The HR Diagram of Globular Clusters: Theorist’ view(s)

F. D’Antona

Osservatorio Astronomico di Roma, Italy

Abstract: I list the characteristic features of Globular Cluster (GC) HR diagrams which provide a complete test of the stellar evolution of low mass stars: morphologies describing the different evolutionary phases, number ratios and luminosity functions, which add quantitative information. Then I explore the stage of today’s understanding of the classical distance scale indicators (providing warnings against model construction which, underneath, already is based on a choice of distance), and compare them to the “new” indicators, such as the white dwarfs and the first and second kink of the low main sequence. The classical and new distance indicators are still subject to uncertainties due to tiny details of the theory, which are all of the same order of magnitude, \( \sim 0.25 \text{mag} \) and the absolute ages of GCs can not be constrained to better than \( 10 – 16 \) Gyr. However, most of recent theoretical and observational results (including both classical and new indicators) point more towards the lower range of ages (10-12) than to the upper range (15-16).

1 Introduction

It is now close to forty years that Globular Clusters (GCs) HR diagrams are used to derive the age of the oldest stars of the Galaxy, but today they provide a very complete test of the predictions of stellar evolution of low mass stars. This is easily recognized by looking at the composite HR diagram of the GC NGC 6397 shown in figure 1, and illustrated in figure 2 by recent stellar models. The diagram shows the core H–burning phases (main sequence –MS– and turnoff –TO– regions, the H–shell burning of the evolving mass (\( M \sim 0.8 M_\odot \)) including the red giant branch –RGB–, the Helium core burning phase (horizontal branch –HB–) and the double shell burning phase (asymptotic giant branch –AGB–). The Planetary Nebula phase is too short (only two planetaries are known in the galactic GC system) but the white dwarf –WD– cooling is well represented. The MS ends at the top with the evolving stars, and at the bottom with the lowest masses which are able to ignite hydrogen. The characteristic shape of the MS well below the turnoff displays characteristic details of the physics of the atmospheres and interiors of low and very low mass stars (see, e.g. D’Antona 1995): it changes slope twice, at a first, more luminous “kink” (FK) at \( M \sim 0.5 M_\odot \), and at a second kink (SK), very close to the end of hydrogen burning structures. So the HR diagrams provide morphological information and reference luminosity indicators (TO, HB, WDs) which give constraints on the cluster stars evolution. In addition the number ratios (luminosity functions (LFs), “clumps”, gaps, ratio of HB to RGB number stars) add valuable quantitative information to the morphology.
In particular, the LF of the turnoff and giant branch depends mostly on the age of the system, while the mass function affects its unevolved part. The LF below the TO presents a characteristic broad maximum, due to the functional form of the mass – luminosity relation, whose peak becomes dimmer when the metal content increase (for a full description see, e.g., Silvestri et al. 1998).

In my opinion, the two fundamental questions which we would like to address in a meeting on the comparison between GCs and halo field stars are the following:

1. is our knowledge sufficient to constrain the GC ages at a level at which they can be interesting as indicators of the age of the Universe?

2. are GC stars identical to their halo counterparts of similar metallicity?

The answers to these questions are simple and a bit uncomfortable:

- Details of the theory determine the precise absolute ages of GCs: till now it is difficult to constrain the ages to better than from 10 to 16Gyr (but see later);

- The distance scale of GCs is necessary to know their ages. Its calibration necessarily relies on the hypothesis that GC and halo stars are strict relatives, unless we put all our faith on theoretical models only.

In the following I describe the ways in which we can try to determine the distance scale of GCs and the hidden dangers in the playing of the “isochrone fitting computer game”, mainly those related to the use of the giant branch location. I will finally show how the new distance indicators emerging in the latest years (WDs, FK and SK of the low MS) are consistent with the traditional distance scales based on the fit of ground based photometry and on the HB models.

