The Age of Globular Clusters

Lawrence M. Krauss [a,1],

[a]*Departments of Physics and Astronomy, Case Western Reserve University,
10900 Euclid Ave. Cleveland OH, USA*

Abstract

I review here recent developments which have affected our understanding of both the absolute age of globular clusters and the uncertainties in this age estimate, and comment on the implications for cosmological models. This present estimate is in agreement with the range long advocated by David Schramm. The major uncertainty in determining ages of globular clusers based upon the absolute magnitude of the main sequence turn-off remains the uncertainty in the distance to these clusters. Estimates of these distances have recently been upwardly revised due to Hipparcos parallax measurements, if one calibrates luminosities of main sequence stars. However, it is important to realize that at the present time, different distance measures are in disagreement. A recent estimate is that the oldest clusters are 11.5 ± 1.3 Gyr, implying a one-sided 95% confidence level lower limit of 9.5 Gyr, if statistical parallax distance measures are not incorporated. Incorporating more recent measures, including Hipparcos based statistical parallax measures, raises the mean predicted age to 12.8 ± 1 Gyr, with a 95 % confidence range of 10-17 Gyr. I conclude by discussing possible improvements which may allow a more precise age distribution in the near future.

Key words: Globular Clusters, Cosmology, Stellar Evolution
PACS: 98.80.-v, 96.30.Ks, 96.40.Jw

1 Introduction and Overview: Some Personal Reflections

I remember the first time I discussed the globular cluster age problem with David Schramm. This was long before I knew much at all about the detailed issues associated with fitting the main sequence turn-off magnitudes. At the time I was at Yale University, and my colleague in the Astronomy Department

---

[1] E-mail: krauss@theory1.phys.cwru.edu

there, Pierre Demarque, was using the new Yale isochrones and finding good agreement with ages for the oldest globular clusters in the range 16-20 Gyr. Pierre suggested that this number was accurate to perhaps 20 %, although he felt that this could just as likely result in longer ages rather than shorter ones. This age estimate was clearly in conflict with the estimate for the age of a flat matter-dominated Universe, then the preferred cosmological model, $t_{universe} = 6.6(1/h)$ Gyr, unless the Hubble constant $H_0 = 100 \ h \ kms^{-1}Mpc^{-1}$ was uncomfortably small.

When I spoke to David about this apparent further confirmation of the long-standing age problem, he smiled and with his usual confidence he asserted (colored of course by his firm belief in a flat Universe, as predicted by Infla-tionary models) that there were likely to be additional systematic uncertainties which could shift the allowed range. In the end he felt the allowed age range would be closer to 10-14 Gyr. I was somewhat surprised at the time by his confidence in this claim, but I shouldn't have been. David had an astute sense of what the key issues were in astrophysics, and where there were weaknesses or loopholes, even if he didn't always annunciate these in public.

At around that time I was investigating another issue of great interest to David, Big Bang Nucleosynthesis. I had decided to utilize Monte Carlo tech-niques to determine the actual theoretical uncertainties in BBN predictions for light element abundances. At that time computational resources had ad-vanced to the point that it was practical to alter BBN codes to run many different times with individual nuclear reaction rates chosen at random from various distributions with ranges appropriate to the individual experimental uncertainties. This allowed one to quote quantitative confidence limits on BBN predictions, and also to explicitly explore the dominant uncertainties in the analysis.

Almost a decade later, after moving to Case Western Reserve University, I de-cided to take David's concerns about globular cluster age estimates to heart, and attempt a similar analysis in this regard. I contacted Pierre Demarque, and his former student Brian Chaboyer, who I also knew from Yale, and who was then a postdoc at CITA in Toronto. Brian and Pierre not only had good stellar evolution codes, but they were fully familiar with the important ob-servational literature, which we would have to scour in order to assess the input uncertainties in the globular cluster age estimates, and equally impor-tant, to assess the fits to observations. Peter Kernan at CWRU and I had familiarity, from our BBN work, with Monte Carlo techniques and the related statistical analysis of data, and so it seemed like a good combination. Our geographic proximity allowed us to meet together to go over each facet of the input data in order to agree on appropriate uncertainties, and then we were able to rewrite the stellar evolution codes to accomodate a Monte Carlo over the following months. Moreover, because of another quantum leap in compu-

tational resources, one could now run a stellar evolution code to produce a set of isochrones in several minutes, so it was feasible to sample millions of different models using several months of dedicated computer time.

