Update on globular cluster ages

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Abstract. We update globular cluster age estimates and discuss their implications in the context of present knowledge in cosmology. On the basis of the best information now available, the ages of the oldest globular clusters are estimated at 13.0±1.5 Gyr. If this result, whose main uncertainty is primarily in the distance scale, continues to hold, the long standing discrepancy between the stellar evolution timescale and the universal expansion timescale will have been resolved.

Keywords: globular clusters, stellar ages

1. Introduction

Globular clusters hold a special place in studies of stellar chronology, because they contain the oldest known stars in the Galaxy. As such, the ages of the oldest globular clusters set a lower limit to the age of the Universe. Equally important, the distribution of the ages of globular clusters throws light on the formation process, evolution and chronology of the Galactic bulge and halo.

Already fifty years ago, we knew, and gained comfort from, the fact that the ages derived for the oldest star clusters were of the same order of magnitude as the Hubble time derived from the expansion of the Universe. However the uncertainties in observations of globular clusters and in stellar evolution calculations remained very large, and estimates of the Hubble constant H_0 oscillated between 50 and 100 km/s/Mpc. The problem was seen as a competition between the stellar evolution timescale and the expansion timescale derived from the value of H_0 in a universe with $\Lambda = 0$. And until recently, the large ages derived for globular clusters from color-magnitude diagrams (CMD) and stellar evolution calculations have been difficult to reconcile with the usually shorter expansion age derived for the Universe. At the Symposium on Observational Tests of Cosmological Inflation held ten years ago in Durham (Shanks *et al.* 1991), the age for the oldest globular clusters was quoted in the range 13-15±3 Gyr by Renzini (1991), while Demarque *et al.* (1991) estimated their minimum age at 14 Gyr (1991).

The situation had not much changed only five years ago, when on the basis of a Monte Carlo study of the ages of the oldest globular clusters (Chaboyer *et al.* 1996), the conclusion was reached that to the best of our knowledge, the mean age of the oldest globular clusters is 14.6 Gyr, with a 5% probability that it is below 12.1 Gyr or above 17.1 Gyr (Demarque 1997).

In this paper, we survey briefly the progress made in the last few years. Better globular cluster observations are available. The physics of stellar evolution has improved. The Hipparcos satellite has forced a revision of the accepted distance scale. The combination of all these factors has resulted in a reduction in the age estimate for the oldest globular clusters to about 13.0±1.5 Gyr. At the same time, the HST key project has led to a concensus on the value of H_0, with $H_0 = 72 \pm 8$ km/s/Mpc (Freedman *et al.* 2001).

The most surprising result has been the evidence for a non-zero cosmological constant (in the vicinity of 0.7), on the basis of distances based on SNIa observations. And from these observations, two independent groups have derived a dynamical age for the Universe of 14.2±1.7 Gyr (Riess *et al.* 1998), and 14.9+1.4 − 1.1(0.63/h) Gyr (Perlmutter *et al.* 1999), respectively. The particular role of the cosmological constant Λ, given a value of H_0, is to increase the age estimate of the Universe. Consistency with a globular age of 14 Gyr would require that H_0 must be less than 45 km/s/Mpc in a Universe with ($\Omega = 1.0, \Lambda = 0.0$), and $H_0 \leq 58$ km/s/Mpc in a Universe with ($\Omega = 0.2, \Lambda = 0.0$). On the other hand, with a cosmological constant $\Lambda \simeq 0.7$, a maximum globular cluster age as high as 14 Gyr is marginally compatible with $H_0 \simeq 70$ km/s/Mpc.

One of the consequences of these developments is that although many uncertainties remain, for the first time, *there is no apparent inconsistency between the ages derived for the oldest globular clusters and the age of the Universe.*

2. Advances in globular cluster research

In the last ten years, the quality and quantity of globular cluster CMD's has made rapid strides, thanks to CCD detectors and to the HST. Chemical abundances are also better known within globular clusters and among field halo stars. In particular, more evidence has been gathered concerning variations in $[\alpha/Fe]$ for stars of different $[Fe/H]$ in the Galactic halo and elsewhere. (Carney 1996).

