Relative ages of inner-halo globular clusters

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Abstract.  
We present preliminary results from our on-going survey of Galactic globular clusters relative ages. The investigation is based on $V, I$ images obtained at the ESO and La Palma telescopes, which make up the largest homogenous photometric catalog to date. A second, independent sample of globulars observed in the $B, V$ bands provides an independent check of the results based on the ground-based data.

Age-dependent morphological parameters are measured on the CMDs and are compared with two sets of independent models. We find that the so-called “vertical” and “horizontal” methods give compatible results when the ground-based dataset is used, and that in both cases the observed trends are well reproduced by the isochrones. The interpretation of the HST data trends are more controversial, due to both a stronger dependence on metallicity, and to the discrepancies in the theoretical loci.

Our data clearly show that (a) no age dispersion can be revealed for the bulk of the GGCs at the $\sim 1$ Gyr level; (b) no age-metallicity relation is found, although the age dispersion is somewhat larger for intermediate and higher metallicity clusters; and (c) there is no clear trend with the galactocentric distance, out to the present limits of our survey ($R_{GC} < 22$ Kpc).

1. Introduction

Galactic globular clusters (GGC) are the oldest components of the Galactic halo. The determination of their relative ages and of any age correlation with metallicities, abundance patterns, positions and kinematics allows to establish the formation timescale of the halo and gives information on the early efficiency of the enrichment processes in the proto–galactic material. The importance of these problems and the difficulty in answering to these questions is at the basis of the huge efforts dedicated to gather the relative ages of GGCs in the last
30 years or so (VandenBerg, Stetson, and Bolte 1996, Sarajedini, Chaboyer, Demarque 1997, SCD97, and references therein).

Any method for the age determination of GGCs is based on the position of the turnoff (TO) in the color–magnitude diagram (CMD) of their stellar population. We can measure either the absolute magnitude or the de-reddened color of the TO. In order to overcome the uncertainties intrinsic to any method to get GGCs distances and reddening, it is common to measure either the color or the magnitude (or both!) of the TO, relative to some other point in the CMD whose position does not depend on age.

Observationally, as pointed out by Sarajedini & Demarque (1990) and VandenBerg et al. (1990, VBS90), the most precise relative age indicator is based on the TO color relative to some fixed point on the red giant branch (RGB). Unfortunately, the theoretical RGB temperature is very sensitive to the adopted mixing length parameter, whose dependence on the metallicity is not established yet. As a consequence, investigations on relative ages based on this method (“horizontal method”) might be of difficult interpretation, and need a careful calibration of the relative TO color as a function of the relative age (Buonanno et al. 1998, B98). The other age indicator is based on the TO luminosity relative to the horizontal branch (HB). Though this is usually considered a more robust relative age indicator, it is affected both by the uncertainty on the dependence of the HB luminosity on metallicity and the empirical difficulties to get both the TO magnitude and the HB magnitude for clusters with only blue HBs.

Despite the intrinsic difficulties in gathering relative ages, it is nevertheless astonishing, for those not working in the field, to read the totally contradictory results coming from different groups.

We are still debating whether GGCs are almost coeval (Stetson et al. 1996) or whether the GGCs have continued to form for 5 Gyr (SCD97) or so (i.e. for 30-40% of the Galactic halo lifetime).

Indeed, there is a major limitation to the large scale GGC relative age investigations: the photometric inhomogeneity and the inhomogeneity in the analysis of the databases used in the various studies. And even worst, these etherogeneous collections of data do not allow a reliable treatment of the empirical errors, which sometimes must be guessed, with questionable results (Chaboyer et al. 1996).

Prompted by this major drawback, two years ago our group began the collection of an homogeneous photometric material for a large sample of GGCs, in order to obtain accurate relative ages by using both the horizontal and vertical method in a self-consistent way. The strategy was decided after a preliminary analysis of published CMDs both in the $B, V$ and $V, I$ bands (Saviane, Rosenberg, and Piotto 1997; hereafter SRP97). SRP97 showed that the $V - I$ color differences are less sensitive to metallicity than the $B - V$ ones (while retaining the same age sensitivity). SRP97 also suggested that a high-precision, large-scale investigation in the $V$ and $I$ bands would have allowed a relative age determination through the horizontal method without the usual limitation of dividing the clusters into different metallicity groups (VBS90).

Here we present the first exciting results of this investigation.
2. Data base

In the present investigation only two telescopes (one for the northern and one for the southern sky GGCs) have been used.

Thirty-nine clusters have been observed with the ESO/Dutch 0.9m telescope at La Silla, and 16 at the RGO/JKT 1m telescope in la Palma. A total of 30 clusters had CMDs useful for the relative age determinations.

In this observing campaign (the first step of our investigation) all the clusters with \((m - M)_V < 16\) have been observed with 1-m class telescopes. We have also observed 16 clusters within \((m - M)_V < 18\) with 2-m class telescopes, and observations at 4-m class telescopes for the farthest clusters are planned.