Our first analysis[1] suggested a best fit median age of 14.2 Gyr, and several other groups at the time also reported best fit ages in the 14-15 Gyr range, based on independent methods, and differing input physics. However, it also appeared that existing uncertainties could allow, at the 95% confidence level, ages as low as 11.8 Gyr. This was still somewhat uncomfortable for a flat matter- dominated Universe, given the Hubble Key Project estimate of $H_0 \approx$ 80 for the Hubble constant, but the disagreement was much smaller, and David was quite enthused by the results. Our other chief result confirmed that it was not stellar model uncertainties which dominated the overall uncertainty in our globular cluster age estimates, but rather the observational uncertainty in the distance to globular clusters. Because we normalized our absolute magnitude to the Horizontal Branch RR Lyrae stars, this distance uncertainty translated into an uncertainty in the the RR Lyrae distance modulus.

Then about a year after these analyses, the Hipparcos satellite produced its catalogue of parallaxes of nearby stars, causing an apparent revision in distance estimates. The Hipparcos parallaxes seemed to be systematically smaller, for the smallest measured parallaxes, than previous terrestrially determined parallaxes. Could this represent the unanticipated systematic uncertainty that David has suspected? Since all the detailed analyses had been pre-Hipparcos, several groups scrambled to incorporate the Hipparcos catalogue into their analyses. The immediate result was a generally lower mean age estimate, reducing the mean value to 11.5-12 Gyr, and allowing ages of the oldest globular clusters as low as 9.5 Gyr. However, what is also clear is that there is now an explicit systematic uncertainty in the RR Lyrae distance modulus which dominates the results. Different measurements are no longer consistent. Depending upon which distance estimator is correct, and there is now better evidence that the distance estimators which disagree with Hipparcos-based main sequence fitting should not be dismissed out of hand, the best-fit globular cluster estimate could shift up perhaps 1σ, or about 1.5 Gyr, to about 13 Gyr.

While all this has happened, a number of other important revolutions have been taking place in observational cosmology. The HST Key Project has lowered their best fit Hubble Constant value to $H_0 = 70 \pm 7$ [2], raising the upper limit on the allowed age of the Universe for a given cosmological model. At the same time, observations of Type 1a Supernovae have provided direct evidence in support of the growing suspicion that the cosmological constant is non-zero. Previously the cosmological constant was invoked as one way out of the age problem, as it can raise the age of a flat Universe by an arbitrary amount for a fixed Hubble constant, depending upon the value of the cosmological con-

stant. If the cosmological constant is indeed non-zero, then one will have no difficulty reconciling globular cluster ages with the Hubble age. If it turns out to be zero, we cannot yet definitively rule out a flat matter dominated universe on the basis of globular cluster ages alone, although the current results require pushing all uncertainties to their limit in order to get concordance.

It is a pleasure to dedicate this personal overview of recent developments in Globular Cluster age estimation to David's memory. He helped inspired my own interest in trying to pin down globular cluster ages, and it is satisfying that the results seem to at least partly confirm his own suspicions. It also goes without saying that much of what I will describe here I learned from my collaborators.

2   Main Sequence Fitting of Globular Cluster Ages: An Overview

This will not be an encyclopedic overview. There are many good reviews of the field [4,1]. I will try and stress the key features that underlie different estimates, and which have been affected by recent developments.

The basic idea behind main sequence fitting is simple. A stellar model is constructed by solving the basic equations of stellar structure, including conservation of mass and energy and the assumption of hydrostatic equilibrium, and the equations of energy transport. Boundary conditions at the center of the star and at the surface are then used, and combined with assumed equation of state equations, opacities, and nuclear reaction rates in order to evolve a star of given mass, and elemental composition.

Globular clusters are compact stellar systems containing up to 10^5 stars, with low heavy element abundance. Many are located in a spherical halo around the galactic center, suggesting they formed early in the history of our galaxy. By making a cut on those clusters with large halo velocities, and lowest metallicities (less than 1/100th the solar value), one attempts to observationally distinguish the oldest such systems. Because these systems are compact, one can safely assume that all the stars within them formed at approximately the same time.

