Towards an accurate determination of the age of the Universe

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Abstract.
In the past 40 years a considerable effort has been focused in determining the age of the Universe at zero redshift using several stellar clocks. In this review I will describe the best theoretical methods to determine the age of the oldest Galactic Globular Clusters (GC). I will also argue that a more accurate age determination may come from passively evolving high-redshift ellipticals. In particular, I will review two new methods to determine the age of GC. These two methods are more accurate than the classical isochrone fitting technique. The first method is based on the morphology of the horizontal branch and is independent of the distance modulus of the globular cluster. The second method uses a careful binning of the stellar luminosity function which determines simultaneously the distance and age of the GC. It is found that the oldest GCs have an age of $13.5 \pm 2$ Gyr. The absolute minimum age for the oldest GCs is 10.5 Gyr and the maximum is 16.0 Gyr (with 99% confidence). Therefore, an Einstein-De Sitter Universe ($\Omega = 1$) is not totally ruled out if the Hubble constant is about $65 \pm 10$ km s$^{-1}$ Mpc$^{-1}$. On the other hand, the newly discovered red elliptical 53W069 ($z = 1.43$) provides an stronger constraint since its minimum age is 3.2 Gyr, thus ruling out an Einstein-De Sitter Universe unless the Hubble constant is $\leq 45 \pm 10$ km s$^{-1}$. Using 53W069 we find an age at $z = 0$ of $13 \pm 2$ Gyr, in excellent agreement with the GC determination.

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1. Globular cluster ages

GCs are the best stellar clocks to establish a lower limit to the age of the Universe at $z = 0$ since they fulfill the following properties: all the stars were born at the same time, the population is chemically homogeneous and there has been no further episodes of star formation that gave birth to new stars which could cover up the oldest population. Support for GCs being old comes from two facts: their metallicity is as low as 1/100 of solar and the characteristics of their colour-magnitude diagram are those corresponding to ages larger than 10 Gyr, i.e. the stars around the main sequence turn-off have masses lower than 1 $M_\odot$. Despite the continuous effort carried out during more than 40 years to give a precise value for the age of GCs, the uncertainty in their age still remains about 4Gyr. The problem is particularly complicated because age and distance have the same effect on the morphology of the main sequence turn off point (MSTO). Deficiencies in the input physics combined with the uncertainties in cluster distances and interstellar reddening have made it difficult to determine globular cluster ages with an accuracy better than about 25%.

In this review I present two alternative methods used to derive ages of GCs that are independent of the traditional MSTO fitting. The first method is based on the morphology of the horizontal branch (HB), and uses the reddest points in the HB to determine the mass of the stars in the RGB (Jimenez et al. 1996). This method is independent of the distance modulus, and is therefore a useful tool to compute systematics in age determinations using the traditional MSTO fitting technique. The second of the methods is based on a careful binning of the luminosity function (LF), and determines simultaneously the age and distance of a GC. It is therefore a very useful technique to determine distances to GC independently of the subdwarf fitting and RR-Lyrae techniques. It is also very powerful in determining relative ages of GCs with little error.

1.1. The Isochrone fitting method

The first (and more obvious) method to compute the age of a GC is to exploit the fact that the locus of the MSTO in the plane $T_{\text{eff}}$ vs. $L$ changes with age (mass). In this way one computes different isochrones, i.e. tracks in the plane $T_{\text{eff}}$ vs. $L$ at the same time for all masses, with the chemical composition of the GC to find the better fit to the MSTO region. To do this a very important step is needed: the distance to the GC has to be known in order to transform the theoretical luminosity into observed magnitudes in different bands, and here is where the trouble starts. If the distance to the GC is unknown, there is a degeneracy between age and distance and we can simulate a different age by simply putting the GC closer or more distant.
to us. If we assume the GC is closer than it really is, we will overestimate its age.

