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The Ages of the Galactic Globular Clusters

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Abstract. The Galactic globular clusters are believed to be among the most ancient objects for which reliable ages can be determined. As the Universe can not be younger than the oldest object it contains, the oldest Galactic globular clusters provide one of the few most important constraints that one can have on cosmological models. Latest estimates indicate that the absolute age of the oldest globular clusters is 14 ± 3 Gyr. The calibration of absolute ages is still subject to observational and theoretical uncertainties at the ≈ 20% level, and represents a major limitation on our ability to test cosmological models. However, relative ages are starting to be much better known due to the super colour-magnitude diagrams that have been obtained through the use of CCD detectors on large telescopes and the Hubble Space Telescope. The available data are consistent with the majority of Galactic globular clusters being virtually coeval but with a minority having significantly lower ages. The existence of "prehistoric" clusters with ages of around 50 Gyr, as hypothesised in the quasi-steady state cosmology, should be readily recognised.

Key words. Stellar system—star clusters—ages.

1. Introduction

The age of a star is an important parameter for a number of astrophysical investigations and its determination is one of the fundamental problems of present day research. In order to estimate the age of a star, one should know at least its intrinsic luminosity, effective temperature, chemical composition, and evolutionary stage. Therefore, from the observational point of view, the ages of members of star clusters are more easily estimated than that of field stars. Sagar (1985) has discussed the existing methods for age estimation of open clusters of our galaxy alongwith the uncertainties arising from the different sources. In this work, the uncertainties and difficulties present in the age estimation of Galactic globular clusters (GCs) are analysed.

A nearly spherical spatial distribution of the Galactic GCs about the galactic centre and their low metallicity indicate that they were among the first objects to form in our galaxy. An accurate determination of their ages is, therefore, essential not only for providing constraint on the observed age of the Universe in cosmological models but also for telling us whether the collapse of the galactic halo was rapid or slow – thus providing initial input into our understanding of the evolution of galaxies. Recent technological advances, in particular the advent of CCD detectors and modern data reduction techniques, have led to a dramatic improvement in the accuracy of photometry and abundance determination of stars in clusters. Consequently, the uncertainties in the derived ages of the GCs are steadily being reduced. This review presents a status report of our current understanding.

2. Absolute globular cluster ages

In order to determine the absolute age of a given GC, appropriate theoretical stellar evolutionary isochrons are fitted to its observed colour-magnitude diagram (CMD). For reliable age estimation, not only the temperature scale of the models and transformation relation between T_{eff} and colour have to be known accurately, but also the reddening, distance and metallicity of the cluster. One of the great uncertainties in stellar models is the treatment of convection. Hence, stellar models are somewhat uncertain in regions where convection is important. This includes the outer layers of the model for the low-mass main-sequence (MS) stars which make up globular clusters. As the cores of such stars are not convective, the modeled stellar lifetimes and luminosities are reliable. Consequently, luminosity (Mv(TO)) of the main sequence turn-off (MSTO) is the best stellar clock which can be used to determine the absolute ages of GCs. The latest review on this topic is by VandenBerg *et al.* (1996). They firstly assess implications of our present understanding at absolute cluster ages on cosmological models. The precision with which MSTO and unevolved MS stars could be photometered increased very dramatically, due to availability of CCD detectors on 4-metre class telescopes e.g., see CMD of NGC 6752 obtained by Penny & Dickens (1986) using 3.9 metre Anglo-Australian Telescope. This has led to more precise determination of the MSTO colour and brightness. However, a small error in colour (which can be due to calibration inconsistencies, uncertainties in the reddening and in [M/H] for cluster stars) near the MSTO would lead larger error in Mv(TO) since the slope of the zero-age main sequence (ZAMS) is steep (Δ(B-V)/Δ(Mv) $\approx$ 5.5) around that point. Consequently, an uncertainty of 0.02 mag in colour would translate into an error of $\approx$ 0.1 mag in the derived distance modulus and hence $\approx$ 1.5 Gyr in age.