Observers measure the color and luminosity of stars in such clusters, producing color-magnitude diagrams of the type shown in Figure 1.

Next, using stellar models, one can attempt to evolve stars of differing mass for the metallicities appropriate to a given cluster, in order to fit observations. A point which is often conveniently chosen is the so-called main sequence-turnoff (MSTO) point, the point in which hydrogen burning (main sequence)
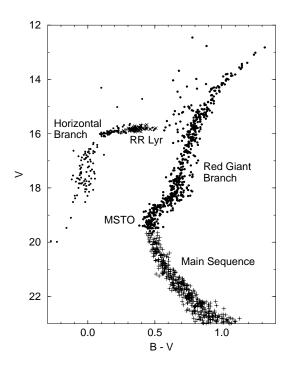
4

Fig. 1. Color-magnitude diagram for a typical globular cluster, M15[5]. Vertical axis plots the magnitude (luminosity) of the stars in the V wavelength region and the horizontal axis plots the color (surface temperature) of the stars.

stars have exhausted their supply of hydrogen in the core. After the MSTO, the stars quickly expand, become brighter, and are referred to as Red Giant Branch (RGB) stars. Higher mass stars develop a helium core that is so hot and dense that helium fusion begins. These form along the horizontal branch. Some stars along this branch are unstable to radial pulsations, the so-called RR Lyrae stars mentioned earlier, which are important distance indicators. While one in principle could attempt to fit theoretical isochrones (the locus of points on the predicted CM curve corresponding to different mass stars which have evolved to a specified age), to observations at any point, the main sequence turnoff is both sensitive to age, and involves minimal (though just how minimal remains to be seen) theoretical uncertainties.

Dimensional analysis tells us that the main sequence turnoff should be a sensitive function of age. The luminosity of main sequence stars is very roughly proportional to the third power of solar mass. Hence the time it takes to burn the hydrogen fuel is proportional to the total amount of fuel (proportional to the mass M), divided by the Luminosity— proportional to M^3. Hence the lifetime of stars on the main sequence is roughly proportional to the inverse square of the stellar mass.

Of course the ability to go beyond this rough approximation depends completely on the on the confidence one has in one's stellar models. It is worth noting that several improvements in stellar modeling have recently combined to lower the overall age estimates of globular clusters. The inclusion of dif-

fusion lowers the age of globular clusters by about 7% [6], and a recently improved equation of state which incorporates the effect of Coulomb interactions [7] has lead to a further 7% reduction in overall ages. Of course, what is most important for the comparison of cosmological predictions with inferred age estimates is the uncertainties in these and other stellar model parameters, and not merely their best fit values.

The uncertainties in determining each of these parameters leads to uncertainties in fitting the age of globular clusters. One of the advantages of determining globular cluster ages by fitting the MSTO is that the low metallicity main sequence stellar models are relatively simple, so that some of the theoretical complexities of solar physics that plague attempts to understand certain classes of stars are minimized here. In particular, probably the least understood aspect of stellar modeling involves the treatment of convection. Main sequence and red giant stars have surface convection, so that the surface properties such as color are rather uncertain, whereas horizontal branch stars have convective cores and thus the predicted luminosities and lifetimes of these stars are highly uncertain.

The remaining key parameter uncertainties of these main sequence stellar models include: pp and CNO chain nuclear reaction rates, stellar opacity uncertainties, mixing length, diffusion uncertainties, helium abundance uncertainties, and uncertainties in the abundance of the α-capture elements (O, Mg, Si, S, and Ca).

3   Monte Carlo Estimates of Age Uncertainties resulting from Model Parameter Uncertainties

In order to account for the impact of these uncertainties in the input parameters on the eventual derived ages, one can take a Monte Carlo approach. In this case, many different stellar models are run on a computer. In each model different values of the input parameters are chosen, and these values are allowed to run over a distribution which is based on the assumed uncertainty in each parameter. If the uncertainty is dominated by statistics, a gaussian distribution in this variable is chosen. If systematics dominate, as is often the case, a top hat distribution is usually chosen [1,3].