2 The ages paradigm

The distance scale of GCs is the main key to their age determination. There are many “traditional” methods to derive this scale: they can be reduced to the following list:

- Approach based on distance indicators:
  - Fitting of MS to local sample of subdwarfs;
  - Fitting of the GCs RR Lyrae to RR Lyrae in the Magellanic Clouds, distance of LMC calibrated through the Cepheids;
  - Fitting of HB (or RR Lyrae) to local halo HB or RR Lyrae.

- Purely theoretical approach:
  - Fitting of HB (or RR Lyrae) luminosity to HB theoretical models;
  - Fitting of observed MS to theoretical MS (this implies a match of the models colors);
  - Fitting of the morphology of the HR diagram ($\delta(B-V)$ type methods)

The recent, mainly HST based, observations which allow to reach dimmer and dimmer luminosities have added new ways to determine the distance, or at least to check it, which will be examined in sections 5, 6 and 7, namely:
fitting of the location of the low MS, with attention to the location of the FK;

• fitting of the MS region following the SK with the local M subdwarfs sample;

• fitting of the WD sequence to models or disk counterparts.

I will not discuss the approach based on the classical distance indicators, which has known a renewed interest in these years, thanks to the impact of the results from the Hipparcos satellite. The fitting to the local subdwarfs is discussed in Reid 1997, Gratton et al. 1997, Pont et al. 1998 and Chaboyer et al. 1998. The RR Lyrae calibration after Hipparcos data was first rediscussed by Feast and Catchpole (1997). Notice that, while most Hipparcos results imply a more or less stringent confirmation of the so called “long” distance scale for GCs, the local RR Lyrae and HB stars give a much shorter scale (Fernley et al. 1998) consistent with the previous statistical parallax determination by Layden et al. 1996—but see the recent approach by Groenewegen and Salaris 1999.

I will mostly concentrate on the theoretical approach. Actually, none of the theoretical methods has been ever used independently from the others, but a sort of “consistency” between the different aspects of the problems has generally been looked for, including the observational distance indicators. For instance, fitting the morphology (that is, the relative position of RGB and TO) as an absolute method for the age determination has never been taken seriously (see later) but the consistency of the whole HR diagram locations (as shown in figure 1b) has been more or less unconsciously taken as self-evidence of an evolutionary scheme—and thus of a given range of ages—and especially in some comparisons with observations we have seen mention of “spectacular fit”, or “location and shape matched superbly by isochrones” while the truth hidden below is very different.

In the following I will base part of my discussion on a personal interpretation of the events which in recent years led to a revision of the average age of GCs. A look at the literature in fact shows that the ages of GCs quoted before or up to 1996-1997 (pre-Hipparcos) are in the range 13-18Gyr, while the most quoted ages of the years 1998-1999 are 10-14Gyr (post-Hipparcos). Vandenberg et al. 1996 in fact give an age of 15.8 ± 2Gyr to M92, noting that “ages below 12 or above 20Gyr appear highly unlikely”, and Chaboyer et al. (1996) give an average age of 14.6 ± 1.7Gyr to the galactic GCs, putting a 95% lower bound at 12.1Gyr. The turning point seems to have been the results from Hipparcos satellite, which on the one hand made the metal poor subdwarf sequence more luminous (by no more than 0.1mag, the effect being even lower according to some researchers) and on the other hand contributed to raise the zero point of Cepheids’ luminosity, leading thus to confirm a larger luminosity of the RR Lyrae in the LMC. However, the Hipparcos results alone do not justify the global shift of the average age of GCs, which amounts to ~ 4Gyr (from 16 to 12Gyr). In my opinion, Hipparcos has simply given more weight to the the “long” distance scale of GCs, which already had some emphasis in the observational literature (Sandage 1993, Walker 1992).