On the theoretical side, we have seen great advances in the microscopic physics of stellar interiors and stellar evolution (for references, see the review by Demarque 1997). Most significant has been the remarkable agreement between two independent sets of interior opacities using different physical approaches, *i.e.* the opacities from the Opacity Project (Seaton 1996), and those from the Livermore OPAL opacities (Rogers & Iglesias 1996). Low temperature opacities, which include the effects of molecules, have also made impressive advances. This agreement, and the success of the new opacities in resolving several long standing problems in pulsation theory lends much greater credibility in the details of stellar models. The spectacular success of helioseismology (Guenther & Demarque 1997) further strengthen our confidence in the available opacity tables, and in recent advances in the equation of state of stellar matter relevant to globular cluster stars (Rogers, Swenson & Iglesias 1996).

3. The YY isochrones

The YY (Yale-Yonsei) isochrones (Yi *et al.* 2001) use the OPAL (Rogers & Iglesias 1995) interior opacities, the low temperature opacities of Alexander & Ferguson (1994). Particularly important are the improvements in the equation of state of stellar matter (Rogers, Swenson & Iglesias 1996). Helium diffusion (Thoul, Bahcall & Loeb 1994) and convective core overshoot have also been taken into account. The energy generation rates are primarily taken from Bahcall & Pinsonneault (1992), with some revisions. The chemical compositions used in the YY isochrones are: Z = 0.00001, 0.0001, 0.0004, 0.001, 0.004, 0.007, 0.01, 0.02, 0.04, 0.08 and 0.1. ($Z_{\odot} = 0.0181$), $Y = 0.23 + 2Z$ and the ages range from 0.001 to 20 Gyr.

Two significant features of the YY isochrones are (1) that the models start their evolution from the pre-main sequence birthline (Palla & Stahler 1990) instead of the age-zero main sequence, and (2) the color transformation has been performed using both the tables of Lejeune, Cuisinier & Buser (1997, 1998), and an improved version of the Green, Demarque & King (1987) table. Although there are differences, satisfactory agreement has generally been found with the recent work of Girardi *et al.* (2000). Several comparisons of the YY isochrones with observational data can be found in Yi *et al.* (2001). Figures 1 shows the metal-poor halo cluster M68 as an example.

It is noteworthy that the change in the derived ages of star clusters caused by recent updates in stellar models alone is a sensitive function of metallicity. Relative to RYI-based studies (Green, Demarque & King 1987), the globular cluster ages are decreased by amounts varying from 15% (for Z=0.0004) to 11% (for Z=004). On the other hand the ages of

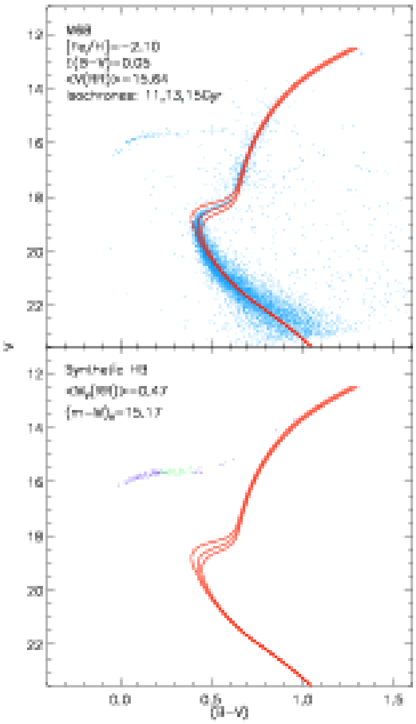

Figure 1. Fit to halo cluster M68. Photometry from Walker (1994). $[Fe/H]$ and reddening from Harris (1996), and $[\alpha/Fe] = 0.3$ adopted.

solar metallicity clusters (Z=0.02) are increased by about 10%. When a simple scaling for α-element enhancement similar to that used by Chaboyer *et al.* (1992) is taken into account as well, the reduction in the ages of the most metal-poor globular clusters is approximately 20%.

4. Quantifying the main uncertainties in dating globular clusters; a Monte Carlo approach

In addition to the uncertainties in the theoretical isochrones themselves, the fitting of globular cluster CMD's involves many steps which are sources of error in age determinations. Chaboyer *et al.* (1996, 1998) have tried to quantify the various source of uncertainties in the age determinations due to the fitting procedure, as well as in the physics input in the stellar models and the composition input parameters. Naturally, the fitting procedure introduces uncertainties of its own. One example is in using the ΔV technique, and assuming that the distance indicator $M_v(RR)$ depends uniquely on metallicity. Similarly, the errors in the treatment of convection were calculated using a fixed mixing length parameter along each evolutionary track. This last assumption, which is standard in stellar evolution calculations, could introduce a bias in the ΔV technique.