The set of input parameters, and the range chosen for the figures displayed here is given in table 1.

When this analysis is completed, one can explore the sensitivity of inferred ages to individual input parameters by plotting this age as a function of the chosen parameter for each stellar model run. An analytical fit to the determined age,

6

Table 1
Monte Carlo Stellar Model Input Parameters

Parameter	Distribution	Comment
mixing length	1.85 ± 0.25 (stat.)	fits GC observations
helium diffusion coefficients	$0.3 - 1.2$ (syst.)	sys. error dominate
high temperature opacities	1 ± 0.01 (stat.)	comparison of OPAL
		& LAOL opacities
low temperature opacities	$0.7 - 1.3$ (syst.)	comparing different tables
primordial ^{4}He abundance	$0.22 - 0.25$ (syst.)	sys. error dominate
oxygen abundance, [O/Fe]	$+0.55 \pm 0.05$ (stat.)	mean from [8]
	± 0.20(syst.)	
surface boundary condition		grey or [9]
colour table		[10] or [11]
Nuclear Reaction Rates:		
$p + p \longrightarrow {}^2\mathrm{H} + e^+ + \nu_e$	1 ± 0.002 (stat.)	see [1]
	$^{+0.0014}_{-0.0009}\ {}^{+0.02}_{-0.012}$ (syst.)	
$^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2p$	1 ± 0.06 (stat.)	[12]
$^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma$	1 ± 0.032 (stat.)	[12]
$^{12}\mathrm{C} + \mathrm{p} \longrightarrow {}^{13}\mathrm{N} + \gamma$	1 ± 0.15 (stat.)	[13]
$^{13}\mathrm{C} + \mathrm{p} \longrightarrow {}^{14}\mathrm{N} + \gamma$	1 ± 0.15 (stat.)	[13]
$^{14}\mathrm{N} + \mathrm{p} \longrightarrow {}^{15}\mathrm{O} + \gamma$	1 ± 0.12 (stat.)	[13]
$^{16}\mathrm{O} + \mathrm{p} \longrightarrow {}^{17}\mathrm{F} + \gamma$	1 ± 0.16 (stat.)	[13]

as a function of the relevant input parameter can then be derived. It turns out that the dominant uncertainty in theoretical models is due to the uncertainty in the abundance of α-capture elements (with oxygen being the dominant such element). Estimates of the oxygen abundance, for example, vary by up to a factor of 3.

As an example of the sensitivity of inferred ages to variations in input parameters I display in Figure 2, the inferred age as a function of the assumed logarithmic abundance of α-capture elements relative to iron [3]. The best fit median along with $\pm 1\sigma$ limits is also plotted. These lines are of the form $t_9 = a + b[\alpha/\mathrm{Fe}]$ with the following coefficients: median $(a, b) = (13.83, -3.77)$, $-1\sigma(a, b) = (13.26, -3.72)$, $+1\sigma(a, b) = (14.54, -4.00)$.

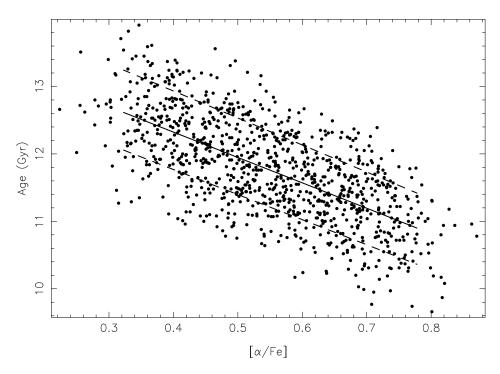Similar curves can be derived for the sensitivity of MSTO age estimates to

Fig. 2. Sensitivity of inferred globular cluster ages to abundance of α-capture elements relative to iron

the other stellar physics input parameters [3]. The net effect of all such uncertainties is in any case relatively small, at the level of 7% or less.

