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The Milky Way Formation Timescale

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Abstract.
Based on a new large, homogeneous photometric database of 69 Galactic globular clusters extended out to 42 kpc from the galactic center, a set of distance and reddening free relative age indicators has been measured: $\delta(V-I)_{@2.5}$ and $\Delta V_{\rm TO}^{\rm HB}$. Using this two independent indicators and two recent updated libraries of isochrones we have found that self-consistent relative ages can be estimated for our GGCs sample.
The main results are: (a) most clusters and all with [Fe/h] < -1.2 are old and coeval; (b) there is no trend of the age with the Galactocentric distance out to 25 kpc from the galactic center; (c) there is a mild indication (but still based on a limited number of clusters) that clusters beyond 25kpc are slightly younger (d) there is no age-metallicity trend and (e) for more metal-rich clusters ([Fe/h] > -1.2) there are indication of a larger age dispersion, of the order of 10-15%.
From these results, a tentative interpretation of the Milky Way formation can be given. First, the GC formation process started at the same zero age throughout the halo including the outer regions, out to the current $\sim$ 42 kpc. The so-called disk globulars were formed at a later time ($\sim$ 15% lower age). Finally, significantly younger halo GGCs are found at any distance out to $R_{\rm GC} \sim 30$ kpc. For these, a possible scenario associated with mergers of dwarf galaxies to the Milky Way is suggested.

Key words. Milky Way – Globular clusters – Color-magnitude diagram

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 provides clues on the formation time-scale 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 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 et al. 1996, Sarajedini et al. 1997, Buonanno et al. 1998, Rosenberg et al. 1999, Salaris and Weiss 2002, and references therein).

The methods at use for the age determination of GGCs are 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. However, 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), the most precise relative age indicator is based on the TO color relative to some fixed point on the red giant branch (RGB). This method is usually called "horizontal method". Unfortunately, the theoretical RGB temperature is very sensitive to the adopted mixing length parameter, whose dependence on the metallicity is not well established yet. As a consequence, investigations on relative ages based on the 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). The other age indicator, the "vertical method", 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 the TO and the HB magnitudes for clusters with only blue HBs.

Given these problems, the question of whether GGCs are almost coeval (Stetson et al. 1996) or whether they have continued to form for 5 Gyr or so (i.e. for 30-40% of the Galactic halo lifetime; Sarajedini et al. 1997) has been the subject of an open debate for a long time; debate which can not be considered definitely closed nowadays.

For several years, a further major limitation to the large scale GGC relative age investigations was the photometric inhomogeneity and the inhomogeneity in the analysis of the databases used in the various studies. Many works frequently combined photometries coming from different databases (obtained with different instruments with uncertain calibrations to standard systems and/or based on different sets of standards), or unappropriated color-magnitude diagrams (CMD; see Stetson et al. 1996 for a discussion).

For this reason, in 1997 (Saviane et al. 1997) we started a long term project to obtain accurate, homogeneous relative ages by using the horizontal and vertical method in the ([Fe/H], δ(V−I)) plane. Our first observational effort was aimed at the inner-intermediate halo clusters and was published in Rosenberg et al. (1999, 2000a, 2000b). The main result reached for that sample was that most globular clusters were old and formed within a time interval of less than 1 Gyr, pointing to a fast collapse of the inner and intermediate Galactic halo. Beside those coeval objects, a significant fraction of younger globular clusters was put into evidence. These younger clusters were found at all Galactocentric distances.

In 1999 we started an extension of our project aimed at including GGCs of the external halo. In collecting the new data set, we payed particular attention to ensure photometric homegeneity with the original sample. In this paper we present preliminary results from this new project.