Distances to GCs are very poorly known since it is impossible to get the parallax of individual stars and therefore ages of GCs are not accurately known using the isochrone fitting method. Usually, there are different methods to compute distances to GCs: the RR-Lyrae method; the subdwarf fitting method; the tip of the red giant branch; and the luminosity function. The RR-Lyrae method consists in using the known Period-Luminosity relation for the RR-Lyrae pulsators in the HB. This method gives an uncertainty of 0.25 mag in the distance modulus determination, which translates to a 3 Gyr error in the age determination. The subdwarf method uses the nearby low metal subdwarfs to calibrate the distance of GCs; again its uncertainty is about 0.2 mag. The tip of the RGB method uses the fact that stars at the tip of the RGB flash have a well defined luminosity (Jimenez et al. 1996); therefore the tip of the RGB is well defined and can be used as a distance indicator. The luminosity function method is explained later in this review. It gives more precise distance determination, and the error in the distance is only 0.05 mag. Recently, new parallaxes of local subdwarfs determined by Hipparcos have increased the distance inferred by the subdwarf method to GCs and have therefore reduced the ages of GCs (e.g. Chaboyer et al. 1998)

In order to circumvent the need for the distance determinations in computing the age, Iben & Renzini (1984) proposed an alternative method for deriving ages using the MSTO, the so-called $\Delta V$ method. The method exploits the fact that the luminosity of the MSTO changes with mass (age) and not only its $T_{\text{eff}}$. Also, the luminosity of the (HB) does not change since the core mass of the He nucleus is the same independently of the total mass of the stars (provided we are in the low mass range), and the luminosity in the HB is provided by the He core burning. Since the method is based on a relative measure (the distance between the HB and the MSTO), it is distance independent. Of course, the method needs the knowledge of at least one GC distance in order to be zero calibrated. Unfortunately, the method has a serious disadvantage: the need to know accurately the location of the MSTO point. This turns out to be fatal for the method since it has associated an error of 3 Gyr in the age determination.

Furthermore, all the above methods are affected by three main diseases: the calibration colour-$T_{\text{eff}}$; the calibration of the mixing-length parameter ($\alpha$); and the need to fit morphological features in the CMD (i.e. the MSTO). See Table 1 for a detailed review of all errors involved in the different methods.

The most common ages obtained for the oldest GCs using the MSTO method are in the range 14-18 Gyr. Nevertheless, an error bar of 3 Gyr is associated with all age determinations using the MSTO methods described
above.

1.2. The Horizontal Branch Morphology Method

The spread of stars along the HB is mainly due to previous mass loss which varies stochastically from one star to another (Rood 1973). The range of colours where zero-age HB stars are found is a function of metallicity (the “first parameter”) and of the range of ZAHB masses. More precisely, the ZAHB colour at given metallicity depends on both the star’s total mass and the ratio of core mass to total mass, but the core mass is essentially fixed by the physics of the helium flash and is quite insensitive to the mass and metallicity. For a given average mass loss, the average final mass is thus a decreasing function of age, which is therefore a popular candidate for the “second parameter” (Searle & Zinn 1978), although other candidates such as CNO abundance have also been suggested. A strong case for age as the chief (though, perhaps, not necessarily the only) second parameter has been made by Lee, Demarque & Zinn (1994), who find a tendency for the clusters to be younger in the outer Galactic halo. Jørgensen & Thejll (1993), using analytical fits to a variety of RGB models and following evolution along the RGB with mass loss treated by Reimer’s (1975) formula, showed that, for clusters with narrow RGBs (the majority), star-to-star variations in initial mass, metallicity or mixing-length parameter can be ruled out as a source of the spread along the HB, leaving as the only likely alternative variations in the Reimers efficiency parameter \( \eta \) (or some equivalent).

A method that is independent of the distance modulus can be developed using the fact that the spread of stars along the HB is mainly due to previous mass loss which varies stochastically from one star to another. It is therefore meaningful to proceed to an analysis of both the RGT and the HB and to link them together to deduce general properties from morphological arguments. The procedure that we use to analyse the morphology of the RGB and the HB together and constrain the mass of the stars at the RGB is as follows: Since the vertical position of the RGB depends only on metallicity and \( \alpha \), once the metallicity is known \( \alpha \) is the only free parameter. Therefore, we can find a fit for the best value of \( \alpha \), using the vertical position of the RGB. The reddest point of the HB corresponds to zero mass loss and therefore to the most massive stars that are alive in the GC and therefore the oldest. Using HB theoretical models we can determine the mass of the reddest point of the HB. So it is possible to compute stellar tracks for a certain input mass and iterate until the track at the zero age horizontal branch matches the reddest point of the observed HB. In Jimenez et al. (1996) we analysed eight GCs using the above method and found that the oldest GCs were not older than 14 Gyr.
1.3. The Luminosity Function Method