What has been happening is schematized in a very naïf way in figure 3: the HB (or RR Lyrae) luminosity has been increased in recent models due to the sum of two small effects (a slight increase in the core mass at the helium flash -by about 0.01 $M_{\odot}$- and a slight increase due to the improvement in the equation of state (EoS)). This has been the most important update in the models, and has shifted the ages to at most a couple of Gyr smaller with respect 1

1 Two notable exceptions are the work by Salaris et al. (1997) and the three papers by our group (Mazzitelli et al. 1995, D’Antona et al. 1997, Caloi et al. 1997) which published post–Hipparcos ages in the pre–Hipparcos years.
At the same time, the TO luminosity corresponding to a given age has been slightly decreasing. The sum of these subtle effects is a good \( \sim 0.27 \text{mag} \) of difference in the absolute TO location at a given age based on old or new models, for a given \( \Delta V \) from the HB to the TO, and thus the net effect is a reduction of 4Gyr in the age. The interpretation which figure 3 gives to the age decrease is not unique: other motivations for a more or less substantial decrease in the age are found in the recent literature. Pont et al. (1998), who do not revise the HB luminosity, remark however a difference in the scale of the \( V \) bolometric corrections (\( BC_V \)) between the models atmospheres employed by Bergbush and Vandenberg 1992, and the most recent scale both by Kurucz and by Bell, amounting to \( \sim 0.1 \text{mag} \), and thus leading to a decrease in the age by \( \sim 1.5 \text{Gyr} \).

It is evident that the HB luminosity of the present models, which in the end represent the most direct classical distance indicator, is in itself still uncertain, unless we believe that we can trust our models at the level of 0.01\( M_\odot \) for the determination of the helium core mass at flash, and that we know perfectly all the other pieces of input physics. At least, discussion is still open on the helium core flash masses. Notice also that, e.g., the most recent HB models (Caloi et al. 1997 versus Cassisi et al. 1998) do not agree on the \( L_{HB} \) at intermediate metallicity (for \([M/H]\) from \( \sim -1.5 \) to \( \sim -1 \)), and it is unclear why. The problem of GC ages is linked to minute details of the input physics, and we can not exclude an uncertainty of \( \sim 0.25 \text{mag} \) in the theoretical determination of the HB luminosity. So the real uncertainty on the age determination from the HB is still of ±several Gyr.

However, why the paradigm of the 15-16Gyr age was so difficult to be abandoned? In my opinion a part of the answer is the following: in the course of many years, the whole theoretical construction of the GC HR diagram had been adjusted to be consistent with about that age, so that is resulted very difficult to make drastic changes to that view. This interpretation becomes more clear by examining the relative location of TO and RGB in stellar models.

The TO color location is discussed in section 3. The input physics may affect it at a level of \( \sim 0.05 \text{mag} \). On the other hand, the RGB colors heavily depend on the treatment of convection. By changing the ratio mixing length to pressure scale height (\( \alpha = l/H_p \)) in the MLT formulation, the color location of the RGB may vary by tenths of magnitude (e.g. Vandenberg 1983). Although everybody knew that the \( \alpha \) choice was ‘ad hoc’, the “old” distance scale had this interesting outcome: by chance it had the additional bonus of giving a very good fit of the MS and RGB locations, if the models employed the same \( \alpha \) parameter which fitted the solar radius at the solar age (solar calibration of the mixing length). In addition, the solar calibration was also in good agreement with the location of the best known subdwarf Groombridge 1830. It was perhaps necessary to add some very small adjustment of colors, but the reproduction of the GC morphologies was indeed very good. The best example of this procedure is given by Bergbush and Vandenberg 1992: they show how they calibrate their color-\( T_{\text{eff}} \) relations (based on quite good model atmospheres) to provide a “consistent” picture for all metallicities. They also explicitly state that the transformations they adopt are OK for their own models, and that different adjustments might be required by other models. In spite of being very careful, the procedure adopted in Bergbush and Vandenberg 1992 (but also by others) implicitly hides both the choice of the distance scale (and thus the resulting 15Gyr or so) and the choice of the convection model, as I will now clarify. The fortuitous coincidence between the RG location in population II models with a solar calibrated \( \alpha \) led researchers to postpone the problem of