2. The Data

The goal of our observational strategy was to obtain a homogeneous data set which would allow measuring color differences near the TO region with an uncertainty $\leq$ 0.01mag, which allows a $\leq$ 1Gyr relative age resolution. As a first step, we used 1-m class telescopes to build a large reference sample including all clusters within $(m - M)_V = 16$. The 91cm ESO/Dutch Telescope (for the southern sky GGCs) and the 1m ING/JKT (for the northern sky GGCs) were then used to cover 52 of the scheduled 69 clusters. In the following, we will refer to this as our first sample. Finally, only 34 clusters were suitable for the study. These clusters are located within 20 kpc of the Milky Way center and provide a good sample of the inner and intermediate halo. The remaining objects were excluded due to several reasons: differential reddening, small number of member stars, large background contamination, bad definition of the RGB or HB. From 2500 to 20000 stars per cluster were measured. The typical CMD extends from the RGB tip to $\geq$ 3 magnitudes below the TO.

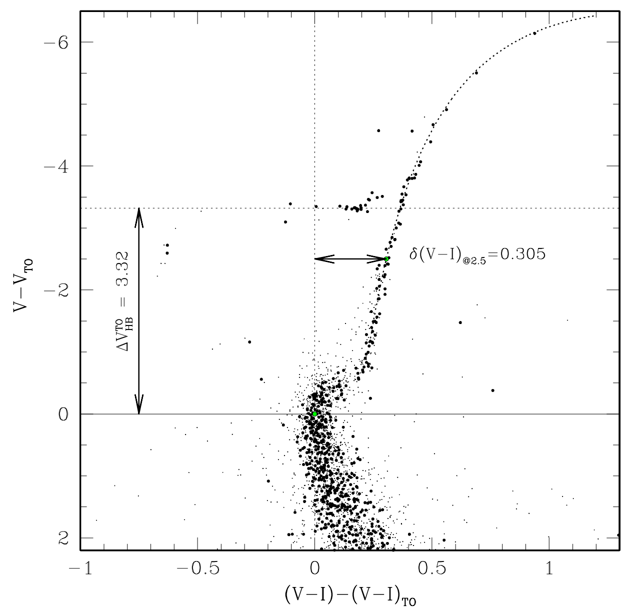

Fig. 1. The vertical and horizontal parameters defined on the color-magnitude diagram of NGC 1851

A detailed description of the observation and reduction strategies are given in Rosenberg et al. (2000a,b), where the CMDs for the whole photometric sample are also presented. The data-base is also available on-line at www.iac.es/proyect/poblestelares. Here suffice to say that the data have been calibrated with the same set of standards, and that the absolute zero-point uncertainties of our calibrations are ≤ 0.02 mag for each of the two bands. Moreover, three clusters have been observed both with the southern and northern telescopes, thus providing a consistency check of the calibrations: no systematic differences were found, at the level of accuracy of the zero-points.

A similar strategy has been adopted for the extension to the outer halo GGCs. A total of 19 GGC at Galactocentric distances between 18 and 42 kpc were included in this sample and observed with the twin 3.5 m telescopes NTT (ESO) and TNG (Roque de los Muchachos). In the following, we will refer to this as our second sample. As for the first sample, the same set of standards has been used and three clusters have been observed with both telescopes and in common with the first sample to assure the full consistence of the calibration.

Finally, we have adopted the metallicities listed in Rutledge et al. (1997) calibrated on the Carretta & Gratton (1997) scale. The main results presented in the following sections would not change adopting the Zinn and West (1984) scale.

3. Results

Our investigation is based on relative age estimates done with two "classical" reddening and distance independent photometric parameters: $\Delta V_{\rm TO}^{\rm HB}$ and $\delta(V-I)_{@2.5}$. These are the magnitude difference between the HB and the TO (vertical method), and the color difference between the TO and the RGB (horizontal method), where the RGB color is measured 2.5 magnitudes above the TO. These quantities are displayed in Fig. 1.

In order to interpret the results of our data samples, the theoretical isochrones computed by Straniero et al. (1997), and VandenBerg et al. (2000) were used. It is important to notice that these theoretical models are completely independent: indeed, they are obtained with different prescriptions for the mixing-length parameter, the Y vs. Z relation, the temperature-color transformations and bolometric corrections, etc.