4 Observational Uncertainties and Globular Cluster Ages

It turns out, however, that the dominant uncertainty in the use of the MSTO luminosity for determining the age of globular clusters arises from the comparison of theoretical predictions to observations. In particular, normalizing the predicted luminosity curves to observed magnitudes requires a distance measurement to the cluster. Moreover, because of uncertainties in the effective surface temperatures of the models, and to remove sensitivity to reddening [4] the turnoff luminosity is compared to the Horizontal branch luminosity as an age discriminant. Specifically, one considers the difference in magnitude between the HB and the MSTO, ΔV_{HB}^{TO}. Furthermore, since the theoretically determined HB luminosity is subject to large uncertainties due to convective effects in the core, one utilizes the observed HB luminosities and the theoretical MSTO luminosities in this subtraction. Determining the absolute luminosity of the HB branch revolves around determining the distance to the cluster. One can parametrize the uncertainty in this distance determination by the uncertainty in the empirical calibration of the absolute magnitude, $M_v(\mathrm{RR})$, of RR Lyrae stars located on the HB.
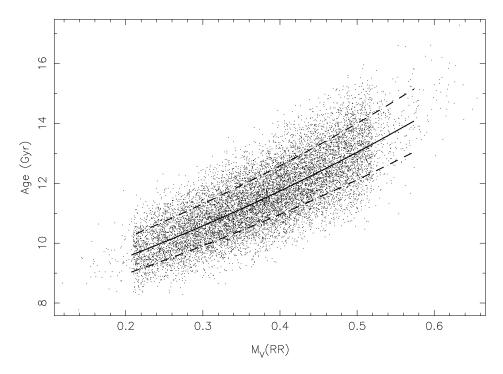
8

Fig. 3. Sensitivity of inferred globular cluster ages to the adopted value of $M_v(\mathrm{RR})$

With a calibration of $M_v(\mathrm{RR})$, one can then use theoretically derived values for $M_v(\mathrm{TO})$ to determine a grid of predicted ΔV_{HB}^{TO} values as a function of age and [Fe/H] that is fit to an equation of the form

$$t_9 = \beta_0 + \beta_1 \Delta\mathrm{V} + \beta_2 \Delta\mathrm{V}^2 + \beta_3 [\mathrm{Fe/H}] + \beta_4 [\mathrm{Fe/H}]^2 + \beta_5 \Delta\mathrm{V}[\mathrm{Fe/H}], \quad (1)$$

The observed values of $\Delta\mathrm{V}_{\mathrm{HB}}^{\mathrm{TO}}$ and [Fe/H], along with their corresponding errors, are then input in (1) to determine the age and its error for each GC in the sample.

The uncertainty in determining $M_v(\mathrm{RR})$, and hence the distance to globular clusters far outweighs any intrinsic stellar model uncertainties as far as globular cluster age determinations are concerned. If we normalize $M_v(\mathrm{RR})$ at [Fe/H] $= -1.9$, then we can display the dependence of globular cluster ages from the fitting equation (1) on this value of $M_v(\mathrm{RR})$ for the locus of evolved stars resulting from the Monte Carlo analysis. This is shown in Figure 3.

5   Distance Estimators and the Age of the Oldest Globular Clusters

In order to derive a reliable age range, then, one must examine in some detail the uncertainties in distance determinations to globular clusters. There are five independent distance determinators that we have used in our own analyses. As described above, with the $\Delta\mathrm{V}_{\mathrm{HB}}^{\mathrm{TO}}$ age-determination technique these can all be

translated into an uncertainty in $M_v(\text{RR})$. Because the various determinations are appropriate for systems of differing metallicity, one must translate the constraints on $M_v(\text{RR})$ to the metallicities appropriate to globular clusters. This of course also introduces uncertainties into the analysis. One assumes a simple linear relation, which we normalize at the mean metallicity of interest:

$$M_v(\text{RR}) = \alpha[\text{Fe/H} + 1.9] + \beta \qquad (2)$$

Various deteminations of this relation imply a weighted mean slope $\alpha = .23 \pm .04$ [1,14], which we have used to translate the distance measures to luminosity determinations at [Fe/H]$= -1.9$.

I briefly describe the different distance determinators, and how we combined them in our analyses of globular cluster ages, and compare these with independent analyses by other groups. In the next section, I will discuss more recent results and their effect on age determinations.