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2Some confusion was however present in the literature up to 1997 as to the absolute visual magnitudes corresponding to the \( \log L/L_\odot \) of the models (see e.g. the display in the lower panel of figure 1 from Caloi et al. 1997), so that the modification induced in HB models might appear more drastic in some authors’ comparisons.
a better understanding of superadiabatic convection. After 1997 the even small change of distance scale implied by the new HB models and by the Hipparcos subdwarfs re-calibration did not allow any longer to forget the problem: the same theoretical RGB, for a smaller age, provides a larger $\delta(B-V)$ and the theoretical RGs were too red. Thus the “new” ages required a change either in the convection modelling, or a different tuning of the correlations $T_{\text{eff}}$, or both. The situation is schematically shown in figure 4, in which I use an extreme difference in the distance modulus (0.25mag) to clarify the problem. Suppose that color magnitude diagram was well fit by an isochrone (open squares in figure 4. An update of the distance modulus to 0.25mag longer (and the adjustment of the color by 0.06mag, in the range of TO color uncertainties) provides now an age $\sim 6$Gyr younger, but it does not allow to fit of the RGB. A good fit requires a bluer RGB.

The modellers have tried to solve the problem of the discrepancy between the $\delta(B-V)$ and the new distance scale in the following ways:

1. they have increased $\alpha$ to obtain again the fit. On theoretical grounds, there is no scientific basis in the assumption that the $\alpha$ in different stars should be the same as in the solar model, so why not? This solution is adopted e.g. by Brocato et al. (1998) who discuss at length the effect described here for the case of the GC M68) and by Cassisi et al. 1998;

2. some researchers have considered again models with solar $\alpha$, but have chosen the color $T_{\text{eff}}$ relation in an appropriate way to reproduce the giant colors (it is generally possible to find good justifications for this choice also). This is the approach by Salaris and Weiss 1997, 1998: they adopt Buser and Kurucz (1978) colors for the giants, which are bluer by several hundredths of magnitude than the more recent ATLAS9 updated colors (see e.g. the comparison in figure 1 of Cassisi et al. 1999). In this way, the $\delta(B-V)$ between the TO and the RGB results smaller and can fit GCs shapes with the new distance scale.

3. there are a few attempts to try different convection models, which will generally not allow a “perfect fit”.

If one adopts the solutions 1) or 2), it is important to remember that the shape of the HR diagram loses any predictive power, as it has been fit already assuming a distance scale: just as the “spectacular fits” of a few years ago produced a 15Gyr answer, present day fits will produce a 10-12Gyr answer, but the quality of the fit has nothing to do with the truth of the answer. A better way of posing the problem, when an observer adopts a given set of tracks to infer the age of a new stellar system, would be to say that the system shows the same age of -or that its age differs from- the GC on which the track set has been more or less explicitly calibrated. It is not clear to me that even relative ages of GCs of different metallicities can be inferred from the $\delta(B-V)$ or $\delta(V-I)$ method, when we use a given MLT prescription which already is tested on the HR diagrams to fit a given distance scale.

The 3rd solution is less misleading, and it could in the end allow progress in the field, but it requires lots of work and maybe frustrating, as it produces results not always in “perfect agreement” with observations. A few such attempts to overcome the MLT are today available:

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3This “canonical” assumption was abandoned only in the Mazzitelli et al. 1995 paper, treating convection according to the Canuto and Mazzitelli (1991) model, and in Chieffi et al. (1995), who propose a calibration of $\alpha$ as a function of the cluster metallicity. This latter paper puts clearly into evidence that no predictions can be made on the RGB location on the basis of MLT models.

4One of the reasons why we could get the hint of a decrease in the GC ages two years before Hipparcos (Mazzitelli et al. 1995) was that we used a convection models by which it was not possible to get a fine tuning of the RG location.
1. the FST (or Full Spectrum Turbulence) models, based on the Camuto and Mazzitelli (1991) formulation, whose fluxes are in good agreement with experimental data, and are computed using modern closures of the Navier Stokes equations, and in which the scale length is assumed to be the distance from the convective boundary. Models have been computed by Mazzitelli et al. 1995, D’Antona and Mazzitelli 1997, Silvestri et al. 1998. This formulation of convection gives a different flavour to the HR diagram shape and it is less tunable than the MLT, an advantage in terms of predictive power, but a real failure if we want to obtain perfect fits. However, the Silvestri et al. (1998) models, which differ from the previous of our group mainly for the updated choice of color-\(T_{\text{eff}}\) transformations (Castelli 1998 versus Kurucz 1993), also provide a reasonable fit of the RGB as shown in figures 2 and 6 –but notice also the discrepancy in the case of M30 in figure 5.