Operationally, Mv(TO) is defined to be the magnitude of the bluest point on the MS. Unfortunately, the MS turnoff region has nearly the same colour over a large range in magnitude. This leads to difficulties in measuring Mv(TO) observationally owing to the scatter in the observed points around the turn-off. Observers typically quote errors of $\approx$ 0.10 mag in Mv(TO), which leads to an error in the derived age of around $\pm$ 1.5 Gyr (e.g. Chaboyer *et al.* 1996a and references therein).

As the MS turn-off region is nearly vertical in the HR diagram, its colour is well defined but not its magnitude. As stars evolve off the MS, they quickly expand, and so points somewhat brighter than turn-off are more horizontal in the HR diagram. Thus, it is easy to measure the magnitude of the point which is brighter than the turn off and 0.05 mag redder defined as Mv(BTO) (see Figs. 1 and 2 in Chaboyer *et al.* 1996b). Ages derived using Mv(BTO), therefore, lead to small observational error. An extensive Monte Carlo calculation carried out by Chaboyer *et al.* (1996b) indicates that the theoretical uncertainty in Mv(BTO) is similar to Mv(TO). As a result, ages derived using Mv(BTO) are at least a factor of 2 more precise than those derived using Mv(TO).

Another major problem in determining the absolute ages of the GC is the wide range in "observed" metallicities for many clusters, e.g., the value of [M/H] for a well studied GC like NGC 6752 ranges from –1.09 to –1.66. Under such circumstances, the interpretation of its very tight MS locus (see Penney & Dickens 1986) is going to depend on the chemical composition which is assumed in the models. An uncertainty of ±0.2 dex in [Fe/H] leads to a few Gyr of error in cluster age.

The calibration of absolute age is still subject to observational and theoretical uncertainties at the ≈ 20% level, and represents a major limitation on our ability to test cosmological models. Nevertheless, it is quite possible to determine relative GC ages with sufficient precision and the same is the topic of discussion in the next section.

3. Measurement of relative globular cluster ages

In order to avoid most of the problems mentioned in the last section, one can measure relative cluster ages where the zero point of the distance scale is not important and also the stellar models can be used differentially or not at all (cf. review by Stetson *et al.* 1996 and references therein). The methods used for determining the relative cluster ages, along with their short comings are discussed in the following subsections.

3.1 Δ*Mv (HB-MSTO)*

The use of the brightness difference between the HB and the MSTO for determining relative cluster ages was first suggested by Iben & Faulkner (1968). Later on, Sandage (1982) and Iben & Renzini (1984) used it extensively. The basis of the method is that for ages > 10 Gyr, the HB luminosity is only weakly dependent on the total mass of the stars at the MSTO. The brightness of HB stars is set by the core mass of the stars evolving up the first ascent giant branch and, as a cluster ages, the total mass of the stars at the MSTO decreases, the core mass stays constant and the decreasing total mass is reflected in a smaller envelope mass. Therefore, as a cluster ages, its HB stars tend to be bluer at constant brightness. The luminosity of the MSTO, on the other hand, decreases with increasing cluster age. Consequently, the value of ΔMv(HB-MSTO) increases with time. For a 15 Gyr old cluster with [M/H]= –1.5, the increase is approximately 0.09 mag/Gyr. A particularly desirable attribute of this quantity is that, for a given age, it is not very sensitive to uncertainties in composition (see Fig. 1 in VandenBerg 1988).

In practice, there are some important limitations to this method. Many globulars show only a very blue or a very red HB and it is by no means a straightforward task to estimate the location of the ZAHB at the colour of the turn-off. This and other problems related to this method have been discussed in detail recently by Bolte (1993). The observed value of ΔMv(HB-MSTO) in most GCs therefore can not be estimated better than ±0.15–0.2 mag, which puts limitation on precise age estimations. The other problem has to do with the interpretation of the distribution of ΔMv(HB-MSTO) for the Galactic GC even if this distribution could be reliably determined with small errors. For this the slope C_1 in the relation

$$Mv(HB) = Co + C_1[M/H]$$

should be known precisely. There is currently much debate over the value of C_1. A constant value for Mv(HB) for all the GC (i.e. C_1 = 0) would suggest a large age-metallicity relationship in the sense that the metal-poorest clusters are ≈ 5 Gyr younger. The same data would be interpreted as describing a situation where all clusters, independent of [M/H], are coeval if C_1 = 0.4. Although, a large number of methods for measuring C_1 indicate its value ≈ 0.25.