5.1 Statistical Parallax:

This is a traditional method used to determine RR Lyrae star absolute magnitude, and has been applied to stars in the field [15]. It involves the use of observed proper motions and radial velocities with statistical estimates for the total velocities, in order to infer distances to these systems. Because this yields estimates for $M_v(\text{RR})$ for stars in the field, we did not, in our 1998 analysis, include this distance measure, as we reasoned that there could be systematic effects differentiating this sample from globular cluster RR Lyrae stars. As I shall describe, there are more recent reasons to believe that this is not the case. It is also interesting that the Hipparcos satellite provided a large number of proper motions which can be used in this analysis, the net effect of which is to drive $M_v(\text{RR})$ in the *opposite* direction from the direction favored by main sequence fitting due to Hipparcos, as I discuss shortly.

5.2 Astrometric Distances

This method is in fact similar to the statistical parallax method, except that it is applied directly to globular clusters [16]. It requires a dynamical model for the cluster, but nevertheless provides an otherwise direct measure of distance, independent of a "standard candle".

5.3 LMC Distance Measures

Several independent distance measures to the LMC allow the calibration of the magnitude of RR Lyrae stars in this system. These distance measures include the use of Cepheid variable period-luminosity relations [17,18], or SN 1987A light echoes [19,20].

5.4 Theoretical HB Models

As indicated earlier, theoretical modeling of the luminosity of HB stars is subject to possible large systematic uncertainties due to the effects of convection in the cores of these systems, and on great sensitivity to the assumed primordial helium abundance. Nevertheless, theoretical models have improved greatly [21,22], and theoretical predictions can be compared with observations to attempt to constrain distances to globular clusters using this method.

5.5 Main Sequence Fitting

If one can measure parallaxes to nearby field stars, one can attempt to determine the position of the zero age main sequence, and then, via comparison to globular cluster CM diagrams, obtain a direct estimate to the distance to the cluster. Indeed, perhaps the greatest shift in estimates of globular cluster ages came about as a result of the parallax data from the Hipparcos satellite. Hipparcos parallaxes appeared to be systematically smaller than those obtained from the ground, suggesting brighter stars, which in turn would suggest shorter times for evolution off the main sequence. However, there are several problems with a naive extrapolation of the Hipparcos results to globular cluster age estimates. In particular, the Hipparcos stars are not measured at similar metallicities in most cases, and metallicity- dependence could easily introduce uncertainties which can overwhelm any systematic shifts due to the smaller parallaxes.

In any case, the excitement over the Hipparcos results has caused a number of groups to determine distances to globular clusters on the basis of main sequence fitting [23–25,3]. Care must be taken to isolate those stars with low metallicity, and also to remove possible binary systems from the analysis [3].

5.6 White Dwarf Fitting

A similar analysis can compare the parallaxes of local white dwarfs to the recent accurate photometric measurements from the HST of white dwarfs in clusters to dtermine distances [26].

5.7 Combined Results

One can combine the results of the different measures above, along with an attempt to estimate statistical and systematic uncertainties in each method, in order to determine an appropriate value of $M_v(RR)$ for use in globular cluster age estimates. I display the individual results in Table 2.

Table 2
$M_v(RR)$ Calibration

Method	[Fe/H]	$M_v(RR)$	$M_v(RR)$ at [Fe/H] $= -1.9$
Statistical Parallax	-1.6	0.77 ± 0.13	0.70 ± 0.13
Astrometric	-1.59	0.59 ± 0.11	0.52 ± 0.11
White dwarf fitting to N6752	-1.51	0.45 ± 0.14	0.36 ± 0.14
Subdwarf fitting to N6752	-1.51	0.30 ± 0.15	0.21 ± 0.15
Subdwarf fitting to M5	-1.17	0.54 ± 0.09	0.37 ± 0.09
Subdwarf fitting to M13	-1.58	0.36 ± 0.14	0.29 ± 0.14
LMC RR Lyr	-1.90	0.44 ± 0.14	0.44 ± 0.14
Theoretical HB models	-2.20	0.36 ± 0.10	0.43 ± 0.10

Clearly, the final range of ages determined for globular clusters will depend on how one combines these different, often inconsistent, distance determinators. In our comprehensive analysis of 1998, we did not include the statistical parallax results, and combined the other results using a top-hat distribution which ranged from the lowest mean value to the highest. Sampling randomly over such a distribution, and incorporating the Monte Carlo age estimates for the 4 million stellar models we evolved, we determined a best estimate age for the 17 oldest globular clusters to be 11.5 ± 1.3 Gyr, with a one-sided 95% confidence lower limit of 9.5 Gyr. The derived distribution[3] is shown in Figure 4.