2. Freytag and Salaris (1999) have calibrated the MLT \(\alpha\) by RHD models based on grids of 2D hydrodinamic simulations by Ludwig et al. 1999. Although numerical simulations are able to take into account only a relatively small number of eddies for a realistic description of turbulence, the Freytag and Salaris approach is an interesting novelty for this field.

3. an incongruence of FST models and of models not adopting a plain MLT description is that in any case they use till now grey boundary conditions, and the colors are obtained through transformations based on MLT model atmospheres. Models including, e.g., FST model atmospheres should be built up to get selfconsistent colors (Kupka, Schmidt and D’Antona 1999);

3 The TO and upper MS location

The location of the TO is affected by many uncertainties in the input physics, although not at the level of the RGB. If we wish to use the theoretical MS colors to determine an age, we must shift vertically the cluster HR diagram until it is superimposed to the MS of the observed metallicity, and then we determine the age from the TO luminosity. The MS is very steep in the TO region: a simple shift in color of the theoretical MS by +0.02mag implies a determination of age smaller by 2Gyr, not to talk about the possible uncertainty in the reddening. The main inputs affecting the MS and TO location are the following:

1. the convection description affects both the TO color and its shape (see the comparison between the MLT based description and the FST models in Mazzitelli et al. 1995 and D’Antona et al. 1997);

2. The helium gravitational and thermal settlings (diffusion) affect both the TO color and the age. A number of models are available, starting from Proffitt and Michaud 1991, up to D’Antona et al. 1997, Straniero et al. 1997 and Cassisi et al. 1998);

3. the color - \(T_{\text{eff}}\) relation is affected by the convection treatment in the atmosphere (cf. Kurucz 1993 versus Castelli 1998 models).

Everything included, the absolute determination of the TO and upper MS colors is uncertain by \(\sim 0.05\)mag, so that it is better not to rely on colors for age determination.

I add a few words about the possible effect of helium diffusion. It is today well settled that it is necessary to include the treatment of microscopic helium diffusion to account for some details. 

\(^5\)see Kurucz website [http://cfaku5.harvard.edu](http://cfaku5.harvard.edu)
of the seismic Sun (Bahcall and Pinsonneault 1995, Basu et al. 1996), but the evaluation of the diffusion coefficients is difficult, and its application to models not always well clear in the researchers description. The diffusion affects both the TO color and the age: age reductions from 5-10% to 20% are found, and the TO color may be affected up to 0.1mag in some models. An important warning first issued by Deliyannis and Demarque (1991) must be kept in mind: diffusion affects lithium nearly in the same way as helium, thus: “the properties of the Spite plateau in population II severely restrict the amount of diffusion induced curvature that can be tolerated in a lithium isochrone”. In other words, the effect of “too much” diffusion would appear in a smaller lithium abundance for the hotter population II stars, a fact which is not verified in the halo subdwarfs, which show a remarkably flat lithium abundance versus $T_{\text{eff}}$ (the Spite and Spite 1982 plateau)\footnote{Here again we attribute to GCs stars the same properties of the nearby subdwarfs. Actually, the lithium behaviour at the TO of GCs might be a bit different than in the field stars. Boesgaard et al. 1998 show that the M92 TO stars have a larger scatter in lithium than field stars. The Spite’s plateau must still be confirmed by extensive GC stars observations, which are becoming possible with the new generation telescopes.}. Chaboyer et al. 1992 show that an age reduction up to 3Gyr (15%) is in principle possible for GCs when diffusion is included in the computation, but they find that the lithium isochrones imply a maximum age reduction by 1Gyr ($\sim$ 7%).