The LF seems to be the most natural observable to try to constrain both age (Paczynski (1984); Ratcliff (1987)) and distance at the same time. The LF is a natural clock because the number of stars in a given luminosity bin decreases with time, since more massive stars evolve more rapidly than less massive ones. The fact that small differences in stellar masses correspond to large differences in evolutionary time explains the power of the LF clock, rather than being a source of uncertainty in obtaining GC ages (as it is in the MSTO method). The LF is also a natural distance indicator, because the number of stars in a given luminosity bin depends on the position of the bin.

For a determination of both distance and age, one needs to obtain from the LF at least two independent constraints, which means three bins in the LF, since one is required for the normalization. A fourth bin is also very useful in order to check for the completeness of the stellar counts. The second bin, the main constraint for the distance modulus, is positioned between the RGB and the SGB (sub-giant branch), in order to partially contain the steepest section of the LF (this gives the sensitivity to a translation in magnitude.). The third bin, the main constraint for the age, contains the SGB, because this is the part of the LF that is most sensitive to age. The fourth bin is just next to the third one, and will typically include the upper part of the main sequence. The procedure to obtain the LF from evolutionary stellar tracks is illustrated in Jimenez and Padoan (1996). A power law stellar mass function is assumed here, as in that work.

In Fig. 1 I show the result of applying the LF method to the galactic globular cluster M55. The plot shows contour plots for the error in the determination of the distance modulus and age of M55 simultaneously. The contour plots correspond to different values for the uncertainty in the number of stars in the luminosity function. If stellar counts are within an uncertainty of 5%, then the age is determined with an uncertainty of 0.5 Gyr, and the distance modulus with an uncertainty of 0.06 mag. The LF method is therefore an excellent clock for relative ages of GCs, and also a very good distance indicator. In other words, its application provides very strong constraints for the theory of the formation of the Galaxy.

An age of 12 Gyr obtained for M55 confirms the conclusion of the Hubble morphology method that GCs are not older than 13 Gyr.

1.4. Discussion

Table 1 lists the uncertainties involved in each of the three methods described above to determine GC ages. As already discussed the MSTO
Figure 1. Distance and age for the low metallicity globular cluster M55 simultaneously determined using the LF method (see main text). The contour lines show that the age can be determined with 1 Gyr accuracy and the distance modulus with 0.05 provided the number of stars in the LF can be complete to a level of 5%.

method is largely affected by the uncertainty in distance, but also uncertainties in the mixing length, diffusion of heavy elements and in the colour-$T_{\text{eff}}$ relation.

The HB method uses the fact that mass loss along the RGB is the chief cause of the HB morphology. This may seem to introduce an additional uncertainty in the method since mass loss in low mass stars is unknown. In

Table 1. Errors associated with the different methods described in the text to compute the age of the oldest globular clusters. The first column lists the main uncertainties when computing GC ages.

|                  | MSTO | HB  | LF  |
|------------------|------|-----|-----|
| Distance Modulus | 25%  | 0%  | 3%  |
| Mixing Length    | 10%  | 5%  | 0%  |
| Colour-$T_{\text{eff}}$ | 5%  | 5%  | 0%  |
| Heavy Elements Diffusion | 7%  | 2%  | 7%  |
| $\alpha$-elements | 10% | 5%  | 10% |
| Reddening        | 5%   | 10% | 0%  |
fact the only stars used to determine the mass at the RGB are the reddest ones, that do not suffer any mass loss. The evolution with mass loss along the RGB was done using the method developed in Jimenez et al. (1996) that describes the mass loss efficiency parameter with a realistic distribution function and minimizes its model dependence. Furthermore, the HB method is insensitive to changes in CNO abundances. The reason for this is that if CNO is enhanced with respect to iron the HB becomes redder leading to a smaller mass for the reddest point of the HB but since the stellar clock also goes faster, both effects compensate. The HB morphology method is weakly sensitive to diffusion by heavy elements (J. MacDonald private communication).

