^{0.05}$ *vs* [Fe/H] plane.

Since there are various possible calibrations depending on the actual choices, we have reported the various constant–age loci in different panels of Fig. 7, 8, and 9. On the same plots we have also reported the observed values for a sample of Galactic globular clusters for which accurate photometry is available.

From the analysis of the theoretical calibrations, one can draw some general considerations:

1. although the calibrations clearly change with varying ingredients, it is evident that the overall behaviour is substantially the same. The variation of the observable $\Delta V^{0.05}$ with the age is quite large (*i.e.* the sensitivity to age variations is high), and the dependence on metallicity is small. This ensures that errors in metallicity (still as large as 0.2 dex) have negligible impact on the estimated ages
2. by interpolating in any plot in Fig. 7, 8, and 9, it is possible to estimate age differences –Δt_9– for any cluster with known $\Delta V^{0.05}$ (or ΔV_{HB}^{TO}) and [Fe/H] relative to an arbitrary isochrone taken as the reference zero-point
3. since this parameter is *differential*, the problematic effects induced by the use of different transformations are reduced. In fact, as we see in Fig. 8, a compensating mechanism is at work which in practice makes almost neglegible the impact of this specific item. This represents of course one of the major advantages of differential methods
4. while the adoption of different slopes in the M_V^{HB} *vs* [Fe/H] calibration (or in any sub-interval of the whole metallicity range) modifies the shapes of the isochrones, a simple shift in the zero-point of the same relationships would correspondly shift the whole pattern, without affecting the relative ages

In conclusion, despite several differences do exist between different calibrations and transformations, it is possible to select a region of the $\Delta V^{0.05}$ (or ΔV_{HB}^{TO}) *vs* [Fe/H] plane where to locate clusters coeval within a given age interval, independent of the chosen calibration. In particular, in the following sections, we will show that it is *actually* possible to extract a sub-set of clusters which can be considered to be *substantially* coeval (*i.e.* within a *conservative* estimate of the errors) independently of the adopted calibrations. This sample of ”coeval” clusters will allow us to make some interesting checks on the internal consistency of the models themselves.

2.5. Additional useful remarks on the $V_{0.05}$ parameter

To have a better insight on the properties of this new parameter, we report the results of several specific tests we originally carried out using the former isochrones computed by Straniero & Chieffi (1991 –SC91) and the ZAHB models of Castellani, Chieffi & Pulone (1991). These theoretical models have the advantage to have adopted homogeneous input physics with no ”a priori” variations of the helium content Y and of the mixing–length parameter α, nor of the alpha-elements (O, Ca, Si, etc.) as a function of [Fe/H] . They represent thus a ”classic, standard” reference grid.

Within this framework, one may wonder whether the present uncertainties in the treatment of convection and in the assumed constancy of the mixing–length parameter for stars of different

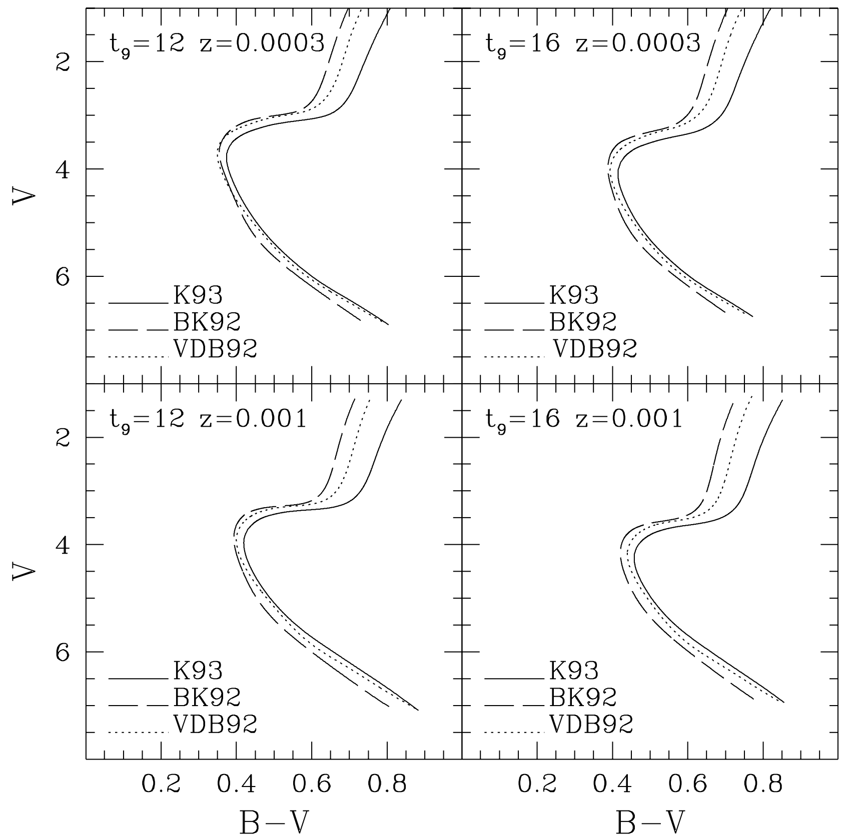

Fig. 4. The effect of adopting different theoretical–to–observational plane transformations. The isochrones by SC96 transformed following K93, BK92 and VDB92 are plotted for two ages and two metallicities. Sizeable variations of the colors, the color-differencies, and also of the luminosities are clearly evident

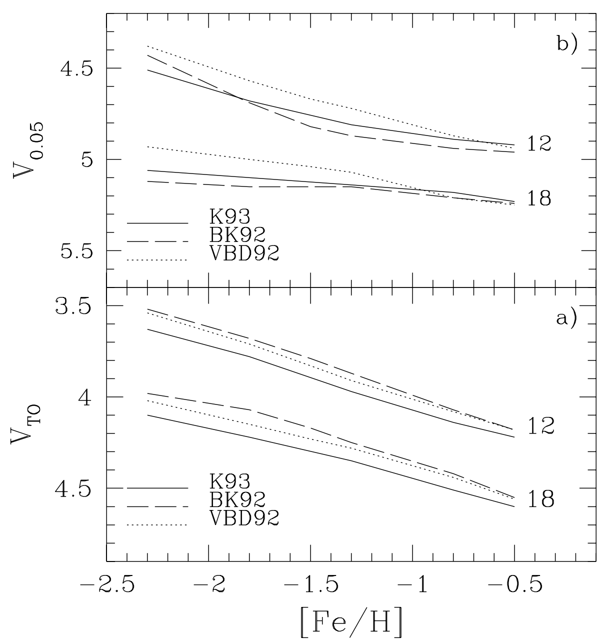

Fig. 5a and b. The TO (panel **a**) and the $V_{0.05}$ (panel **b**) luminosities derived from the SC96 isochrones, converted into the observational plane using three different temperatute–color and luminosity–magnitude transformations compared as a function of metallicity, [Fe/H]

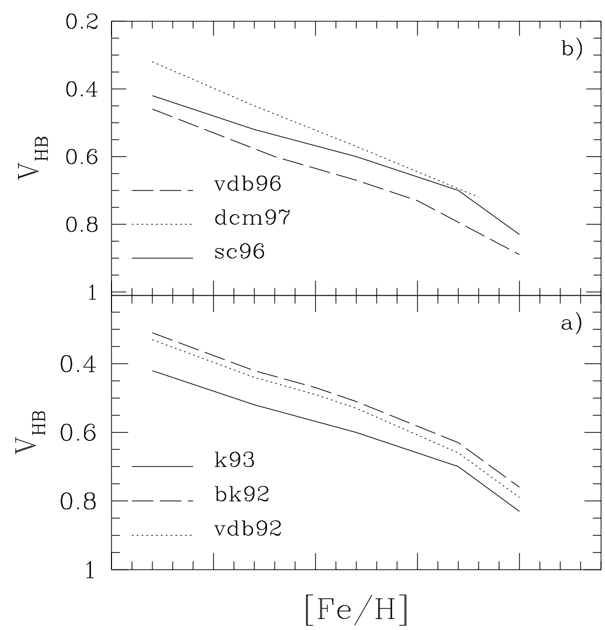

Fig. 6a and b. The luminosity of the HB at the RR–Lyrae color as a function of metallicity: **a** SC96, DCM97 and VDB96 models, **b** SC96 models (transformed with K93, BK92 and VDB92). The slope of the M_V^{HB} vs [Fe/H] function varies with the models, the zero–point changes also with the adopted transformations

metal abundance may undermine the quasi–independence of $\Delta V^{0.05}$ from the metallicity. To check this point we computed specific models using the same code as SC91 and obtained that for Z=0.001 and t=16 Gyr, $\Delta V^{0.05}$ varies from 4.960, to 4.980 and to 5.013 mag, with α varying from 2.0, to 1.6 and 1.0, respec-