With these provisos, the Monte Carlo study by Chaboyer *et al.* (1998) provides useful quantitative estimates of the relative importance of the uncertainties in globular cluster dating. The paper contains quantitative corrections that can be applied as input parameters improve with time. As suspected, the dominant source of error lies in the distance estimate of the cluster (in this case the appropriate value of $M_v(RR)$), which in this study is responsible for a 16% uncertainty in the derived ages. The quantity $[\alpha/Fe]$ is next by introducing a 7% age uncertainty, followed by the treatment of convection (5%).

4.1. The distance scale and Hipparcos

As emphasized above, the distance scale remains the main question mark in the dating of the globular clusters. The Hipparcos mission has led some authors to surprisingly large increases in distance estimates. For illustration, the post-Hipparcos age estimate for the oldest globular clusters derived by Chaboyer *et al.* (1998) is 3 Gyrs larger than the pre-Hipparcos age derived on the basis of the same stellar models (Chaboyer *et al.* 1998). This revision, which may have been too extreme, illustrates how sensitive globular cluster ages depend on distances, all else being equal.

The YY isochrones agree with the position of subdwarfs in the HR-diagram observed by Hipparcos (Figure 2). Data from Reid (1998) were used, following the criterion that $[Fe/H] < -0.55$, $M_v > 4.5$, and $\sigma_\pi/\pi < 0.07$. The adopted chemical composition was $[\alpha/Fe] = +0.4$ and $+0.2$ for $[Fe/H] \leq -1.0$ and $[Fe/H] = -0.5$, respectively. The YY isochrones are also compatible with the theoretical synthetic HB models of Demarque *et al.* (2000). This distance scale agrees with the Walker (1992) and Freedman *et al.* LMC distance modulus of 18.5 ± 0.15. It is therefore internally consistent with the derived cosmological dynamical ages of the Universe quoted earlier. Future observations will test whether these conclusions are correct.

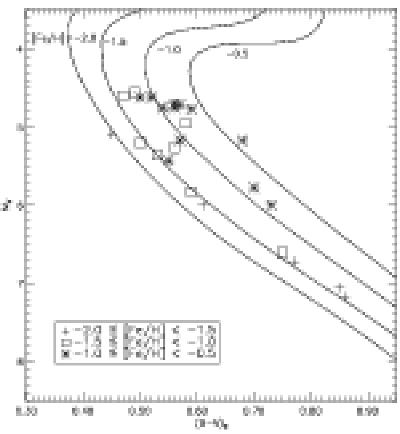

Figure 2. A test of the subdwarf main sequence stars whose distance have been determined by Hipparcos observations.

5. Summary and future prospects

To summarize, recent advances lead to an age estimate for the oldest Galactic globular clusters of 13.0±1.5 Gyr. Important issues regarding globular cluster ages will be resolved during the next few years. A more precise absolute age for the oldest clusters, will be derived with improvements in the distance scale (first from the space mission FAME, then from GAIA and SIM). Better abundances for main sequence stars in globular clusters will soon be available from the 10-meter class ground-based telescopes. More realistic models of convection will improve atmospheric models and surface boundary conditions of cool star models (Kim & Chan 1998; Demarque, Guenther & Kim 1999). Much work remains to be done on stellar atmospheres and on the conversion of observable parameters to effective temperatures and surface gravities.

Beyond determining the ages of the oldest star clusters, refining age determinations in globular clusters is also needed for improving the chronology of the Galaxy and understanding its formation and evolution. Answers to fundamental and still controversial questions such as the chronology of halo, disk and bulge formation will guide us in exploring how other galaxies form (Stetson, VandenBerg & Bolte 1996; Sarajedini, Chaboyer & Demarque 1997; McNamara 2001).

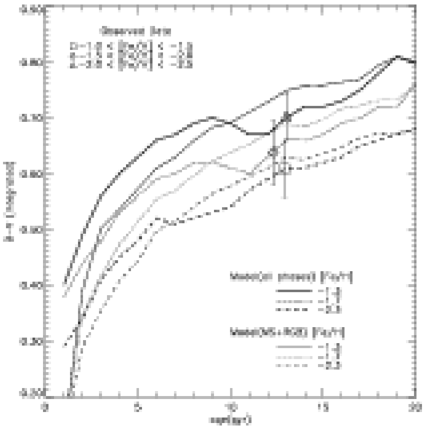

Figure 3. Evolution in integrated color of metal-poor populations. Compared are the observed integrated colors of Galactic globular clusters with $E(B-V) < 1.0$. The cluster data are from Harris (1996).