The LF method needs to know the metallicity of the GC. Apart from this, the LF method is the one with the smallest errors among the three methods described here. The biggest advantage of the LF method is that it is insensitive to the mixing-length, reddening and colour-T\textsubscript{eff} transformation. Since the LF method is based on counting stars in several bins, it is independent of fitting to morphological features in the observed CMD of the GC. Therefore the LF method is a superb technique to determine relative ages of GCs.

2. Determining the age of the Universe from its high-redshift galaxies

Traditionally, the aim of determining the age of the Universe has been focused on stellar objects at z = 0. The reasons are obvious: individual stars can be resolved in stellar populations and 4m class telescopes can be used to achieve high signal-to-noise ratios. Furthermore, at redshift larger than 0.5 is impossible to identify the globular clusters of a host galaxy. One would wish to identify galaxies that are themselves good stellar clocks, i.e. their stellar population was born at once with no further episodes of star formation. However, the most problematic issue is how to find galaxies at high redshift. The study of ‘normal’ star-forming galaxies at z > 2 has developed into a booming astronomical industry over the past 3 years (e.g. Steidel et al. 1997). Since most high-redshift galaxies are optically selected, one is biased towards blue objects that show recent star formation, i.e. biased towards composite stellar populations with several episodes of star formation. In this way, one can only hope to determine the age of the youngest stars at high-redshift, not a very useful age indicator. Nevertheless, a few valiant efforts have been carried out in order to determine the age of the stellar populations in high-redshift galaxies (Chambers & Charlot 1990).

A more promising way to find passively evolving objects is utilizing radio galaxies. One of the cleanest results in extra-galactic astronomy is
Table 2. A comparison of age estimates for the stellar population of 53W069 as derived from the instantaneous burst models of Bruzual & Charlot (B&C), Worthey (1998) (W) and Jimenez et al (1999) (J99), when used to fit different spectral indicators of age.

| Feature   | B&C     | W98     | J99     |
|-----------|---------|---------|---------|
| UV-SED    | 3.3 Gyr | 3.2 Gyr | 4.0 Gyr |
| $R - K$   | 1.6 Gyr | 3.0 Gyr | 4.0 Gyr |
| 2649 Å    | 5.0 Gyr | 4.0 Gyr | 4.0 Gyr |
| 2900 Å    | 4.5 Gyr | 4.2 Gyr | 4.5 Gyr |

that all powerful ($P > 10^{24}$ WHz$^{-1}$sr$^{-1}$) radio sources in the present-day universe are hosted by giant ellipticals. It is then reasonable to assume that high-redshift radio sources also reside in ellipticals or their progenitors. By selecting radio galaxies at mJy flux levels we (Dunlop et al. 1996, Spinrad et al. 1997, Dunlop 1998, Dey et al. 1999) have shown that it is possible to find examples of well evolved galaxies at $z \sim 1.5$ whose near-ultraviolet spectrum is uncontaminated by a recent burst of star formation or by an AGN. Keck spectroscopy of these objects has yielded the first detection of stellar absorption features from old stars at $z \leq 1.5$ and thus the first reliable age-dating of high-redshift objects. The best example in our sample is 53W069 and I will concentrate in the rest on this review in giving a robust estimate of this object’s age.

2.1. The age of 53W069

The spectral energy distribution (SED) of 53W069 is presented in Fig. 2. In order to determine its age I have performed properly weighted chi-squared fits to the ultra-violet SED using the popular Worthey and also Bruzual & Charlot synthetic stellar population models and the models developed by our group (Jimenez et al. 1999). The results are listed in Table 2. A few important points are obvious from this table. First, all models yield ages larger than 3 Gyr for 53W069. Second, column 1 shows that the Bruzual & Charlot models seem to be internally inconsistent in the sense that they are capable of reproducing very red $R - K$ colours at a much younger age than they can reproduce the ultraviolet SED or the spectral breaks. However, since $R - K$ is mainly affected by the evolution of the late stages of stellar evolution, once should focus on ages derived from the UV-spectrum since this only depends on the correct prediction of the MSTO, a simpler and thus an easier part to model. Indeed, not do so it tantamount to throwing away the new, more robust information which can be gleaned from the
Figure 2. Left panel: the spectrum of 53W069 overlaid with the best fitting Bruzual-Charlot model, which has an age of 3.3 Gyr. Right panel: Same as before but now overlaid with the best fitting model from Jimenez et al. (1999), which has an age of 4.0 Gyr.