The data have been calibrated with the same set of standards. The observations, reduction, and photometry will be described in forthcoming papers. Here suffice to say that the zero-point uncertainties of our calibrations are < 0.03 mag for each band. Three clusters were observed both with the southern and the northern telescopes, thus providing a consistency check of the calibrations: no systematic differences were found, at the level of accuracy of the zero-points.

We are also collecting an independent and even more homogeneous database in the \(B\), and \(V\) bands. The data come from two HST programs (GO6095 and GO7470). Within GO7470 we should observe with the WFPC2 the core of 46 clusters; With the already available archive data by the end of GO7470, all the GGCs with \((m - M)_B < 18\) should have been observed with HST. Though the programme main objectives are different, most of the data are suitable for this project. This database allows an independent check of the results from the groundbased data.

In order to have well defined fiducial lines for each CMD, a selection on the photometric catalogs of each cluster was applied by imposing a threshold on the photometric errors, and only the less crowded regions were used. The following points were then measured on the CMD, both for the HST and groundbased samples: Magnitude and color of the TO; Magnitude of the MS point 0.05 mag redder than the TO; Color of the RGB at \(\Delta m\) magnitudes above one of the two previous points (where \(\Delta m\) was 1.5, 2.0, 2.5, 3.0, 3.5); The magnitude level of the HB. These values were used to calculate a set of both vertical and horizontal parameters. We will name these parameters, generically, \(\delta_{x|y}\) or \(\delta_{x|y^{0.05}}\). For example, \(\delta(V-I)^{0.05}_{@1.5}\) is the difference between the \((V-I)\) color of the RGB and that of the TO. In this case, the RGB point is measured 1.5 mag above the MS point 0.05 mag redder than the TO. In the following, we will use \(\Delta V^{TO}_{HB}\) as vertical parameter and \(\delta(V-I)^{0.25}_{@2.5}\) as horizontal parameter. However, the results presented below are independent from this choice, as will be shown in Rosenberg, Saviane, and Piotto (1999, RSP99).

3. Methodology

Basically, we followed the B98 strategy. In view of the uncertainties associated to the interpretation of the horizontal parameter (cf. Section 1), we first identified a set of coeval clusters by means of the vertical method. These coeval GGCs allowed to identify an empirical “isochrone” in the \(\delta\) color vs. [Fe/H] plane (a straight line in B98). These isochrones were then compared with the theoretical
Figure 1. The parameter $\Delta V_{\text{TO}}^{\text{HB}}$ is plotted versus the metallicity. The dashed lines in the two panels show the theoretical trend of the parameter for the models of SCL97 (top) and V98 (bottom), assuming that $M_V^{\text{HB}} = 0.20 [\text{Fe/H}] + 0.98$. The isocrones are separated by 2 Gyr. Open circles identify the groundbased sample, while open triangles identify the HST sample; the typical error is shown by the cross in the lower panel. Heavy symbols represent the fiducial coeval clusters, selected as described in the text.

predictions. Finally, the color differences from the mean line were converted into an age.

The choice of the metallicity scale will be discussed in details in RSP99. In view of its homogeneity, we used the Rutledge et al. (1997) compilation on the Carretta & Gratton (1997) metallicity scale.

3.1. Coeval clusters

In Fig. 1, the parameter $\Delta V_{\text{TO}}^{\text{HB}}$ is plotted vs. metallicity, both for the groundbased and the HST sample of GGCs. In the same figure, the theoretical isochrones are represented as dashed lines. The theoretical $\Delta V_{\text{TO}}^{\text{HB}}$ was calculated from the TO of VandenBerg et al. (1998, V98) and Straniero et al. (1997) models, and assuming $V_{\text{HB}} = 0.20 [\text{Fe/H}] + 0.98$ (Chaboyer et al. 1996). These models were chosen, since they are the most recent ones offering both $B - V$ and $V - I$ colors.

With our choice for the $V_{\text{HB}}$ vs. $[\text{Fe/H}]$ relation, and within the observational errors, the theoretical isochrones and the observed values show similar trends with metallicity. It must be clearly stated that this result depends on the choice of the theoretical HB luminosity, though the conclusions would be the same if the slope of the $V_{\text{HB}}$ vs. $[\text{Fe/H}]$ relation is changed by not more than $\pm 15\%$ (see also below). Note that the zero point of the relation for $V_{\text{HB}}$ does not affect the relative age. The isochrones can be used to tentatively select a sample of coeval clusters. We will use these clusters to test the isochrones in the $\delta(V - I)_{0.25}$ vs $[\text{Fe/H}]$ plane (B98). We somehow arbitrarily defined as coeval (from here on fiducial coeval GGCs), those clusters whose vertical parameter
Figure 2. Plot of the parameter $\delta(V-I)_{@2.5}$ vs. metallicity for the ground-based sample. Two sets of theoretical models are also represented (dashed lines), SCL97 (top panel) and V98 (bottom panel). Again, heavy symbols mark the fiducial coeval clusters, and the typical errors are represented by the cross. The isochrone used for the relative age determination is displayed as a solid line was within $\pm 1\sigma$ from the isochrone which better fit the data distribution in the $V_{\text{HB}}$ vs. [Fe/H] plane. These object are marked by heavy symbols in Fig. 1. Interestingly enough, the same set of coeval clusters is selected using either the SCL97 or the V98 isochrones, and using a slope $\alpha$ for the $V_{\text{HB}}$ vs. [Fe/H] relation in the range $0.17 < \alpha < 0.23$ for the V98 isochrones and $0.15 < \alpha < 0.20$ for the SCL97 isochrones. The observed dispersion is $\sigma = 0.1$ mag with respect to both the SCL97 and V98 isochrones, i.e. fully compatible with the uncertainties in $\Delta V_{\text{TO}}^\text{HB}$, strengthening the idea that the selected clusters must be coeval.