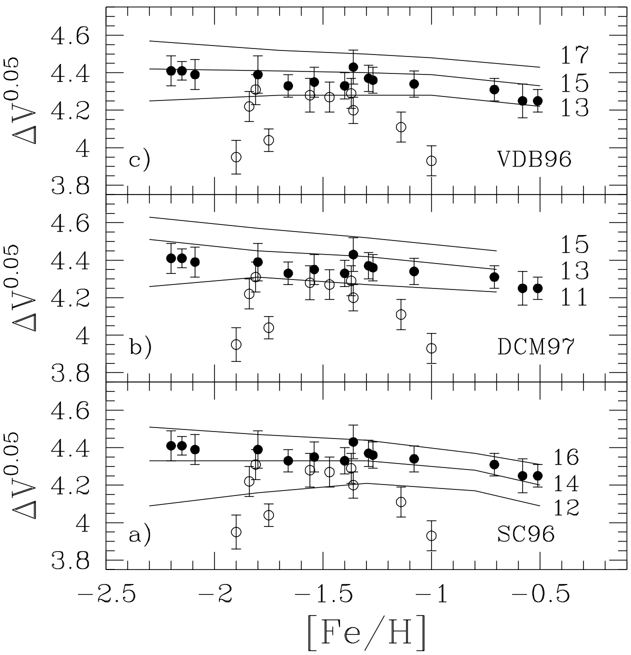

Fig. 7a–c. $\Delta V^{0.05}$ for 24 clusters superimposed to a theoretical calibration grid derived from **a** SC96, **b** DCM97 and **c** VDB96. The transformations are those by K93. The clusters have been selected according to the requirement of having a well–populated horizontal portion of the HB. The bulk of the clusters turn out to be confined in a quite narrow age range, with only a few clusters clearly younger than the average. Note the 14 clusters (marked as full dots) located within a 2 Gyr strip in all the calibrations

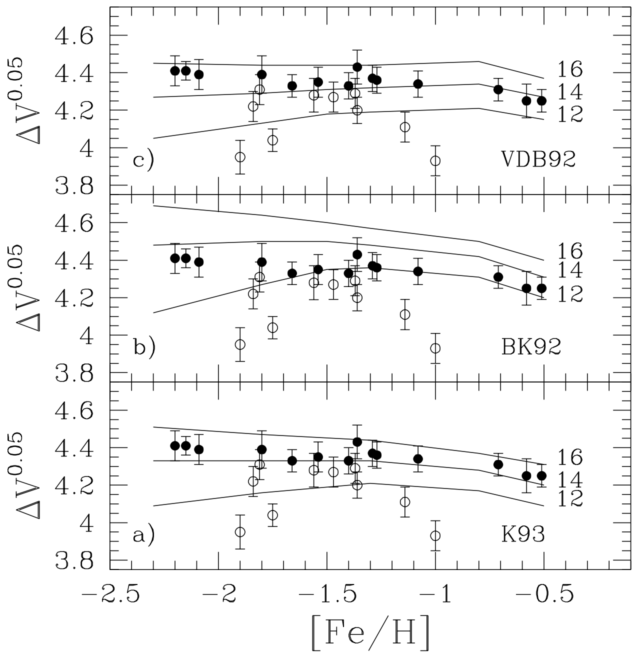

Fig. 8a–c. The effect of different color–transformations on the theoretical calibrations of $\Delta V^{0.05}$ derived from SC96. The position and the shape of the calibration–grid show some variations, but it is always possible to select the same sample of 14 clusters, included within a 2 Gyr strip

tively. In turn, having fixed all the other quantities, the *largest* expected difference in age due to mixing-length variations is of only 0.5 Gyr.

As regards the effect on $\Delta V^{0.05}$ of possible enhancements of the α–elements, from the models of Salaris, Chieffi & Straniero (1993), one gets a maximum variation of $\sim$ –0.7 Gyr with an overabundance of +0.3 dex in the α-elements at the low metallicity tail ([Fe/H] $\sim$ -2.3), and the difference decreases progressively with increasing metallicity.

Variations of the primordial helium content have an important effect on the $\Delta V^{0.05}$ parameter as well as on ΔV_{HB}^{TO} . In fact, changing Y one gets sizeable differences in V_{HB} but small variations of $V_{0.05}$, and therefore $\Delta V^{0.05}$ varies significantly. By theoretical isochrones computed at different Y, we have obtained $\Delta V^{0.05}$ / Δ Y $\sim$ 2. Hence, ΔY~ 0.05 mimics a difference in age of about 1 Gyr. However, since the available estimates of Y in GGCs indicate a constant primordial helium for all the GGCs within ΔY< 0.03 (Buzzoni et al. 1983), then the dependence of $\Delta V^{0.05}$ on Y should be actually negligible.

3. The data

3.1. The cluster sample

For a practical application of this method we have selected from the literature the GGCs for which high precision CMDs exist for both the TO *and* the HB regions. In particular, we have restricted the sample to clusters having a well populated HB at the TO color to avoid any contamination due to uncertain extrapolation of the actual HB luminosity level. Such an assumption strongly limitates the extension of the sample, but it is useful to make the whole procedure as straightforward as possible.

As horizontal age–parameter we will use here $\Delta_{RGB-TO}^{(B-V)}$ the difference between: 1) the color of the RGB at a luminosity level 2.5 mag brighter than the MS point which is 0.05 mag redder than the TO; 2) the color of the TO point. Such a parameter can be read on the CMD and can be measured for each cluster, independently of the HB morphology. It is a function of the cluster age, but also of the cluster metallicity, as discussed by VBS which used exclusively it in differential form and in narrow metallicity boxes.

Concerning the estimates of the various quantities deduced from the CMDs and involved in the definition of the age–parameters $\Delta V^{0.05}$ and $\Delta_{RGB-TO}^{(B-V)}$ with their associated errors, we are in presence of different situations:

1. Clusters for which the photometric data of the CMD are available to us in machine–readable form. These clusters have been marked with the label CMD in the *"source"* column of Table 1.
   For them, a statistical analysis of the distribution of the stars in the various CMD sequences allows a quantitative determination of the observational uncertainties associated to the measured quantities (V_{HB} ,$V_{0.05}$,$(B-V)_{TO}$ and $(B-V)_{RGB}$). The associated errors have been calculated following the procedure described by VBS (see their Sect. III and

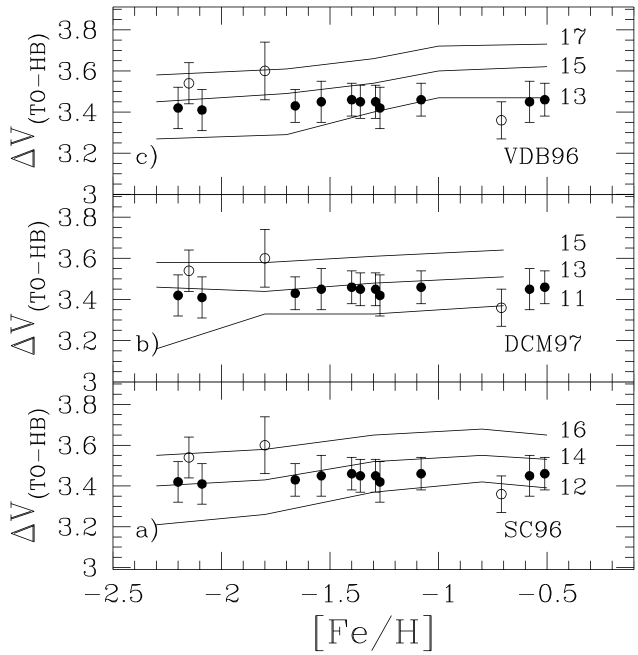

Fig. 9a–c. The observed ΔV_{HB}^{TO} of the 14 clusters selected in Fig. 7 and Fig. 8 superimposed to the calibration of ΔV_{HB}^{TO} derived from the SC96 and DCM97 models. Though there is some dispersion (possibly due to observational difficulties in deriving ΔV_{HB}^{TO}), yet 11 out of the 14 clusters selected with the procedure described at Sect. 3.2 (and Fig. 7,8) can still be considered "coeval" within the uncertainties

Table III) as we already did in previous papers (Buonanno et al. 1993 and Buonanno et al. 1995). Shortly, the errors have been estimated from the scatter of the stars with respect to the parabolic arc best fitting the considered CMD sequences.

2. Clusters for which the photometric quantities have been read on the published mean–ridge–lines. These clusters are identified by a label MRL in column 7 of Table 1.
   For these clusters, it is impossible to give a quantitative measure of the errors, so we are forced to adopt just educated estimates. To this aim, we based our estimates mainly on the similarity of the CMDs to clusters for which a machine-readable data-base is available.

The errors in $\Delta V^{0.05}$ have been obtained by combining the estimated errors in V_{HB} and V_{TO} . The *formal* errors in $\Delta^{(B-V)}_{RGB-TO}$ for the clusters with CMDs in machine–readable form turned out to be always less than 0.01 mag. Thus we adopted an error of 0.01 mag for all the $\Delta^{(B-V)}_{RGB-TO}$ entries in Table 1.

Before proceeding, some further notes must be added for the metal rich GGCs ([Fe/H] > -1): it is well known that for the most metal rich GGCs the HB collapses to a red clump of stars which is slightly brighter (by a quantity $\Delta V_{HB}^{rich} \sim 0.06 - 0.10$mag) than the average luminosity of the RR Lyrae variables located at the center of the instability strip and used to measure $\Delta V^{0.05}$ (see Sarajedini et al. 1995, Ajhar et al. 1996, Catelan and de Freitas Pacheco 1996, for discussion and references). Following the above authors, we have considered a correction $\Delta V_{HB}^{rich} = 0.07$mag to the values of the observed V_{HB} for the clusters with [Fe/H] > -1, as a compromise.

Most of the adopted metallicities come from the compilation by Zinn & West (1984), superseded and supplemented by Armandroff & Zinn (1988). For the young clusters we adopted the metallicities derived from the CMDs; therefore in Table 1 are reported: for Ruprecht 106 the estimate of Buonanno et al. (1993), for Arp 2 that of Buonanno et al. (1995b), for Terzan 7 the estimate of Buonanno et al. (1995a), and for IC 4499 that of Ferraro et al. (1995). The helium abundance Y has been assumed as constant at Y$= 0.23$ for all the clusters, according to Buzzoni et al. (1983).