It is heartening, perhaps, that several independent analyses, all using main sequence turn-off as an age indicator, but using different stellar models and input physics, and different globular cluster distance estimators, nevertheless produce roughly consistent age estimates (see Table 3). All of these are roughly
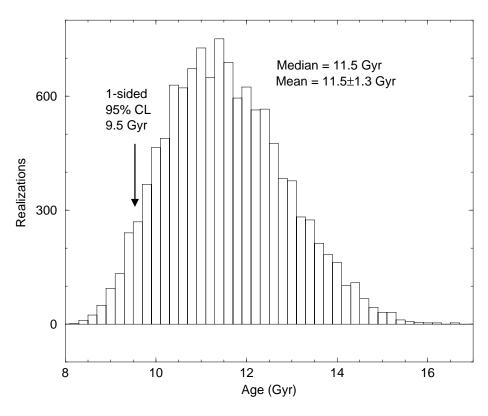
Fig. 4. Histogram of globular cluster ages

2-3 Gyr younger than previous estimates, due in part to the new longer distance scale suggested by Hipparcos, and also due to improved input physics in the models.

Table 3
Different Main Sequence Turn-off Estimate for Globular Cluster Ages

Age (Gyr)	Distance determinator	Study
11.5 ± 1.3	5 techniques (discussed here)	[3]
12 ± 1	main sequence fitting (post Hipparcos)	[23]
11.8 ± 1.2	main sequence fitting (post Hipparcos)	[25]
12 ± 1	Theoretical HB models, main sequence fitting (post H.)	[27]
12.2 ± 1.8	Theoretical HB models	[28]

6 Conclusions: Work in Progress

Where do we go from here? The results of recent years suggest younger ages than previously determined for globular clusters, and also give us more reliable estimates of the uncertainties in the presumed ages, just as David would have liked. Nevertheless, the current results, while barely marginally consistent with a flat matter dominated Universe for the recent HST Key Project Hubble constant measurement, are still consistent with a vast range of cosmological models. It is clear that systematic uncertainties dominate the analysis, and little significant improvement will be possible until consistency is achieved between different age estimators.

There have nevertheless been several recent observational results that suggest a possible shift from the mean globular cluster age estimate quoted above. In particular, a recent comparison of Hipparcos main sequence fitting for subdwarfs with LMC distance measures has suggested that this Hipparcos distance estimator is perhaps 1σ too long [29], leading to a revised age estimate of approximately 13 Gyr. Also, recent studies of the field RR Lyrae stars used in statistical parallax studies suggest that previous concerns about systematic shifts between field and cluster stars may have been unwarranted. We have recently completed a preliminary analysis of globular cluster ages, including the statistical parallax measure[30], and also updating various stellar model parameters [31], and arrive at a new mean value of 12.8 ± 1 Gyr, with a 95 % confidence range of 10-17 Gyr. This age range is now inconsistent with a flat matter dominated universe for the HST Key project value for H_0.

At the same time as these developments have taken place, important new developments have occurred in our understanding of BBN, a subject near and dear to David's heart. New observations of primordial deuterium suggest a primordial helium abundance of perhaps 24.5-25 % If this the case, then the best fit age may be lowered by perhaps .3 Gyr. While it will not significantly alter the conclusions one might draw, I find it poetically just that David's beloved BBN theory has the effect of lowering globular cluster ages, as he would have liked.

One may wonder what further dramatic improvements might be possible in advance of improved distance determinations. One area where significant improvement is possible is in the determination of the age of individual globular clusters. Here, the MSTO method presently leads to uncertainties on the order of $\pm 1 - 2$ Gyr. There is, however, nothing sacred about the use of the MSTO in the analysis. Indeed, as we demonstrated in a separate analysis [32], the theoretical uncertainties remain comparable, but observational uncertainties are greatly reduced if one considers determining ages using a point on the subgiant branch that is 0.05 mag redder than the turnoff point . At the time,

computational limits prohibited carrying out detailed Monte Carlo estimates further up the subgiant branch. However, the speed of computers has altered this situation. We are currently undertaking a new analysis which will systematically explore using a variety of points along the CM diagram for globular clusters to explore globular cluster ages. We expect in this way to be able to reduce the individual uncertainty in relative age of globular clusters by up to an order of magnitude. This will in turn lead to a more restricted distribution in mean ages of the oldest globular clusters.