Finally, one should note the importance of extragalactic globular clusters in the Local Group. Globular clusters in the LMC and other Local Group galaxies now serve as stepping stones to the more distant stellar populations in which individual stars cannot be resolved. It is encouraging to note that when the post-RGB stages of evolution are included, the ages of the globular clusters derived from integrated colors are consistent with the isochrone fitting ages. This point is illustrated in Figure 3.

Acknowledgements

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References

Bahcall, J. N. and M. H. Pinsonneault, M.H. *Reviews of Modern Physics*, 64, 885-926, 1992; and private communications.

Chaboyer, B., C. P. Deliyannis, P. Demarque, M. H. Pinsonneault & A. Sarajedini. *Astrophysical Journal*, 388, 372-382, 1992.

Chaboyer, B., P. Demarque, P. J. Kernan & L. M. Krauss. *Science*, 271, 957-961, 1996.

Chaboyer, B., P. Demarque, P. J. Kernan & L. M. Krauss. *Astrophysical Journal*, 494, 96-110 , 1998.

Demarque, P. In *The Extragalactic Distance Scale*, eds. M. Livio, M. Donahue & N. Panagia, Cambridge U. P.), pp. 30-48, 1997.

Demarque, P., C. P. Deliyannis & A. Sarajedini. In *Observational Tests of Cosmological Inflation*, eds. T. Shanks, A. J. Banday, R. S. Ellis, NATO ASI Series, pp. 111-128, 1991.

Demarque, P., D. B. Guenther & Y.-C. Kim. *Astrophysical Journal*, 517, 510-515, 1999.

Demarque, P., R. Zinn, Y.-W. Lee & S. Yi. *Astronomical Journal*, 119, 1398-1404, 2000.

Freedman, W. *et al*. *Astrophysical Journal*, 553, 47-72, 2001.

Girardi, L., A. Bressan, G. Bertelli, G. & C. Chiosi. *Astronomy & Astrophysics Supplement*, 141, 371-383, 2000.

Green, E. M., P. Demarque & C. R. King. *The Revised Yale Isochrones and Luminosity Functions*, Yale Univ. Obs., New Haven, 1987.

Harris, W. E. *Astronomical Journal*, 112, 1487-1488, 1996.

Iglesias, C. A. & F. J. Rogers. *Astrophysical Journal*, 464, 943-953, 1996.

Kim, Y.-C. & K. L. Chan. *Astrophysical Journal*, 496, L121-124, 1998.

Lejeune, Th., F. Cuisinier & R. Buser. *Astronomy & Astrophysics Supplement*, 125, 229-246, 1997.

Lejeune, Th., F. Cuisinier & R. Buser. *Astronomy & Astrophysics Supplement*, 130, 65-75, 1998.

McNamara, D.H. *Publications of the Astronomical Society of the Pacific*, 113, 335-343, 2001.

Palla, F. & S. W. Stahler. *Astrophysical Journal*, 360, L47-50, 1990.

Perlmutter, S. *et al*. *Astrophysical Journal*, 517, 565-586, 1999.

Reid, N. *Astronomical Journal* 115, 204-228, 1998.

Renzini, A. In Observational Tests of Cosmological Inflation, eds. T. Shanks, A. J. Banday, R. S. Ellis, NATO ASI Series, pp. 131-146, 1991.

Riess, A. G. *et al*. *Astronomical Journal*, 116, 1009-1038, 1998.

Rogers, F. J., F. J. Swenson & C. A. Iglesias. *Astrophysical Journal*, 456, 902-908, 1996.

Sarajedini, A., B. Chaboyer & P. Demarque. *Publications of the Astronomical Society of the Pacific*, 109, 1321-1339, 1997.

Seaton, M. *Monthly Notices of the Royal Astronomical Society*, 279, 95-100, 1996

Stetson, P. B., D. A. VandenBerg & M. Bolte. *Publications of the Astronomical Society of the Pacific*, 108, 560-573, 1996.

Thoul, A. A., J. N. Bahcall & A. Loeb. *Astrophysical Journal*, 421, 828-842, 1994.

Walker, A.R. *Astrophysical Journal*, 390, L81-84, 1992.

Walker, A.R. *Astronomical Journal*, 108, 555-584, 1994.

Yi, S., P. Demarque, Y.-C. Kim, Y.-W. Lee, Y.-W., C.-H.Ree, Th. Lejeune & S. Barnes. *Astrophysical Journal Supplement* in press (Astro-ph/0104292), 2001.