In conclusion, also the theoretical TO – upper MS color location is affected by uncertainties by which the absolute age determination, again, can not be known to better than $\pm$ several billion years.

4 Location of the lower MS

The “double kink” shape of the low MS of GCs is due to the influence of the interior physics on the structure of low mass stars. The appearance of the FK is attributed mainly to the to the lowering the adiabatic gradient when the $H_2$ dissociation begins to be present in envelope (below $\sim$ 5000K). The SK is associated with the reaching of degeneracy in the interior (D’Antona and Mazzitelli 1996). The shape of the low MS can be a powerful tool, first to constrain the models, and then to constrain the GC parameters.

As first shown by Baraffe et al. 1995, when the formation of molecules begin to be important in the stellar atmosphere (at $T_{\text{eff}}$ $\lesssim$ 5000K) the grey atmospheric integration fails to give a good description for the boundary conditions: in summary, it underestimates the opacities and does not account for the opacity distribution with wavelength. The net effect is that the grey integration provides much larger pressure and density at the bottom of the atmosphere. In the interior, the temperature gradient is the adiabatic gradient, so that finally the same central conditions give a larger $T_{\text{eff}}$. Figure 5 shows in fact that, for the same chemistry, non–grey models are redder by $\sim$ 0.06mag with respect to grey models. This also implies that the metallicity and probably also the element to element ratios, are important to determine the location of the FK. This is certainly a powerful tool, but also makes the region below the FK very dependent on the model inputs.

Te EoS adopted for these low mass models is also an important ingredient. It determines the slope of the region between the two kinks and, together with the atmospheric integration, it influences the mass luminosity relation, which is the most important input for the interpretation of the luminosity functions of the MS in terms of mass function. There are still substantial uncertainties close to the bottom of the main sequence (see Montalban et al. 1999).

Figure 5 summarizes the uncertainties in the low MS location and part of the uncertainties in the upper MS and TO locations. We see that there is a region between $M_v = 6$ and 7 at which the uncertainties in color transformations, convection, diffusion, boundary conditions...
seem to play almost no role: This region, then, is the best to be used as distance indicator for the MS.

5 Consistency of HB and low MS distance indicators

The new HST data which have so much extended our knowledge on the low luminosity part of the HR diagram put an interesting problem: is there consistency between the “optical” traditional distance indicators for GCs and the location and shape of the low MS?

We can check this idea by following this procedure: first we can fit the optical data to the RR Lyrae (or HB) to derive a distance, and check the reddening by controlling the MS location at \( M_v \sim 6 - 7 \); then we adopt the same reddening and distance modulus for the MS HST data. This allows us to see if the MS and first kink location are consistently reproduced.

We show in the figures \( \text{\textbullet} \) and \( \text{\textbullet} \) the check on the low metallicity ([M/H]=-2) clusters M92 and M30, finding excellent consistency. The comparisons are equally good in the HST color bands (F555 and F814) and in the transformed Johnson–Cousins bands \( V \) and \( I \) (in fact these HST bands and the standard magnitudes are only marginally different). Thus, on the one side the location of the FK provides a check of the distance, on the other side we gain confidence in the good quality of the low mass models including non grey boundary conditions.

Here again we must admit that this result is not unique: if we assume for M30 a short distance modulus, say \((m - M)_0 = 14.5\), the general agreement of the sequences would still be reasonable (and the age would increase to \(~ 16\text{Gyr}\)). Of course our HB models would not fit the HB luminosities of the cluster, but we have agreed that even a small change in the input physics may lead to less luminous HBs.