3.2 *Colour-difference method*

In this method, the colour difference Δ(B-V) (RGB-MSTO) between the base of the red giant branch and MSTO in the CMD is used to derive relative cluster ages. The method has been suggested by VandenBerg, Bolte & Stetson (1990) and Sarajedini & Demarque (1990). The physical concept which the method uses has been described somewhere else (see Fig. 2 in Bolte 1993).

The advantage with the method is that one compares the fiducial CMD sequences for the two GC instead of isochrones. The horizontal registration eliminates reddening and colour zeropoint calibration differences, while the vertical one takes care of distance modulus differences between the two clusters. The resulting comparison is, therefore, independent of these quantities. The clusters are co-eval, if the fiducial lines after the registration coincide over the region from the MSTO to the base of the giant branch. If the sequences do not coincide, the only possibility appears to be an age difference between the two clusters. The value of Δ(B-V) (RGB-MSTO) decreases with age at the rate of ≈ 0.01 mag/Gyr. As it is a true differential measurement, its precise determination is possible. Stetson *et al.* (1996) have quantified the errors present in the relative cluster ages derived using this method. By fitting parabolas to the large number of stars in the region of the MSTO, the MSTO colour can be defined to a few thousandths of a magnitude even from a moderately good photometric data (individual stars measured to 0.04 mag). Generally the precision of the relative cluster age measurement is set by the number of subgiant and giant stars.

This method fails for metal-rich star cluster with [Fe/H] > –1.2 since the effects of decreasing age and increasing [Fe/H] are similar (see Sarajedini *et al.* 1995). However, the colour difference method is abundance independent when comparing clusters with similar abundance, at least for [Fe/H] ≤ −1.2, as the ±0.2 dex uncertainty in [Fe/H] measurements is not going to change the slope of isochrones.

4. Age differences in globular clusters

From the discussions in the last section, it is clear that one may not be confident about the relative ages of clusters with different chemical composition. On the other hand, there is a considerable advantage in comparing the morphological features of the clusters having very similar composition. VandenBerg *et al.* (1990) applied the colour difference method to a number of clusters for which suitable photometry existed in the literature and found that the six most metal-poor clusters [Fe/H]≈ -2 have identical ages to within 0.5 Gyr, the five clusters with [Fe/H]≈ –1.6 show somewhat larger dispersion, while the clusters with [Fe/H] ≈ −1.3 had a significant dispersion of several Gyr.

These are some convincing cases for the presence of age spread in the Galactic GCs and they are described below:

4.1 *NGC 288 and NGC 362 cluster pair*

The overall metallicities, as measured by various parameters which essentially depend on the abundance of iron, are almost identical for the clusters NGC 288 and NGC 362. These two clusters are, therefore, an ideal pair for a differential age study. The very different HB morphologies of these clusters indicate age difference between them because as a cluster ages, the distribution of stars on the HB will shift to increasingly bluer colours. Bolte (1989) and Green & Norris (1990) have independently obtained precise CMDs for both clusters, using CCDs. Both studies come to the same conclusion: the MSTO in NGC 288 is about 0.3 mag fainter than that in NGC 362, implying that NGC 288 is $\approx$ 2.5 Gyr older (see Fig. 1 in Bolte 1993).

4.2 *Individual clusters*

A few clusters listed in Table 1 seem to be unambiguously “young” compared to clusters of similar metallicities. Table 1 lists the metallicity; ΔMv(HB-MSTO) and Δ(B-V) (RGB-MSTO) for the clusters alongwith the references. These parameters indicate that they are atleast 3–4 Gyr younger than the clusters of similar metallicity.