A final caveat:

– We are aware that the *true* errors in the measured observables can be significantly larger, at least for some clusters. However, since our basic aim here is to present a procedure which can be improved with progressively improving the quality of the data-base, this would not undermine the overall approach.
– The same consideration can be applied to the adopted metallicity scale. In fact, it is well known that the scale of Zinn and West (1984) was at the state of the art at that time and deserves revisiting as for instance stated by Carretta and Gratton (1997). However, as noted by Rutledge et al. (1997), it is still unclear which scale could approximate the true [Fe/H] scale more closely. Therefore, we will use the scale of Zinn and West (1984) allover the paper, and the possible impact of a different adoption has to be evaluated subsequently.

A summary of the adopted observables is listed in Table 1 which contains:

1. the cluster identification;
2. the adopted metallicity;
3. the apparent V magnitude of the HB –V_{HB} – at the TO color;
4. the reference point $V_{0.05}$;
5. the magnitude difference $\Delta V^{0.05}$;
6. the color difference $\Delta^{(B-V)}_{RGB-TO}$ between thr RGB and the TO;
7. the source type of the data (machine–readable or mean–ridge–line);
8. the reference(s) to the adopted CMD(s).

3.2. *The sub-sample of clusters "coeval" within the uncertainties*

The observed $\Delta V^{0.05}$ values for the 24 clusters with appropriate HB reported in Table 1 have been plotted in Fig. 7 a, b, c superimposed on the calibration of $\Delta V^{0.05}$ in terms of the SC96 and DCM97 and VDB96 models. These values result restricted in a quite narrow range for the bulk of the clusters, independently of metallicity, with only 4–5 clusters showing clearly less–than–average values.

Table 1. Observables of 36 selected clusters

Cluster	$[Fe/H]$	V_{HB}	$V_{+0.05}$	$\Delta V^{0.05}$	$\Delta^{(B-V)}_{RGB-TO}$	*Source*	*CMDs References*
104	-0.71	14.14±0.06	18.45±0.02	4.31±0.06	0.291	MRL	Hesser et al. 1987
288	-1.40	....	....	....	0.250	MRL	Bolte 1992
362	-1.27	15.43±0.07	19.79±0.02	4.36±0.07	0.263	MRL	Harris 1982, Bolte 1987, VBS
1261	-1.29	16.70±0.06	21.07±0.04	4.37±0.07	0.261	MRL	Bolte & Marleau 1989
1851	-1.36	16.15±0.06	20.35±0.03	4.20±0.07	0.274	MRL	Walker 1992
1904	-1.68	....	....	....	0.248	CMD	Ferraro et al. 1992
2298	-1.81	....	....	....	0.219	MRL	Janes & Heasley 1988
2808	-1.37	16.19±0.07	20.48±0.03	4.29±0.08	0.270	CMD	Ferraro et al. 1990
3201	-1.56	14.74±0.08	19.02±0.04	4.28±0.09	0.243	MRL	Brewer et al. 1993
4147	-1.80	16.95±0.09	21.34±0.04	4.39±0.10	0.230	MRL	Friel et al.1987
4590	-2.24	15.64±0.08	20.03±0.02	4.39±0.08	0.224	MRL	McClure et al. 1987 , Brocato et al. 1994
5053	-2.20	16.70±0.08	21.13±0.02	4.41±0.08	0.223	MRL	Fahlman et al. 1991
5272	-1.66	15.67±0.06	20.00±0.02	4.33±0.06	0.249	CMD	Buonanno et al. 1994
5904	-1.40	15.11±0.06	19.44±0.03	4.33±0.07	0.250	CMD	Buonanno et al. 1981
6101	-1.81	16.46±0.08	20.80±0.02	4.31±0.08	0.239	MRL	Sarajedini & Da Costa 1991
6121	-1.36	13.50±0.07	17.93±0.03	4.43±0.08	0.248	CMD	Marconi et al. 1997, in preparation
6205	-1.65	....	....	....	0.250	MRL	Richer at al. 1986
6218	-1.61	....	....	....	0.250	MRL	Sato et al. 1989
6254	-1.60	....	....	....	0.244	MRL	Hurley at al. 1989
6341	-2.24	....	....	....	0.218	MRL	Stetson & Harris 1988
6352	-0.51	15.27±0.06	19.52±0.02	4.25±0.06	0.285	CMD	Buonanno et al. 1997 in preparation
6362	-1.08	15.34±0.06	19.56±0.03	4.34±0.07	0.264	CMD	Buonanno et al. 1997 in preparation
6397	-1.91	....	....	....	0.220	CMD	Alcaino et al 1987, Buonannno et al. 1989
6584	-1.54	16.55±0.07	20.00±0.04	4.35±0.08	0.248	MRL	Sarajedini & Forrester 1995
6752	-1.54	....	....	....	0.250	CMD	Buonanno et al 1986
6809	-1.82	....	....	....	0.225	MRL	Schade et al. 1988
6838	-0.58	14.51±0.08	18.75±0.04	4.25±0.09	0.293	MRL	Cudworth 1985, Hodder et al. 1992
7078	-2.15	15.86±0.05	20.27±0.02	4.41±0.05	0.212	MRL	Durrel & Harris 1993
7099	-2.13	....	....	....	0.217	MRL	Richer et al. 1988
7492	-1.51	....	....	....	0.241	CMD	Buonanno et al. 1987
Pal5	-1.47	17.40±0.07	21.67±0.03	4.27±0.08	0.266	MRL	Smith et al. 1986
Pal 12	-1.14	17.10±0.08	21.21±0.03	4.11±0.09	0.319	MRL	Stetson et al. 1989
Rup106	-1.90	17.90±0.07	21.85±0.03	3.95±0.08	0.261	CMD	Buonanno et al. 1993
Ter 7	-1.00	17.83±0.07	21.76±0.03	3.93±0.08	0.348	CMD	Buonanno et al. 1995a
Arp 2	-1.84	18.30±0.07	22.53±0.03	4.22±0.08	0.248	CMD	Buonanno et al. 1995b
IC4499	-1.75	17.63±0.05	21.67±0.03	4.04±0.06	0.241	CMD	Ferraro et al. 1995

We intend to use the clusters in Table 1 and Fig. 7 in order *to select a subsample of clusters to be considered "coeval" within the uncertainties, and then to derive differential ages for all the clusters in the sample*.

As a selection criterion we consider as coeval all the clusters which have the observable $\Delta V^{0.05}$ contained within the strip defined by the 14 and 16 Gyr isochrones in Fig. 7a. In particular, considering the 1σ error in $\Delta V^{0.05}$ reported in Table 1 and Fig. 7, we selected the clusters which have ages included between 14–16 Gyr with probability $P > 50\%$.

In other words, by adopting as "reference clock" the calibration of $\Delta V^{0.05}$ obtained by using the SC96 models for both MS and HB with the K93 transformations, we pick up the clusters in Fig. 7a which have a mean (absolute) age of 15 Gyr with a "clock read–out–noise" of 1 Gyr. Note that the quantity 1 Gyr is not the error in the estimate of the (absolute) age, but only the arbitrary confidence limit we adopted for the selection of "bona fide" *coeval* clusters.

Following the above criterion, we selected as "coeval" the following clusters: NGC 104 (47 Tuc), NGC 362, NGC 1261, NGC 4147, NGC 4590 (M68), NGC 5053, NGC 5272 (M3), NGC 5904 (M5), NGC 6121, NGC 6352, NGC 6362, NGC 6584, NGC 6838 and NGC 7078 (M15).

Now the question is: *is this sub-sample of claimed coeval clusters robust enough to survive as "truly" coeval with changing the reference clock (i.e. the theoretical models and/or the transformations)?*

A quick look at Fig. 7 *panel b,c* gives already a first answer: the use of the isochrones computed by DCM97 and VDB96 would lead to the selection of the same sub-sample of "coeval" clusters, the only difference being a systematic shift in the absolute age.

The three panels shown in Fig. 8 allow also to check the degree of compatibility of our selected sub-sample of 14 ”coeval” clusters (based on SC96 models and the K93 transformations) with alternative calibrations, where the transformations of VDB92 and BK92 are instead used. As already noted, both shape and position of the isochrones change with changing the color–transformations, but we can still claim that the 14 selected clusters can be considered coeval within the uncertainties, though the mean absolute age (the reference zero–point) is shifted.

From the above analysis, discussion and checks reported in Sect. 2.2–2.5, we are confident that the sub-sample of 14 clusters we have chosen can safely considered to be ”coeval” (as measured by the $\Delta V^{0.05}$ age-indicator) within the intrinsic ”read-out-noise” of $\pm$1Gyr, independently of the assumed theoretical clock.

3.2.1. A further check

We have also verified how these 14 clusters behave, using the classic vertical parameter ΔV_{HB}^{TO} . The ΔV_{HB}^{TO} values (estimated from the CMDs in Table 1) for these clusters are $3.36 \pm 0.09, 3.42 \pm 0.10, 3.45 \pm 0.08, 3.60 \pm 0.14, 3.41 \pm 0.10, 3.42 \pm 0.10, 3.43 \pm 0.08, 3.46 \pm 0.08, 3.45 \pm 0.08, 3.46 \pm 0.08, 4.46 \pm 0.08, 3.45 \pm 0.10, 3.45 \pm 0.10, 3.54 \pm 0.10$ for NGC104, NGC 362, NGC 1261, NGC 4147. NGC 4590, NGC 5053, NGC 5272, NGC 5904, NGC 6121, NGC 6352, NGC 6362, NGC 6584, NGC 6838 and NCG 7078, respectively.