6 The distance through the fit to the lowest MS

This approach has been applied by Reid and Gizis (1998) to the only cluster for which the lowest main sequence, the post-SK region, is known, namely NGC 6397 (figure 1). This part of the HR diagram is populated by stars which are close to degeneracy in the interior, so they are close to the minimum mass which can ignite hydrogen. The mass–luminosity relation here is very steep, that is, the stars have practically all the same mass, and the HR diagram location follows a constant radius line. In addition, the degeneracy radius is not so much dependent on the details of the structure, and this locus is very similar for all GC metallicities. Thus, although the models are not well understood in detail here (Montalban et al. 1999), if we have a reasonable sample of M subdwarfs with known distances and accurate colors, we can fit the GC sequence to the nearby sequence and get the distance modulus. The example of the fit by Reid and Gizis (1998) is very interesting, and provides for NGC 6397 a not unreasonable modulus \((m - M)_0 = 12.13 \pm 0.15\text{mag}\), again consistent with the long distance moduli and short ages. We need a better definition of the lowest MS through a larger sample of M subdwarfs, and more GC explored down to the post-SK region, to make this distance indicator more useful.

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7Some further indications on the choice of the “best” distance can come from the comparison of the observed and theoretical luminosity functions: D’Antona (1998) and Silvestri et al. (1998) show that the non monotonic mass functions derived, e.g. by Piotto et al. 1997, and by others, were mostly due to the use of too short a distance modulus for the examined clusters.
7 White dwarfs

There are by now three well defined WD sequences for GCs: NGC6752 (Renzini et al. 1996), NGC6397 (King et al. 1998, see figure 1) and M4 (Richer et al. 1997). For the two latter clusters, the location of the WD sequence is consistent with the cooling track for $M \simeq 0.5 M_\odot$ by Wood (1995) models transformed into the observed magnitudes by means of Bergeron et al. (1995) model atmospheres (see Richer et al. 1997). The errors on the reddening of the clusters and on the model observational colors are yet such that we can not quantify better this general statement. The data of NGC6752 have been compared by Bragaglia et al. with a “standard” sequence of field WDs spectroscopically determined to be of mass $\simeq 0.5 M_\odot$ (from the list of Bragaglia et al 1995). They obtain a “short” distance modulus, and an age of $\sim 15$Gyr (even assuming a large $\alpha$–enhancement). This result is then marginally discrepant from the others we have quoted so far.

On the other hand, from Wood (1995) models we see that $\Delta M_v/\Delta M_{wd} \simeq 2.5$. In other words, a small uncertainty (by 0.1$M_\odot$) in the mass determination for the field WD sample produces a noticeable difference (by 0.25mag) in the WD sequence location, which results in an age difference close to 4Gyr. Do we know the spectroscopic masses within 0.1$M_\odot$? We know that the spectroscopic masses of helium atmosphere WDs are highly uncertain, some uncertainty surely weighs also on the DA type WDs. It is also possible that the field WDs differ from the GC WDs in other ways: the environment in which they are born is very different and may imply, e.g., different accretion rates, much larger in the disk than in the GC, which is devoid of gas and dust. Although the sedimentation of metals is very efficient in these high gravity stars, it is well possible that some residual effect from accretion affects the stellar radius.

8 Summary

I conclude with the following short summary:

- Morphological fits including the RGB are meaningless in terms of age determination;
- The traditional best theoretical distance scale still mostly relies on HB models, and on the MS colors at $M_v \sim 6 - 7$.
- the small versus large ages only require a difference of $\simeq 0.25$mag of distance modulus;
- The uncertainties in HB, TO, MS, WDs sequences location are all of the same order of magnitude: namely: $\sim 0.25$mag;
- then we can make no firm choice between 10-12 and 14-16Gyr age;
- however most recent theoretical and observational results, including the new constrains on distance by the very low luminosity stars, all point towards the smaller range of ages.

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Figure 1: Composite HR diagram for the stars in NGC6397. The upper part is adapted from Kaluzny 1997, the giants and turnoff data are from Cool 1997, and the main sequence down to its low end, plus the white dwarfs are from King et al. 1998.

Figure 2: Main evolutionary and structural phases in the HR diagram: WD: 0.5\(M_\odot\)CO cooling track from Wood 1995; MS: from Baraffe et al. 1997 (BCAH97) for [M/H]=-1.5; TO+RGB: 12Gyr isochrone from Silvestri et al. 1998; HB from Caloi et al. 1997; AGB is schematized.