Spectroscopy. If one focuses on the results of 53W069 then, ignoring the anomalously young $R - K$ age produced by the Bruzual &Charlot models, all models are basically in good agreement that the overall shape of the UV SED and the strengths of the main spectral features are consistent with an age in the range 3.0 to 4.0 Gyr, and certainly yielding a robust (99% confidence) minimum age of 3.0 Gyr.

Spectroscopically, 53W069 thus appears to be the best known example of old, passively-evolving elliptical galaxies at redshifts as high as $z \sim 1.5$.

Using WPFC2 and NICMOS images below and above the 4000 Å break we have verified that this also holds for its morphological properties and scalelengths (Dunlop 1998). Using a 2-dimensional fitting code it is possible to show that 53W069 is consistent with a $r^{1/4}$ law and inconsistent with an exponential disc profile. Furthermore, a physical half-light radius of $r_e \approx 4$ kpc has been obtained assuming $\Omega = 1$ and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, which lies exactly in the Kormendy relation for ellipticals.

In summary, the new data on 53W069 clearly show that the Universe at $z \sim 1.5$ contains stellar systems whose populations are 3 to 4 Gyr old. At $z \sim 1.5$ the Universe was less than 30% of its present age, and the uncertainties are largely independent of those encountered in GCs studies. The existence of 53W069 permits only low Hubble constants and/or low cosmic densities; in particular, an $\Omega = 1$ Universe requires $H_0 \leq 45$ km s$^{-1}$ Mpc$^{-1}$. On the other hand, in an Universe with a cosmological constant, 53W069 requires $\Omega_\Lambda \geq 0.4$ if $H_0 \geq 60$ km s$^{-1}$ Mpc$^{-1}$
3. Conclusions

The main conclusions of this review are:

1. The two methods presented in this paper agree on an age of about 13 Gyr for the oldest GCs. The minimum possible age is 10.5 Gyr and the maximum 16 Gyr, with 99% confidence.

2. A more accurate determination of the age of the Universe can be obtained using high-redshift elliptical galaxies. 53W069 is one of the reddest objects at $z \sim 1.5$ and has an age of at least 3 Gyr. This yields to an age of the Universe of 13 Gyr at $z = 0$, in excellent agreement with the GC determination. This age totally rules out an Einstein de-Sitter Universe unless $H_0 \leq 45 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

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References

Chaboyer, B., Demarque, P., Kernan, P.J., Krauss, L.M., 1998, ApJ, 494, 96.
Chambers, K.C., Charlot, S., 1990, ApJ, 348, L1.
Dey et al., 1999, in preparation.
Dunlop, J., 1998, astro-ph/9801114.
Dunlop J., Peacock J., Spinrad H., Dey A., Jimenez R., Stern D., Windhorst R., 1996, Nature, 381, 581.
Iben I., Renzini A. (1984) Phys. Rep., 105, 329.
Jimenez et al., 1999, MNRAS, in press.
Jimenez R., Padoan P. (1996) ApJ 463, 17L.
Jimenez R., Thejll P., Jørgensen U.G., MacDonald J., Pagel B. (1996) MNRAS, 282, 926.
Jørgensen U.G., Thejll P. (1993) A& A, 272, 255.
Lee Y., Demarque P., Zinn R. (1994) ApJ, 423, 380.
Ratcliff S. (1987) ApJ, 318, 196.
Reimers D. (1975) ‘Circumstellar envelopes and mass loss of red giants’, In: Problems in stellar atmospheres and envelopes, Springer-Verlag, p. 229.
Rood R.T. (1973) ApJ, 184, 815.
Searle L., Zinn R. (1978) ApJ, 225, 357.
Spinrad H., Dey A., Stern D., Dunlop J., Peacock J., Jimenez R., Windhorst R.,
1997, ApJ, 484, 581.
Steidel et al., 1997. astro-ph/9708125.
Paczynski B. (1984) ApJ, 284, 670.
Padoan P., Jimenez R. (1997) ApJ 475, 580.