Fig. 9 shows the calibration of ΔV_{HB}^{TO} obtained using the SC96 (*panel a*), DCM97 (*panel b*), and VDB96 (*panel c*) models, with the observed values of ΔV_{HB}^{TO} for the 14 clusters selected above superimposed to the grids.

It is readily evident that not all the selected ”coeval” clusters pass the ΔV_{HB}^{TO} – test. In fact only 11 out of 14 clusters still lie in the same ”two-Gyr-strip”, independently of the assumed model. The other 3 (NGC 104, NGC 4147, and NGC 7078) shows a spread in age as large as 4-5 Gyr as seen by the ΔV_{HB}^{TO} observable.

While it is expected that data-points are more spread out in the plane of Fig. 9 than in the $\Delta V^{0.05}$ *vs* $[Fe/H]$ plane because of the greater measurement errors associated with V_{TO} , such a large difference can hardly be accounted for given the adopted error bars. In our view there are only two possible explanations: *a)* there are systematic errors in the ΔV_{HB}^{TO} measures of the three “anomalous” clusters, or *b)* the errors have been largely underestimated. It is very difficult to discriminate between these different possibilities: both cases *a* and *b* cannot be easily excluded since the sources of the photometry are necessarily very hetherogeneous and a really exaustive check is impossible.

However, since the main purpose of this paper is to define a procedure to establish a general scale for the relative–age of galactic globulars and to explore all the possible problems connected with the definition of such a scale in general, independent of the adopted method, it seems useful to proceed for a further step in our route using just the 11 clusters which survived the ΔV_{HB}^{TO} –test, being at the same time aware of the uncertainties emerged till now.

Table 2. Relative ages

$Cluster$	$[Fe/H]$	$\Delta t_9(v)$	$\Delta t_9(h)$	Δt_9	R_g
104	-0.71	0.5±1.2	-1.0±2.0	-0.3±1.6	8.1
288	-1.40	....	0.4±2.0	0.4±2.0	12.1
362	-1.27	0.0±1.3	-0.4±2.0	-0.2±1.7	9.9
1261	-1.29	0.2±1.3	-0.3±2.0	-0.1±1.7	18.3
1851	-1.36	-2.7±1.2	-2.0±2.0	-2.4±1.6	16.5
1904	-1.68	....	-0.6±2.0	-0.6±2.0	19.5
2298	-1.81	....	2.0±2.0	2.0±2.0	16.2
2808	-1.37	-1.3±1.3	-1.6±2.0	-1.5±1.7	11.6
3201	-1.56	-1.4±1.3	0.5±2.0	-0.5±1.7	9.5
4147	-1.80	0.0±1.5	0.8±2.0	0.4±1.8	19.9
4590	-2.09	-0.1±1.0	0.2±2.0	0.1±1.6	10.1
5053	-2.20	0.2±1.0	-0.1±2.0	0.0±1.6	17.4
5272	-1.66	-0.8±1.0	-0.6±2.0	-0.7±1.6	12.6
5904	-1.40	-0.7±1.2	0.4±2.0	-0.1±1.6	6.6
6101	-1.81	-1.1±1.1	-0.2±2.0	-0.6±1.6	11.6
6121	-1.36	1.1±1.3	0.8±2.0	0.9±1.7	6.4
6205	-1.65	....	-0.7±2.0	-0.7±2.0	8.9
6218	-1.61	....	-0.4±2.0	-0.5±2.0	5.0
6254	-1.60	....	0.2±2.0	0.2±2.0	5.3
6341	-2.24	....	0.2±2.0	0.2±2.0	9.8
6352	-0.51	0.1±1.1	0.5±2.0	0.3±1.6	3.4
6362	-1.08	0.0±1.4	0.3±2.0	0.1±1.7	5.5
6397	-1.91	....	1.4±2.0	1.4±2.0	6.9
6584	-1.54	-0.5±1.2	-0.0±2.0	-0.2±1.6	6.9
6752	-1.54	....	-0.2±2.0	-0.2±2.0	5.9
6809	-1.82	....	1.3±2.0	1.3±2.0	4.7
6838	-0.58	-0.2±1.6	-0.7±2.0	-0.4±1.8	7.4
7078	-2.15	0.2±0.9	1.3±2.0	0.7±1.5	10.4
7099	-2.13	....	0.8±2.0	0.8±2.0	7.2
7492	-1.51	....	0.9±2.0	0.9±2.0	18.7
Pal 5	-1.47	-1.6±1.2	-1.6±2.0	-1.6±1.6	16.5
Pal 12	-1.14	-4.0±1.6	-5.9±2.0	-4.9±1.8	16.0
Rup106	-1.90	-3.5±1.0	-2.9±2.0	-3.2±1.6	23.5
Ter 7	-1.00	-6.7±1.2	-8.4±2.0	-7.6±1.7	28.4
Arp 2	-1.84	-2.0±1.0	-1.3±2.0	-1.6±1.6	20.4
IC4499	-1.75	-3.4±1.0	-0.1±2.0	-1.8±1.6	14.9

3.2.2. The basis for a temptative relative–age scale

We can select above a sample of clusters of different metallicity, which are *coeval within* $\pm$1*Gyr*. The relative ages finally adopted for the GGCs listed in Table 1 (and having a measured $\Delta V^{0.05}$) are reported in Table 2, column 3. They have been determined by using as reference the isochrone grid presented in Fig. 7 *panel a* and by computing (at the [Fe/H] value adopted for the cluster) the residual with respect to the 15 Gyr isochrone, taken as ”0–age” reference line. The errors reported in Table 2 have been determined transforming the $\Delta V^{0.05}$ error bars into δt_9 using the procedure described above, with no allowance for errors in [Fe/H] .

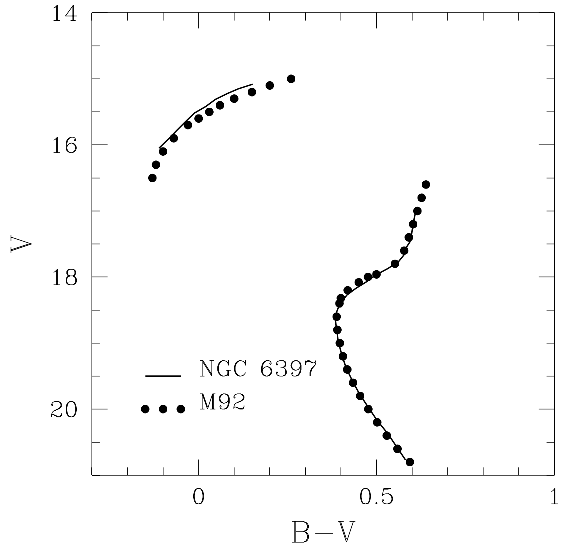

Fig. 10. Comparison of M92 fiducial ridge lines for the main sequence (Stetson & Harris 1988) and horizontal branch (Buonanno et al. 1985) with the corresponding ones of NGC 6397 (Buonanno et al. 1989, Alcaino et al. 1987). The latter were registered to the former by adding to the observed magnitudes and colors $\Delta V = +2.17$ mag and $\Delta(B-V) = -0.168$ mag. The abscissa and ordinate zero-points correspond to the M92 turnoff color (B-V)$_{TO}$=0.388 and V$_{0.05}$ =19.64. Even if the overall coincidence of the two fiducial main sequences seems to indicate a similar age, it appears a clear vertical displacement between the HBs. This can be interpreted as due to age differences (see Sect. 4.1)

Since we now "know" that these clusters turn out to be coeval based on the vertical method, we can use them as reference grid to calibrate the horizontal method, overcoming so (at least partially) some of its major drawbacks.

4. An empirical calibration of $\Delta^{(B-V)}_{RGB-TO}$ vs [Fe/H]

4.1. Problematic aspects of the "horizontal" method

The main advantage of the age parameter $\Delta^{(B-V)}_{RGB-TO}$ (VBS, SD, SC91) is that it can be applied to any cluster having a good photometry in the TO region, irrespective of its HB morphology.

Nevertheless, this method presents some disadvantages, the most important being a large dependence on metallicity of the colors of the two reference points (located at the main sequence TO and on the RGB) and, in turn, of their difference $\Delta^{(B-V)}_{RGB-TO}$.

This intrinsic weakness of the method has been widely recognized, and even its proposers (VBS, SD) recommended not only to apply this procedure to study just *relative* ages, but also to restrict the direct comparisons to clusters having *the same* metallicity (within the current measuring errors $\sim \pm 0.2$dex in [Fe/H]). In particular, VBS grouped the GGCs into "metallicity boxes", but often the CMDs are hardly comparable and the claimed age differences could also be interpreted as due to a difference in metallicity.

An example of this problem is shown in Fig. 10, where we report the fiducial sequences of M92 (Stetson & Harris 1988) compared with those of NGC 6397 (Buonanno, Corsi & Fusi Pecci 1989). The ridge lines of the two clusters have been registered following the procedure of VBS (in their Fig. 4 *panel c*). In particular, NGC 6397 has been shifted by +2.17 mag in V and -0.168 mag in B-V. As can easily be seen from Fig. 10, while the MS, the TO and the SGB of M92 and NGC 6397 are fully overlapping, the two HBs show a clear displacement. Hence, the conclusion drawn for instance by VBS that the two clusters are *coeval within 0.5 Gyr based on the identity of the parameter* $\Delta^{(B-V)}_{RGB-TO}$ is hardly supported at this level of accuracy by the comparison of the whole CMDs.