The same morphological parameters already defined for the observational CMDs were measured on the isochrones. The trends of the theoretical quantities as a function of both age and metallicity were least-square interpolated by means of third-order polynomials, so that the observed parameters can be easily mapped into age and metallicity variations. Finally, in order to calculate the theoretical values of $\Delta V_{\rm TO}^{\rm HB}$ from the obtained TO magnitudes, we have to assume a relation for the absolute V magnitude of the HB as a function of the metal content. In particular, here we adopted $M_V(ZAHB) = (0.18 \pm 0.09) \cdot ([\mathrm{Fe/H}] + 1.5) + (0.65 \pm 0.11)$, from the recent investigation of Carretta et al. (2000).

The former procedure provides an absolute age scale for each photometric parameter and each isochrone set. However, we do not need these absolute age calibrations that will have their own zero points, depending on the internal parameters used to compute isochrones. We are rather interested on relative ages, of which we have four different measurements: one for each photometric parameter and isochrone set. The differences among the relative ages resulting from each scale can be taken as an indication of the (internal) uncertainties intrinsic to our present knowledge of the stellar structure and evolution.

For each cluster, the four relative age estimates follow very similar trends (see Rosenberg et al. 1999 for details). For simplicity, we have averaged them for each cluster and will base the following discussion on the resulting relations. Relative ages are plotted in Fig. 2 as a function of metallicity and the galacto-centric distance. In this figure, filled dots refers to the first sample, published and discussed in Rosenberg et al. (1999, 2000a and 2000b), and are definitive results. Open dots correspond to the second sample and are still provisional results.

In summary, the main strength of the Rosenberg et al. (1999) and of the present effort are: (a) the use of an homogeneous CCD database; (b) the use of two independent methods for the age measurement; (c) the use of two recent, largely independent evolutionary model; (d) the use of V, I photometry to estimate the horizontal parameter, and (e) an homogeneous metallicity scale.

4. Discussion: Globular Cluster Relative Ages

Our results are summarized in Fig. 2. This figure shows the following important features:

- 33 over 45 clusters are distributed around the mean, within an age interval $\Delta_{Age} \leq$ 10% of the mean.
- Our data do not reveal an age-metallicity relation in the usual sense of age decreasing (or increasing) with metallicity. What is found is an increase of the age dispersion for the metal rich. Indeed, for [Fe/H]¿-0.9 there seems to be a lack of old GCs. We think this effect can be real, but the result is statistically not very significant at the moment, and somehow model dependent. The lower metallicity ones ([Fe/H]≤ -1.2) seems to be almost all coeval. There are only two exceptions, Pal 5 and NGC 6229, presently under investigation, which seems to be 20% younger than the average cluster age, despite their intermediate metal content. An increase in the age dispersion at higher metallicities is in agreement with the results of Richer et al. (1996), Salaris & Weiss (2002), Buonanno et al. (1998). On the other side, Chaboyer et al. (1996) proposed an age-metallicity relation, of the order $\Delta t_9/\Delta[\mathrm{Fe/H}] \simeq -4$ Gyr dex^{-1}, which is not present in our data set.
- For clusters with R¡25Kpc, we note a sort of dicotomy in the distribution of the relative ages, with most (74%) of the clusters old and coeval, and 21% about 20% younger, but with a relative age dispersion compatible with the measurement errors. The remaing two clusters with R¡25Kpc and which have an age 40% smaller than the age of the oldest one (Pal 12 and Ter 7),