In conclusion, the past 5 years has seen dramatic improvements in determining the age of globular clusters. The direction has been precisely where David Schramm imagined. The best fit ages are currently 2-3 Gyr smaller than they were a decade ago. At the same time, with improved observational limits on the Hubble constant, and with tentative support for an accelerating Universe, the importance of further improving our knowledge of the age of globular clusters in order to constrain cosmology is, if anything, stronger than it was before. If David were still with us, he would be smiling.

Acknowledgment

References

[1] B. Chaboyer, P. Kernan, P. Demarque, and L.M. Krauss, Science 271, (1996) 957.

[2] e.g. W. L. Freedman, astro-ph/9905222, to appear in "Particle Physics and the Universe", World Scientific (1999)

[3] B. Chaboyer, P. Demarque, P. Kernan, and L. M. Krauss, Ap. J 494 (1998) 96

[4] A. Renzini, in Observational Tests of Cosmological Inflation, eds. T. Shanks, et al., (Dordrecht: Kluwer), 131 (1991); D.A. VandenBerg, M. Bolte, P.B.Stetson, ARA &A 34, 461 (1996); E. Carretta et al, astro-ph/9902086 (1999)

[5] P.R. Durrell and W. E. Harris, AJ, 105, 1420 (1993)

[6] B. Chaboyer, P. Demarque, and A. Sarajedini, Ap. J. 459, 558 (1996)

[7] B. Chaboyer, and Y.-C. Kim, Ap.J. 454, 76 (1995)

[8] P. Nissen et al., A&A, 285, 440 (1994)

[9] K. S. Krishna-Swamy, ApJ, 145, 176 (1996)

[10] E.M. Green et al., The Revised Yale Isochrones & Luminosity Functions (New Haven: Yale Univ. Obs. (1987)

[11] R.L. Kurucz, R.L., in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy, A. Renzini, (Dordrecht: Kluwer), 225 (1992)

[12] J.N. Bahcall and M.H. PinsonneaultRev.Mod.Phys., 64, 885 (1992)

[13] J.N. Bahcall, Neutrino Astrophysics (Cambridge: Cambridge U.P.) (1989)

[14] A. Sarajedini, B. Chaboyer and P. Demarque, PASP 109, 1321 (1997)

[15] A.C. Layden et al., AJ, 112, 2110 (1996)

[16] K.M. Cudworth, AJ, 84, 1212 (1979)

[17] A.R. Walker, ApJ, 390, L81 (1992)

[18] B.F. Madore, and W.L. Freedman, Ap.J. 492, 110 (1998)

[19] A. Gould, ApJ, 452, 189 (1995)

[20] G. Sonneborn, Ap. J., 477, 848 (1997)

[21] S. Cassisi et al, A &A S, 129, 267 (1998)

[22] E. Brocato et al, Ap. J. 491, 789 (1997); V. Caloi et al, A & A, 320, 823 (1997)

[23] I.N. Reid, A.J., 114, 161 (1997)

[24] F. Pont et al A & A 329, 87 (1998)

[25] R. G. Gratton et al, Ap. J. 491, 749 (1997)

[26] A. Renzini et al, Ap. J. 465, L23 (1996)

[27] F. D'Antona, V. Caloi, and I. Mazzitelli, Ap. J. 519, 534 (1997)

[28] M. Salaris et al, Ap. J. 479, 665 (1997)

[29] E. Carretta et al, astro-ph/9902086 (1999)

[30] A. Layden, astro-ph/9810461, to appear in Post-Hipparcos Cosmic Candles, ed. A. Heck and F. Caputo (Kluwer, Dordrecht) (1999)

[31] B. Chaboyer, L.M. Krauss, in preparation

[32] B. Chaboyer, P. Demarque,P.J. Kernan, L. M. Krauss, A. Sarajedini, MNRAS, 283, 683 (1996)