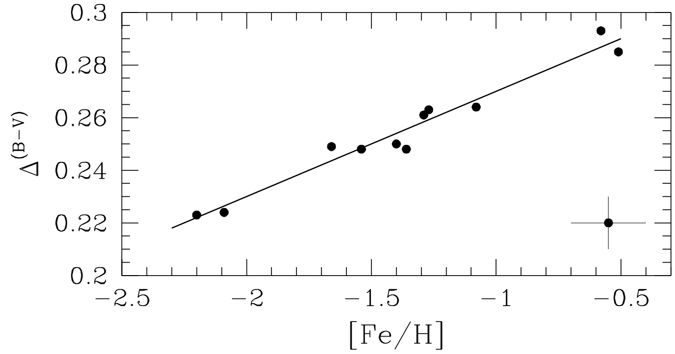

Fig. 11. The observed horizontal parameter $\Delta^{(B-V)}_{RGB-TO}$ as a function of [Fe/H] for the 14 clusters selected as "coeval" on the basis of $\Delta V^{0.05}$ (see Sect.3.2). A linear best fit is also reported (*full line*). The cross at the bottom-right shows the typical error for the two observables

In our view, an alternative interpretation of this inconsistency is that, since M92 and NGC 6397 are different enough in metallicity ([Fe/H] =-2.24± 0.15 and [Fe/H] =-1.91± 0.15, Zinn 1985), then the coincidence of the $\Delta^{(B-V)}_{RGB-TO}$ parameters would actually imply an age difference of ~ 1.5 Gyr, as indicated also by the HB luminosity displacement. Such a conclusion is moreover strengthened by its independence of the adopted theoretical models.

It is therefore evident that without a procedure able to calibrate the dependence of $\Delta^{(B-V)}_{RGB-TO}$ on metallicity, it is almost impossible to build up a self-consistent and reliable *relative* age scale.

4.2. The new calibration

In order to overcome the above limitations, we suggest to use the sub-sample of clusters we found to be "coeval" based on the metallicity independent $\Delta V^{0.05}$ -method (and that passed the ΔV^{TO}_{HB} -test; see sec. 3.2.1), to calibrate the actual dependence of $\Delta^{(B-V)}_{RGB-TO}$ on metallicity. If reliable, such a "direct" calibration (note that the ages are now assumed to be *known* independently) will allow (a) to know experimentally the dependence of the parameter $\Delta^{(B-V)}_{RGB-TO}$ on metallicity, (b) to determine age differences for clusters of any metallicity using the same calibrated scale, once the metallicity is ascertained. Moreover, such a procedure links in a self-consistent approach the two traditional "vertical" and "horizontal" methods for GGC dating

($\Delta V^{0.05}$ and $\Delta^{(B-V)}_{RGB-TO}$). The main step in this procedure is the selection of the "known calibrating" clusters discussed in Sect. 3.2 above.

In Fig. 11 it is reported a plot of the individual $\Delta^{(B-V)}_{RGB-TO}$ parameters *vs* [Fe/H] for the 11 calibrating clusters. A linear best fit to the data of the adopted calibrating clusters (the *full line* in Fig. 11) yields:

$$\Delta^{(B-V)}_{RGB-TO} = 0.040(\pm 0.005)[Fe/H] + 0.310(\pm 0.008) \quad (1)$$

Although the number of calibrating objects is small and the coverage of the metallicity range still poor, it is reassuring that the quality of the fit is good enough to define a clear-cut correlation, whose quality will be easily improved by further data of clusters with independent relative age estimates, or by the availability of more accurate measures for the same objects.

The knowledge of the value of the slope estimated in Eq. (1) immediately allows one to estimate the errors involved in the determination of relative ages with $\Delta^{(B-V)}_{RGB-TO}$ due to the observational uncertainties in the metallicity [Fe/H] : a typical error in [Fe/H] of ± 0.2 dex reflects into an indetermination of about ± 0.008 mag in $\Delta^{(B-V)}_{RGB-TO}$ and, in turn, about $\pm$ 1 Gyr in the relative age.

4.3. *Comparison with the theoretical models: there is a discrepancy*

Supposing that the *relative* ages adopted as *known calibrators* for the coeval sub–sample are correct, it is useful to compare the *empirical* isochrone defined by the coeval sub–sample in the $\Delta^{(B-V)}_{RGB-TO}$ vs. [Fe/H] plane with the corresponding *theoretical* isochrones.

Fig. 12 displays the "constant-age" loci as derived from the models (*dashed lines*) computed by SC96 (panel a), VDB96 (panel b) and DCM97 (panel c), all based on K93 transformations. This figure shows how *the isochrones are generally different either in the zero–point (absolute age), either in the dependence on metal content*. The discrepancy is even more evident looking at Fig. 13, 14 and 15, where the calibrations obtained from the models of SC96, DCM97 and VDB96 transformed following K93, BK92 and VDB92 are compared to the *empirical* isochrone and the GGC data. As can be seen, the transformations have a very strong impact on the comparison. In particular, the 11 calibrating clusters could be "coeval" or even different in age (up to 5 Gyr) depending on the adopted set of models+transformations.

In fact, there is no combination of models and/or transformations able to yield $\Delta^{(B-V)}_{RGB-TO}$ values truly consistent with the previous conclusion that the 11 calibrating clusters are coeval within the quoted uncertainties. One could also note (see Fig. . 12 – 15) that in many cases the observed $\Delta^{(B-V)}_{RGB-TO}$ values do not *match* the theoretical grids, i.e. observations and theoretical predictions strongly disagree also in an absolute sense.

Why do the empirical and theoretical calibrations behave so differently?

In our view there are essentially only two possible answers:

1. The clusters we have adopted to be "bona-fide" age calibrators (based on the vertical, differential methods) are actually non-coeval (i.e. they differ in age by more than 2 Gyr), and, consequently, the linear locus traced in Fig. 11 – 15 is not an *empirical* isochrone. If this is the case, one has to admit that the measurement errors of the vertical age parameters are, on average, greater than assumed, or that the calibrations of the same parameters are in error by a similar amount.
2. If the adopted calibrating clusters are actually coeval within 2 Gyrs, then the theoretical models are somehow wrong, and in particular the scaling of the tracks in the observational plane with varying metallicity would be called into question.

A truly safe choice between the two alternatives can hardly be done at this stage, as the uncertainties affecting the estimates of the relative ages using the vertical methods are still large and, moreover, their calibrations depend on the the theoretical models. However, it is important to note that, while the vertical method rests only on model luminosities (*i.e.* on nuclear burning), the horizontal parameters obtained from the theoretical tracks depend on various uncertain quantities, like the mixing length, the color-temperature transformations, etc. and it is conceivable that errors (varying in size with varying metallicity) can still affect the final horizontal scaling of the tracks in the observational plane.

On the other hand, the existence of such a difficulty to compare horizontal parameters measured from the CMD of clusters having largely different [Fe/H] was clearly pointed out also by the proposers of the "horizontal" method. For instance, VSB note that "it seems unlikely that the predicted variation of $\Delta^{(B-V)}_{RGB-TO}$ with metallicity can be quantitatively correct. Consequently, we recommend that our procedure be applied only to clusters that have the same [m/H] values to within current measuring errors, namely $\sim \pm 0.2$dex".

In conclusion, unless the ages estimated from the vertical method for the 11 calibrating clusters are grossly in error, it seems evident that the comparison of the observational data in the planes $\Delta V^{0.05}$ vs. [Fe/H] and $\Delta^{(B-V)}_{RGB-TO}$ vs. [Fe/H] with the theoretical isochrones leads to a disagreement, worth of further analysis.

This fact carries further support to our approach: given the many problems and uncertainties associated with the theoretical modeling of the $\Delta^{(B-V)}_{RGB-TO}$ *vs* metallicity relation, an empirical calibration based on the most robust "vertical methods" can ultimately prove to be very fruitful, in perspective, to derive a reliable relative–age scale encompassing the whole Galactic globular cluster system. At the same time this procedure can be useful in constraining the models themselves.

In order to show how such a calibration can be obtained and used to derive an age scale, we complete the proposed pipeline in the following sections. Before proceeding, we note that, though based on only 11 clusters and affected by several possible uncertainties (discussed above), our method will yield a scale for the relative ages very similar to those recently obtained by using the "vertical-method" (CDS96) or the "horizontal-method"

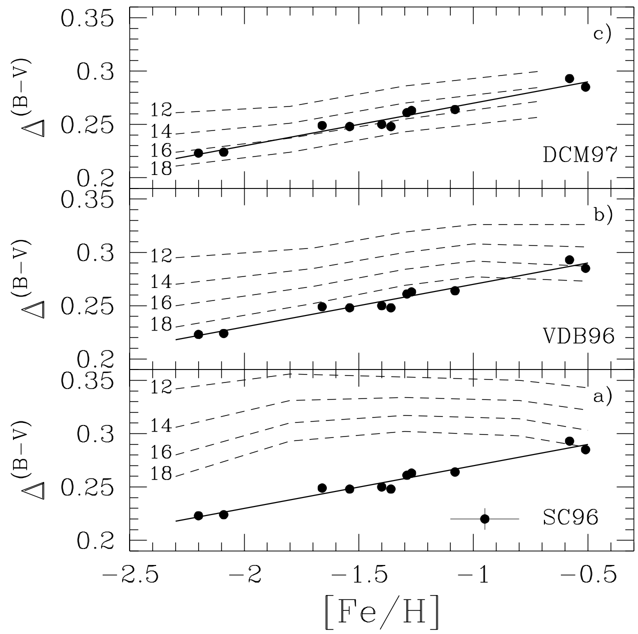

Fig. 12a–c. The "empirical isochrone" in the plane $\Delta^{(B-V)}_{RGB-TO}$, [Fe/H] of Fig. 11 compared to the theoretical calibration grids derived from three different isochrone–sets, all transformed to V, B-V using K93. As can be seen, the overall agreement between the empirical and the theoretical calibrations of ΔV^{TO}_{HB} is poor in any case