3.2. Ages from color differences

In Fig. 2, the parameter $\delta(V-I)_{@2.5}$ vs. metallicity for the ground-based sample is compared with the SCL97 (top panel) and V98 (bottom panel) isochrones. The trend with metallicity of the $\delta(V-I)_{@2.5}$ parameter for the fiducial coeval GGCs (filled circles) is remarkably similar to the theoretical trend. In Fig. 3, the fiducial coeval GGCs are all within a 2 Gyr strip, showing a full consistency with what was found from the vertical method.

The plot in Fig. 3 is the $B-V$ counterpart of Fig. 2. Also in this case most of the GGCs are within a narrow band. However, as pointed out also by B98, the age width of this band is more difficult to obtain, since the isochrones show different trends with [Fe/H]. Also the trend with [Fe/H] of the $\delta(B-V)_{@2.5}$ for the coeval clusters differs from the isochrones. The differences in $\delta(B-V)_{@2.5}$ for different models and different bolometric corrections are widely discussed in B98. Here, we simply note that the recent V98 calculations seem to better approximate the observed data and that, using these isochrones, an age dispersion comparable with that from the vertical method is obtained.
A further remark on the different dependence of the horizontal parameters in \((B - V)\) and in \((V - I)\) on the metallicity. Fig. 2 and 3 are plotted on the same scale. Clearly, \(\delta(B - V)_{@2.5}\) strongly depends on [Fe/H], particularly for [F/H] \(\geq -1.7\), as already pointed out by VBS90. As a consequence, even a small error on the metal content of a cluster can strongly affect the determination of its relative age. This fact might also explain the apparently larger dispersion of the \(\delta(B - V)_{@2.5}\) parameter. \(\delta(V - I)_{@2.5}\) has a much milder dependence on metallicity.

All the above considerations strengthen the conclusions by SRP97 that the \(\delta(V - I)\) parameter is much more reliable than the \(\delta(B - V)\) as a relative age index.

Relative ages were computed only by means of the difference in the \(\delta(V - I)_{@2.5}\) parameter with respect to the 13 Gyr-SCL97 or 14 Gyr-V98 isochrone fitted to the points. The \(\delta(V - I)_{@2.5}\) dispersion is 0.01 mag, as expected on the basis of the errors in measuring this parameter.

4. Discussion

The dispersions in \(\delta(V - I)_{@2.5}\) translate in an age dispersion of 1.4 Gyr (adopting the SCL97 models) or 1.6 Gyr (adopting the V98 models), which lowers to 1.3 and 1.4 Gyr if we remove Pal 12, a known anomalously young cluster (Rosenberg et al. 1998). The age dispersion of the adopted coeval clusters is of 0.75 Gyr for the SCL97 models and 0.70 for the V98 models.

As pointed out above, if we take into account the observational errors, the GGC age dispersion is fully compatible with a null age dispersion.

The relative ages from the horizontal method estimated from Fig. 1 and Fig. 3 are plotted in Fig. 4 vs. [Fe/H] and the Galactocentric distance \(R_{GC}\).
Figure 4. Relative ages obtained from the observed $\delta(V-I)$ using two theoretical relations (see text for details). The trends vs. [Fe/H] (top panel) and the Galactocentric radius $R_{GC}$ (bottom panel) are shown. Open circles represent values obtained using the V98 isochrones, while open triangles are the values obtained using those of SCL97.

The open circles are the ages from V98 models and the open triangles represent the ages from the SCL97 models. Regardless of the model, the relative ages do not depend on the cluster metallicity, though the age dispersion is larger for the intermediate and higher metallicity GGCs. No clear dependence on the galactocentric distance can be identified.

These results indicate that the bulk of the Galactic halo formed on a timescale $\leq 1$ Gyr; a minor fraction of younger clusters is also present, although their true Galactic origin is still debated. These younger clusters tend to be located in the outer halo: the interpretation of this trend is controversial. They could have formed in isolated Searle & Zinn (1978) fragments later accreted into the halo, or else they could be explained by the SGMC GC model formation of Harris & Pudritz (1994). In this context a delayed formation of the outer GCs is naturally explained (see also Harris et al. 1998).

An age-metallicity relation cannot be detected by this investigation. This means that the early chemical enrichment of the Galactic halo took place on a timescale again $< 1$ Gyr, up to values roughly half solar.
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