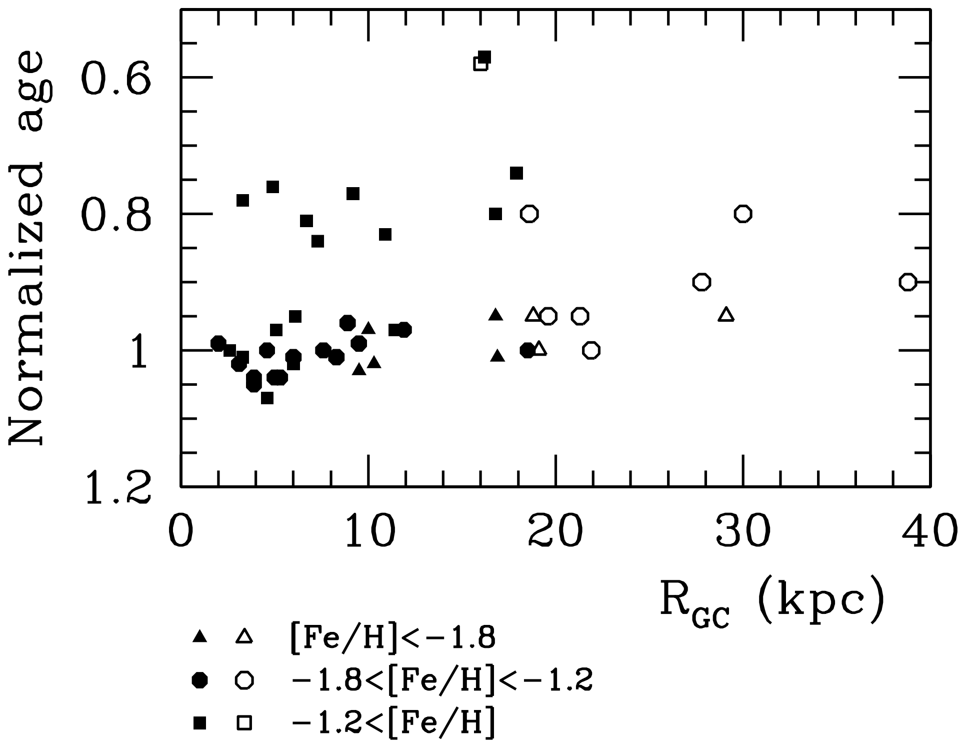

Fig. 2. Mean relative ages for the globular cluster data sample as a function of Galactocentric distance. Filled dots correspond to our first sample (see Rosenberg et al. 1999, 2000a and 2000b). Open dots correspond to our second sample and are still provisional data.

may be part of a Galactic stream (Lynden-Bell and Lynden-Bell 1995).

- Younger clusters appear at every Galactocentric distance. Those located at larger Galactocentric distances have typical halo kinematics.
- There is a mild indication of a Galactocentric age gradient, in the sense that clusters at larger distances could be slightly younger. However, such dependence, if present, relies on provisional results (those corresponding to larger Galactocentric distances), and a very limited number of clusters, and must be confirmed when final data will be available.

5. Discussion: Clues on the Milky Way Formation Time-Scale

The age dating progress that has been discussed so far, has important consequences on our interpretation of the time-scales of the Milky Way formation. In particular, we go from a halo formation lasting for ∼ 40% of the Galactic lifetime (Chaboyer et al. 1996), to the present result of most the halo clusters being coeval (Rosenberg et al., 1999).

Besides this basic result, other clues on the Milky Way formation have been obtained from the previous discussion. Going back to Fig. 2, a chronological order of structure formation can be inferred.

The GC formation process started at the same zero age throughout the halo, at least out to ∼ 25 kpc from the center. Up to 75% of the Galactic GCs formed, almost simultaneously, in this, first epoch. At later (∼ 20%) times the so-called disk globulars are formed. Finally, significantly younger halo GGCs are found at any $R_{\rm GC} > 8$ kpc (clusters at shorter galactocentric distances show possible disc kinematics). These clusters could be the result of a second generation of GCs, or accreted form outside, and therefore associated to some of the so-called ""streams", i.e. alignments along great circles over the sky, which could arise from these clusters being the relics of ancient Milky Way satellites of the size of a dwarf galaxy (e.g. Lynden-Bell & Lynden-Bell 1995, Fusi-Pecci et al. 1995). We are still investigating this possibility. Here we only note that apparently all these "younger" clusters (even those located at $R < 8$ kpc) have a very small age dispersion among them, compatible with the measurement errors.

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