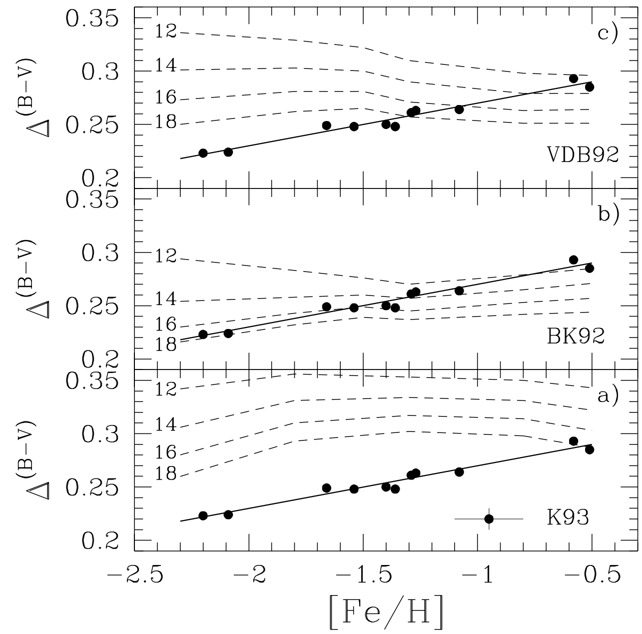

Fig. 13a–c. The effect of varying the temperature–color and luminosity–magnitude transformations on the theoretical calibration of ΔV^{TO}_{HB} . The SC96 models transformed following K93, BK92 and VDB96 are used to build the calibration grids reported in the three panels *dashed lines*. As expected both position and shape of the theoretical isochrones are strongly affected by the choice of the transformation. Yet, in no case there is a satisfactory agreement with the "empirical isochrone"

(Richer et al.1996) (see Sects. 4.6 and 4.7). In our view, such an agreement shows that:

1. The present method already gives performances not worse than the "traditional" ones, and the semi-empirical calibration on which is based can be improved also without having a corresponding significant improvement in the detailed models.
2. One can hardly assume that any of the relative–age scales available in the literature so far can actually yield ages to better than ~ 2 Gyr allover the full metallicity range. In fact, only age differences between couples of clusters sharing the same metal content can be obtained at a higher precision level (1 Gyr), but they cannot then been grouped together to yield a homogeneous scale.

4.4. A possible extension of the calibration: just an example

As noticed at the end of Sect. 3.2, from the analysis of $\Delta V^{0.05}$ only a few clusters are significantly younger than the bulk, namely Pal 5, Pal 12, Ru 106, Terzan 7, Arp 2, NGC 1851 and IC 4499. This sample of young clusters, though well distributed in metallicity, is admittely too scanty to perform an accurate *empirical calibration* of the $\Delta^{(B-V)}_{RGB-TO}$ parameter in terms of age.

However, it is worth checking whether the two indicators, $\Delta V^{0.05}$ and $\Delta^{(B-V)}_{RGB-TO}$, give consistent indications on the relative age of the objects considered in Table 1 and not included in the group of the 11 coeval calibrating clusters. To this aim, we use the "young" clusters in order to derive an "empirical guess" for the dependence of $\Delta(\Delta^{(B-V)}_{RGB-TO}$) *vs* Δage in the $\Delta^{(B-V)}_{RGB-TO}$ – [Fe/H] plane.

Before proceeding, we have also to note that the sample of young calibrating clusters cannot include IC 4499 as the available CMD (Ferraro et al. 1994) presents an intrinsic inconsistency between the two age parameters. In fact, the cluster turns out to be ~ 4 Gyr younger than the average using ΔV^{TO}_{HB} , and nearly coeval to the average using $\Delta^{(B-V)}_{RGB-TO}$. No simple explanation seems to be viable at this stage, further observations are urged.

Adopting for the 6 remaining young clusters the differential age obtained through the vertical parameter, we computed for each cluster the ratio $\delta/\Delta t_9$, where δ indicates the algebrical residual between the observed parameter $\Delta^{(B-V)}_{RGB-TO}$ and the "coeval expected" one computed by inserting the relevant [Fe/H] in Eq. (1). By averaging over the six considered clusters we derive the slope:

$$\delta/\Delta t_9 = -0.0093 \pm 0.0028\ \mathrm{mag/Gyr} \qquad (2)$$

The numerical value of the empirical slope in Eq. 2 is very close to the figures derived by VBS and SC91 from their models. However, we have now obtained a *direct, observational* constraint which allows one to adopt a given set of models+transformations. So doing, $\Delta^{(B-V)}_{RGB-TO}$ can be fruitfully

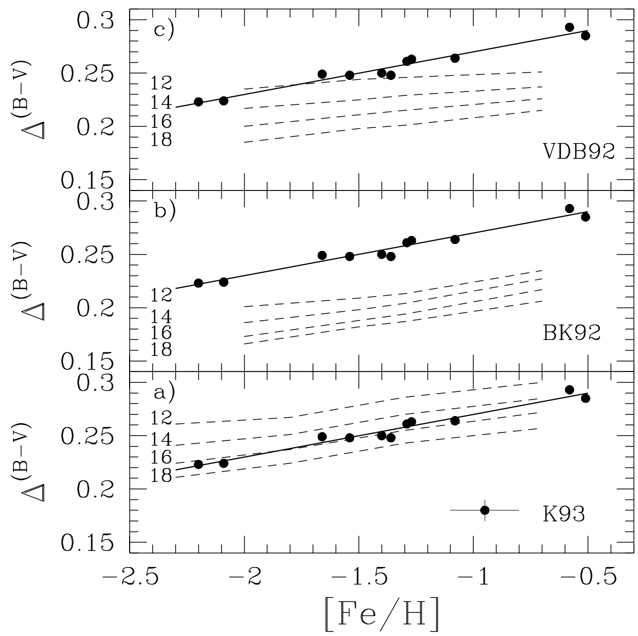

Fig. 14a–c. The DCM97 models are used to derive the calibration grids reported as *dashed lines* in the three panels for different temperature-color transformations. As in Fig. 12 and Fig. 13, the agreement between the theoretical and the empirical isochrones is poor, independent of the adopted choice

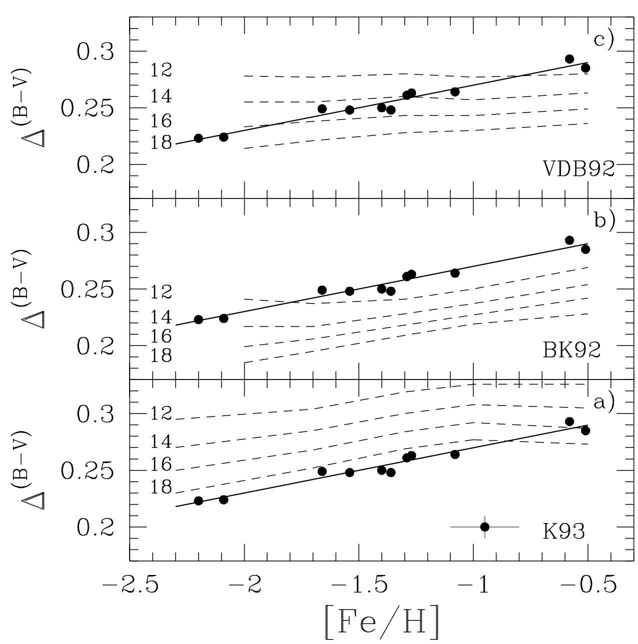

Fig. 15a–c. The case of the ΔV_{HB}^{TO} calibration using the VDB96 models converted into the observational plane with different trasformations is presented in the three panels. The agreement with the empirical calibration is still not satisfactory as in the previous plots

used as a differential age parameter (provided that a proper calibration of its dependence on metallicity has been obtained!).[2]

[2] In fact, the slope in Eq. (2) has been verified only for clusters *younger* than the bulk of the others. Existing data, however, do not allow one to yield a direct check for clusters which are simmetrically *older*. Since old clusters predominantly display Blue HBs (and thus cannot be safely dated using the vertical parameter Δ $V_{0.05}$), it is likely that this lack of data will will not be recovered in the future. Therefore in the following discussion we assume that the slope empirically found for the younger clusters is also valid for the simmetrically older clusters.

In Fig. 16 the $\Delta_{RGB-TO}^{(B-V)}$ of all the clusters in Table 1 have been reported on a "differential–age" grid constructed with the *empirical "0–age" isochrone* of Fig. 11 (*full line*) and the ± 2 Gyr isochrones obtained from the eq (2) (*dashed lines*). The bulk of the clusters sample is confined in the strip ± 2 Gyr, with only a few clusters turning out to be younger than the average. It is noticeable the existence of a spread out of the data, perhaps greater than in Fig. 7, where the $\Delta V^{0.05}$ parameter is adopted. This dispersion can be ascribed to two main reasons: the errors in the measure of the two adopted observables (note that 1–σ errors are always reported in any figure), or the existence of a "true" difference in the relative ages (note also that the sample of clusters in Fig. 16 is about 30% richer than in Fig. 7).