Fusi Pecci *et al.* (1995) have shown that the clusters listed in Table 1 lie near planes passing in the vicinity of some satellite galaxies of the Galaxy and through the Galactic centre itself. This indicates that these clusters may have been captured when similar galaxies were disrupted and merged with the Galaxy.

4.3 *Overall age distribution of clusters*

From the available data, it is not possible to determine the overall age distribution function, especially when clusters of very different abundance are included. However, they are consistent with the majority of Galactic globular clusters being virtually coeval but with a minority having significantly different (younger) ages. Such distribution may indicate a rapid collapse of the galactic halo with rare late infall from large radii or perhaps have been captured from disrupted dwarf spheroidals (cf. Fusi Pecci *et al.* 1995) or stolen from the SMC or LMC (Lin & Richer 1992). However, it

Table 1. List of relatively young Galactic globular clusters.

Cluster	[Fe/H]	ΔMv in mag (HB-MSTO)	Δ(B-V) (RGB-MSTO)	Reference
Arp 2	-1.84 ± 0.25	3.29 ± 0.10	0.248 ± 0.005	Buonanno *et al.* (1995a)
IC 4499	-1.75 ± 0.2	3.25 ± 0.12	0.33 ± 0.05	Ferraro *et al.* (1995)
Pal 12	-1.00 ± 0.2	3.30		Stetson *et al.* (1989)
Rup 106	-1.9 ± 0.2	3.2 ± 0.07	0.261 ± 0.01	Buonanno *et al.* (1993)
Terzen 7	-0.49 ± 0.05	3.2 ± 0.12	0.47 ± 0.05	Buonanno *et al.* (1995b)

is premature to choose between these pictures given the small number of clusters with relative ages precise to a Gyr or less. This situation will certainly improve in the near future, however, the problem of how to accurately compare clusters that differ in metallicities by more than 0.5 dex will prove to be a veering one.

5. The prehistoric globular clusters

In the quasi-steady state cosmological model proposed by Narlikar (1994), the local universe has gone through cycles of expansion and contraction. The prehistoric globular clusters are those which formed in the previous cycles and have survived the contraction phase. Consequently their ages will be ≈ 50 Gyr instead of the usual globular cluster age of $\approx$ 14 Gyr. The MSTO of such clusters would be» ≈ 2 mag fainter than those of general GCs, as fading of the MSTO becomes progressively slower with age and hence, their detection should not be difficult unless some other unforeseen effects come into play (cf. Cannon 1996). However, the HB morphologies of the prehistoric clusters will be quite different as stars populating MSTO regions will never undergo a helium flash. Thus the CMDs, and hence the integrated colours, of prehistoric clusters might be rather different from standard galactic globular clusters. In order to quantify these differences, detailed evolutionary calculations of low mass stars are needed.

6. Discussion

J. C. Pecker

Q: The theoretical models are in error (perhaps!) for at least two reasons: (1) the turbulent diffusion might inject "flash" hydrogen in the stellar core, hence increasing the life-time of the stars. (2) the metallic content, measured from the brightest stars of a cluster is known to be underestimated by perhaps one order of magnitude. These two effects would, I believe, tend to increase the age of the clusters, an age of 15 Gyr would thus be a lower limit of the cluster age. What is your opinion on this?

A: The error introduced in the life time of a star due to not taking into account the turbulent diffusion in the stellar core in the calculations of stellar evolutionary models is much smaller than the error introduced due to other physical effects like mixing-length theory etc. Recent studies indicate that the uncertainty in the metallicity determination of well studied galactic globular clusters and in the input physics may not change the age determination of galactic globular clusters by more than 20%.

I I I I I

C. Arp

Salans, Dy' Innocenti and Weiss have a paper in press in which they change the evolution theory and obtain 12.2 ± 1.86 yrs – about 2.6 yrs less than the usually accepted value you mentioned but with about the same uncertainty

A. The recent determination of the ages of the galactic globular clusters discussed from the observed colour-magnitude diagrams indicate a value 14 ± 2 Gyr which is in agreement within the errors with the values derived by the above mentioned authors.

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