Figure 3: In recent years, very small variations in the HB model luminosity and in the TO luminosity for fixed age have produced a relatively huge effect on the age determination. The “OLD” lines represent a typical location in absolute visual magnitude of HB (top) and TO (bottom) models in old stellar models. A small increase in the HB luminosity (by \(\sim 0.07\)mag) has been due to the update in the interior EoS of HB models (Rogers et al. 1996), another increase by \(\sim 0.07\)mag has been due to a small increase in the core mass at the Helium flash (see Caloi et al. 1997). At the same time, the TO luminosity at a given age has been slightly decreased by updates in the EoS (again it is an effect of the Rogers et al. 1996 EoS, found by Chaboyer and Kim 1995 and D’Antona et al. 1997) and another small decrease (again by \(\sim 0.07\)mag can be attributed either to the convection model (a shape effect due to the Canuto and Mazzitelli 1991 treatment of convection, in Mazzitelli et al. 1995 and D’Antona et al. 1997), and/or to the influence of helium diffusion (gravitational settling). In total, the new models give a \(\Delta V\) between TO and HB which is \(\sim 0.27\)mag larger, and therefore a given \(\Delta V\) corresponds to an age \(\sim 4\)Gyr lower.

Figure 4: A schematic view of the problem with the RGB location is shown: a good fit with a distance scale which would provide 16Gyr age for a cluster, is no longer OK if the distance modulus is increased. Here we show an increase by 0.25mag to emphasize the problem, but the situation is similar if the shift is smaller. In practice, a more efficient convection, or a different color – \(T_{\text{eff}}\) relation for the RGB, is necessary to fit again the RGB, as shown by the dotted line. In this sense, all set of tracks have their convection treatment plus color-\(T_{\text{eff}}\) relations “calibrated” on a distance scale.

Figure 5: In the plane \(M_v\) versus \(V - I\) the effect of some important physical inputs on the HR diagram location is shown. The low main sequence location is about \(0.06\)mag redder when models are computed with non grey boundary conditions (Montalban et al. 1999), with respect to the grey atmosphere models (Silvestri et al. 1998). Luckily, the color-\(T_{\text{eff}}\)relations for the low main sequence are not so dependent on the employed transformations, as shown by the location of the Silvestri et al. models transformed via the Allard and Hauschildt 1997 NextGen models (AH) or with Castelli 1998 models. On the contrary, the transformations produce a small shift of the turnoff color, by \(\sim 0.03\)mag. At the TO, also the treatment of convection affects the isochrone colors. The less critical models are those of masses \(\sim 0.6 - 0.65\)\(M_\odot\) and \(M_v \sim 6 - 7.5\), where the non-grey boundary conditions are not yet important, and where the effect of superadiabaticity and also the effect of diffusion are minimum. This is then the best region where to require a fit of the theoretical and observational main sequence.
Figure 6: Composite HR diagram for M92. The left part shows the fit of the optical ground based data in $V$ versus $B-V$, including the HB (from Buonanno et al. 1985) and the RGB+TO+MS data (from Stetson and Harris 1988). The right part are the Andreuzzi et al. HST data shifted at the distance of and dereddened as the optical data. We adopt $E(V-I) = 1.3E(B-V)$ based on Allard and Hauschildt model atmospheres. The isochrones are from Montalban et al. (1999) for the indicated chemistry.

Figure 7: The same comparison is shown for M30. The optical data (from Piotto et al. 1990 for the MS and TP, and from Buonanno et al. 1985 for the RGB and HB) are fitted by assuming a distance modulus of 14.7 and $E(B-V)=0.04$. The same choice provides a good reproduction of the HST data for the MS including the first kink. The dashed line here and in figure 6 is the corresponding 12Gyr isochrone from D’Antona et al. 1997 (DCM), which employed Kurucz (1993) color transformations and grey atmosphere models.
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