Given the global uncertainties, it is difficult to choose for each individual cluster which might be the dominating factor that causes the observed deviation from the *empirical* isochrone.

However, combining Eqs. (1) and (2) we obtain the final calibration:

$$\Delta t = -107.5\Delta_{RGB-TO}^{(B-V)} + 4.3[Fe/H] + 33.3 \quad (3)$$

This Eq. (3) yields *relative* ages for all the clusters with known metallicity [Fe/H] and color–difference $\Delta_{RGB-TO}^{(B-V)}$, as calibrated using the whole procedure described so far. The relative ages determined for all the clusters in Table 1 using Eq. (3) are reported in column 4 of Table 2. Given the actual uncertainties in the whole procedure, we estimated that the relative ages so obtained can be calculated with an accuracy not better than ± 2 Gyr.

We want to stress here that, in deriving Eq. (3), the theoretical models have been used to define the properties of the luminosity–difference parameter $\Delta V^{0.05}$, to select a subsample of coeval clusters, and to derive the relative ages of 6 well-known young clusters. Therefore, *the whole procedure leading to Eq. (3) rests on the reliability of the TO luminosities as predicted by the models*. The uncertainties in the temperatures and colors typical of the isochrones do not affect the above conclusions and the reliability of the coefficients in the equations above can be improved by increasing the accuracy in the determination of the three involved observables: $\Delta V^{0.05}$, $\Delta_{RGB-TO}^{(B-V)}$ and [Fe/H] .

4.5. A consistency check

It is possible to carry out consistency checks of the above procedure by simply comparing the relative ages obtained using both considered CMD age–parameters.

In Fig. 17, the relative ages obtained through the vertical parameter $\Delta V^{0.05}$ are plotted against the relative ages obtained

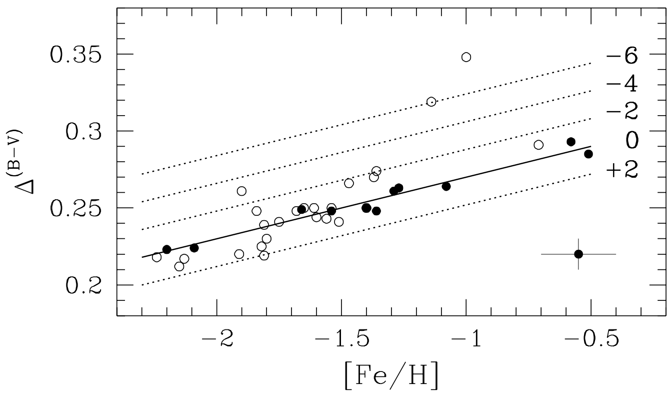

Fig. 16. The observed $\Delta^{(B-V)}_{RGB-TO}$ for all the clusters in Table 1 as a function of [Fe/H] . The *full line* (labeled "0") is the best fit to the coeval clusters *full dots* and the *dotted lines* are the *relative–age* isochrones, empirically calibrated with the $\Delta V^{0.05}$ of the young clusters. This represent the *empirical* calibration for the relative ages we adopt. Using this locus for each cluster with known $\Delta^{(B-V)}_{RGB-TO}$ and [Fe/H] , it is possible to derive a differential age with respect to the adopted zero–age reference line

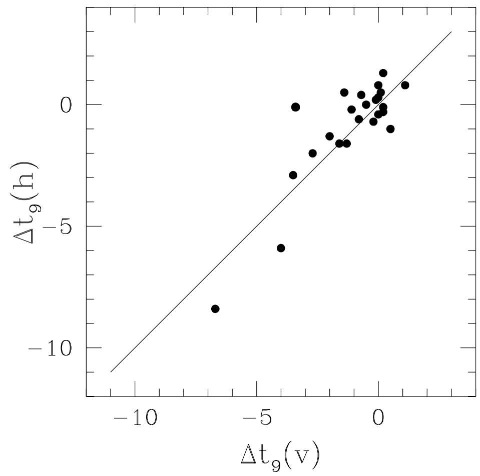

Fig. 17. The relative ages obtained using two different CMD observables (the magnitude difference $\Delta V^{0.05}$ and the color difference $\Delta^{(B-V)}_{RGB-TO}$) are consistent within $\sim$ 1.5 Gyr. The RMS deviation of the 24 points from the 1–to–1 line reported in the figure is 1.1 Gyr. The three exception IC 4499, Palomar 12 and Terzan 7 are discussed in the text (Sect. 4.5)

using the horizontal parameter $\Delta^{(B-V)}_{RGB-TO}$. Of course, the clusters with just blue HB, for which we estimated the age only via the color–difference, are not reported. The relative ages, evaluated using the two methods are in agreement within $\pm$ 1.5 Gyr for the vast majority of the clusters, and most of the younger clusters are confirmed to be so by both methods.

There are only three clusters for which the two age determinations differ by (slightly) more than 2 Gyr: the first is IC 4499 already discussed above, the remainig two are the young metal–poor clusters Palomar 12 and Terzan 7.

The discrepancy resulting for Palomar 12 and Terzan 7 may be originated by the poorly-sampled linear approximation of the Δt_9 vs δ relationship described via Eq. (2). For instance, the differential age loci plotted as *dashed–lines* in Fig. 16 could differ from straight lines, parallel to the zero–age locus. Alternatively, the observed discrepancy could be due to an erroneous estimate of [Fe/H] or to a peculiar distribution in the abundance ratios of the heavy elements, affecting the "horizontal" age determination.

Concerning this last possibility, as already noted by Armandroff and Da Costa (1991) and Buonanno et al. (1995b), there is a significant disagreement between the metal abundance derived from the spectroscopic determinations using the Ca-triplet ([Fe/H] ~ -0.5) and other estimates (for instance from CMD morphology, [Fe/H] ~ -1) for the young metal–rich clusters Pal 12 and Terzan 7. If their metallicity is actually very high, the age discrepancy noticed in Fig. 17 could partially disappear.

Another result emerging from the data in Table 2 and Fig. 17 concerns the classic "second-parameter couple" NGC 288 and NGC 362. In fact, based on the present results, the ages of these two objects commonly presented as the typical example of the existence of a significant age spread among Galactic globulars (Bolte 1989, Green and Norris 1990, but see Catelan and de Freitas Pacheco 1994), would be quite similar ($\Delta t < 1$ Gyr). As already argued by VBS, who carefully compared the CMDs of these two clusters using the $\Delta^{(B-V)}_{RGB-TO}$ method, a difference in [Fe/H] slightly larger than adopted ([Fe/H] =-1.27 for NGC 362 and [Fe/H] =-1.40 for NGC 288, Zinn 1985) could be (at least partially) responsible for the $\sim$ 0.015 mag difference in $\Delta^{(B-V)}_{RGB-TO}$.

The relative ages we finally adopted are listed in column 5 of Table 2. In particular, we decided to adopt the age resulting from Eq. (3) for the blue–HB clusters and the average of the "vertical" Δt_9 (column 2 of Table 2) and the "horizontal" Δt_9 (column 3 of Table 2) for the red–HB clusters. The errors adopted in column 5 of Table 3 are the combination of the errors in the two averaged estimates.

4.6. *Adopted ages and comparison with other recent age determinations*

Confirming the continuous interest devoted to the determination of both the absolute age and the formation time–scale of the Milky Way, there have been a number of recent papers specifically analysing the current status of the issue (see Stetson, VandenBerg and Bolte 1996, for review and references). Therefore, it may useful to briefly compare our results with other age scale determinations.

To this aim, we selected the very recent lists presented by Chaboyer, Demarque & Sarajedini (1996; hereafter CDS96) and Richer et al. (1996), mainly because the first is based on the "vertical" parameter, while the second is based on the "horizontal" parameter.

Since we are interested in comparing only the *relative* ages, a normalization of the different age determinations is necessary before carrying out the comparisons.

As described at Sects. 2.4 and 4.2, the zero–point of our *relative* Δt values reported in Table 2 has been fixed by using the 11 "coeval" clusters defined in Sect. 3.2. So as to allow a direct comparison, we have thus averaged the age determinations listed for the same 11 clusters by CDS96 and by Richer et al. (1996), and have then computed the *relative* age for each cluster as the difference between the individual age and the average value adopted for each catalog, respectively.

The results of the comparisons are shown in Fig. 18 (panel a and b) for the lists of CDS96 and Richer et al. (1996), respectively. The different symbols represent the blue HB clusters (*full dots*) and the red HB clusters (*open dots*).

Considering the different assumptions and methods used in the three compared studies and the uncertainties and difficulties involved in the whole age-determination, the overall agreement of the various relative ages is fairly good. In particular, one can add a few considerations.

First, the existence of a few *young* globular clusters is definitely confirmed by all the authors, and the dispersion of the bulk of the considered objects around the "equal-age" locus is comparable (with just a few exceptions) to the uncertainties in the individual age determinations.

Second, the relative ages derived for the blue–HB clusters by CDS96 using the ΔV_{HB}^{TO} parameter are older than obtained from both our procedure and by Richer et al. (1996). In our view, this probably reflects the difficulty to estimate the HB luminosity when the HB parts adjacent to the instability strip are not populated. This confirms our choice of avoiding the use of the ΔV_{HB}^{TO} method for this kind of clusters.

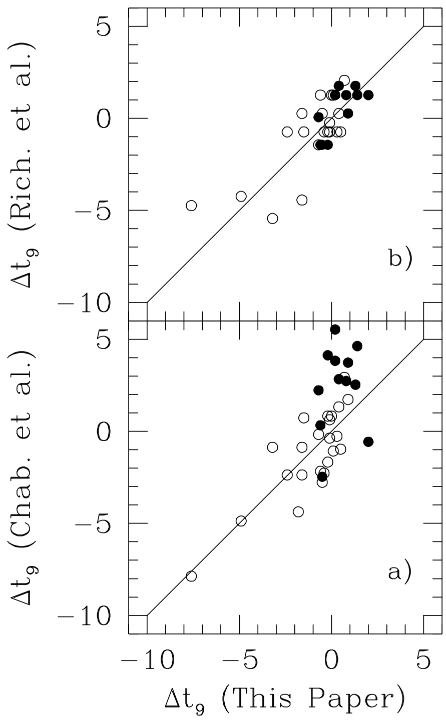

Fig. 18a and b. Our adopted relative ages listed in Table 2 column 5 are compared to those deduced from ΔV_{HB}^{TO} by CDS96 (panel **a**) and from $\Delta_{RGB-TO}^{(B-V)}$ by Richer et al. (1996) (panel **b**). The full dots represent the clusters with blue HB (*(B-R)/(B+V+R)* $<$+0.72)

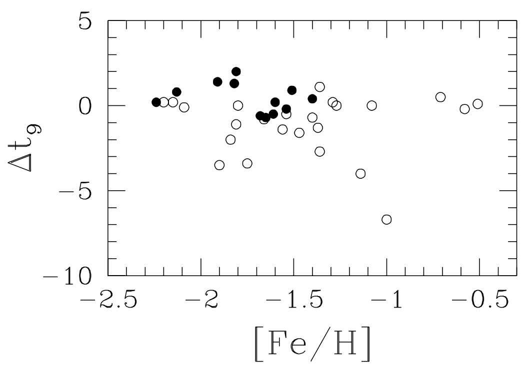

Fig. 19. Our relative ages listed in Table 2 column 5 are plotted vs. [Fe/H] . The red–HB clusters are reported as open dots, the blue–HB as full dots. Leaving out Palomar 12 and Terzan 7 (see Sect. 4.5), any dependece of the age on metallicity seems hardly detectable on the basis of this sample of clusters

4.7. Distributions of the adopted relative ages with metallicity and Galactocentric distance

Although further significant improvements are surely urged, the combined *semi-empirical* calibration of $\Delta V^{0.05}$ (our proposed new observable) and $\Delta_{RGB-TO}^{(B-V)}$ vs. [Fe/H] and t_9 here presented can allow us to estimate via a self-consistent global procedure age differences among globular clusters having *any metallicity and HB morphology*.

Finally, one can briefly look at the distributions of our estimated relative ages as a function of metallicity (Fig. 19) and Galactocentric distance (Fig. 20) of the considered clusters.

Since, in order to avoid any possible bias, we have used a small sample of well-studied clusters, it is impossible to reach any conclusions based on our sample.

However, some preliminary indications can be noted:

1. leaving out the two young metal-rich globulars, Pal 12 and Terzan 7, there is no compelling evidence for any clear-cut age-metallicity relationship among the clusters included in our sample (see Fig. 19).
2. in Fig. 19, there is some spread partially compatible with the associated uncertainties, but could also be intrinsic. In particular, the largest spread in age is found for intermediate metal-poor clusters, [Fe/H] ~ -1.8, which as well known presents the most evident signature of the so-called second parameter effect.
3. the oldest objects in our sample are not the most metal poor but, rather, they are found at the same metallicity ([Fe/H]$\sim$-1.8) where a large spread in age is observed. This result is not really new, as it was nevertheless present in Fig. 7 of VBS which shows that the TO regions of NGC 2298 and of M92 can be perfectly superimposed. Considering that these two clusters differ by 0.4 dex in [Fe/H] (see VBS), the age difference of about 2.5 Gyr we found, would simply be a

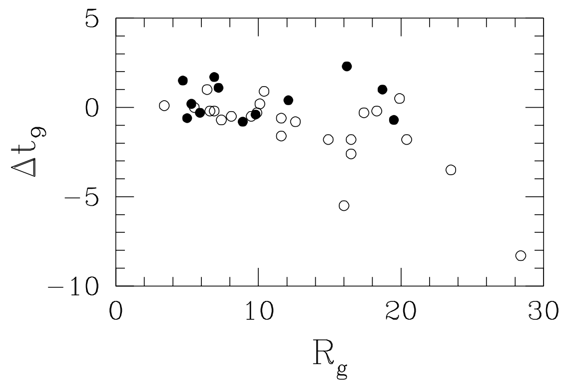

Fig. 20. Our relative ages listed in Table 2 column 5 plotted vs. the Galacticocentric distance. *Open dots* represent the red–HB clusters and *full dots* the blue–HB ones. A slight trend with ages decreasing at increasing distance seems to be present (at least for the red–HB subsample), but the main feature is the age dispersion resulting in the intermediate far halo (see Sect. 4.7)

consequence of the slope $\Delta t/\Delta[Fe/H] \sim 7$ derived from Eq. (3).

4. a weak trend with *older* clusters populating the inner halo and *old and younger* globulars present in the outer regions of the Galaxy seems to be in our data. Apparently, this evidence seems to be quite clear for the sub-sample of red–HB clusters, and uncertain or inexistent for the blue–HB objects. However, especially for this analysis our available sample is insufficient, and the the main feature emerging from Fig. 20 is the dispersion of the ages in the intermediate outer halo, already noticed by several authors (see Stetson et al. 1996 for references).

5. Conclusions

After considering the various pros and cons of the traditional "vertical" and "horizontal" methods for age determination of Galactic globular clusters (based on ΔV_{HB}^{TO} and $\Delta_{RGB-TO}^{(B-V)}$ *vs* age calibrations, respectively), we have defined a new global procedure able to yield homogeneously their *relative* ages.

To this aim we have defined and used a new observable, $\Delta V^{0.05}$, namely the difference in magnitude between an arbitrary point on the upper main sequence (MS) and the horizontal branch (HB). Following VBS, we have adopted as reference $V_{+0.05}$ –the V magnitude of the MS-ridge that is 0.05 mag redder than the MS Turn–off (TO). The observational error associated to $\Delta V^{0.05}$ is substantially smaller than that to ΔV_{HB}^{TO} .

This method shares with other differential techniques the advantage of being strictly independent of distance and reddening and with the "vertical" ΔV_{HB}^{TO} –technique (Iben & Faulkner, 1968) the intrinsic advantage of being based on theoretical *luminosities* rather than on theoretical *temperatures*, which are extremely sensitive to the uncertainties in the treatment of convection and radiative opacity at low temperatures.

We have also shown that the $\Delta V^{0.05}$ *vs* age calibration obtained by using the available theoretical models and different sets of transformations from the theoretical to the observational plane has a quite low dependence on metallicity. Moreover, the estimates of the *relative* age so obtained are also sufficiently invariant (to within ~ 2 Gyr) with varying adopted models and transformations.

Since for clusters where the *horizontal* part of the HB is not populated (e.g. M13, NGC 6752, NGC 6397, 47 Tuc, etc.) the uncertainty in the estimate of the HB luminosity –V_{HB} – directly propagates into the estimate of $\Delta V^{0.05}$, the so-called "horizontal" $\Delta_{RGB-TO}^{(B-V)}$ -method (VBS, Sarajedini and Demarque 1990 –SD) based on color differences remains the most reliable technique to estimate relative cluster ages. However, to reduce the impact of the still high uncertainties in the models, it requires a proper empirical calibration.

We have used the differential ages obtained via the "vertical" $\Delta V^{0.05}$ parameter for a selected sample of clusters (11, with high quality CMDs, well populated HBs, trustworthy calibrations) to perform an *empirical* calibration of the "horizontal" observable $\Delta_{RGB-TO}^{(B-V)}$ in terms of [Fe/H] and age.

A direct comparison with the corresponding calibration determined from the theoretical models reveals the existence of a clear-cut discrepancy with almost any kind of models plus trasformations. Such a disagreement, in general increasing with increasing the cluster metallicity, calls into question the model scaling with metallicity in the observational planes.

Based on the *global* sample of considered clusters, we have so obtained, within an homegeneous procedure, *relative* ages for 33 Galactic globulars having different metallicity, HB–morphologies, and Galactocentric distances. These new estimates have also been compared with previous latest determinations (CDS96, and Richer et al. 1996), and the detected differences have been schematically discussed.

Finally, though the available sample is still insufficient to draw any firm conclusion (as both additional data for other clusters and improvements in the calibrations are urged), we have also briefly discussed the distribution of the cluster ages with varying metallicity and Galactocentric distance. In summary, (a) there is no direct indication for any evident age-metallicity relationship (see Fig. 19); (b) there is some spread in age (still partially compatible with the errors), and the largest dispersion is found for intermediate metal-poor clusters (signature of the so-called second parameter effect?); (c) older clusters populate both the inner and outer regions of the Milky Way (quite independent of metallicity), while the younger globulars are present just in the outer regions, but the sample is too poor to yield statistically significant evidences. If further data would confirm this preliminary results, a natural conclusion is that the Galaxy collapsed with different timescales, very rapidly in the inner zones, and on a much longer period outside. Moreover, accretion phenomena and mergers of small fragments could have taken place at a significant level.

We put forward severe warnings against the uncritical assumption of a given global relative age-scale for globulars with the formal uncertainties derived by propagating observational errors since we have shown that the undeterminacies and the unconsistencies associated with the same *clock* (i.e. models + transformations) on which they are based can be significantly more important than any crude measurement error.

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