

# Age Estimates of Globular Clusters in the Milky Way: Constraints on Cosmology

Lawrence M. Krauss<sup>1\*</sup> and Brian Chaboyer<sup>2\*</sup>

Recent observations of stellar globular clusters in the Milky Way Galaxy, combined with revised ranges of parameters in stellar evolution codes and new estimates of the earliest epoch of globular cluster formation, result in a 95% confidence level lower limit on the age of the Universe of 11.2 billion years. This age is inconsistent with the expansion age for a flat Universe for the currently allowed range of the Hubble constant, unless the cosmic equation of state is dominated by a component that violates the strong energy condition. This means that the three fundamental observables in cosmology—the age of the Universe, the distance-redshift relation, and the geometry of the Universe—now independently support the case for a dark energy-dominated Universe.

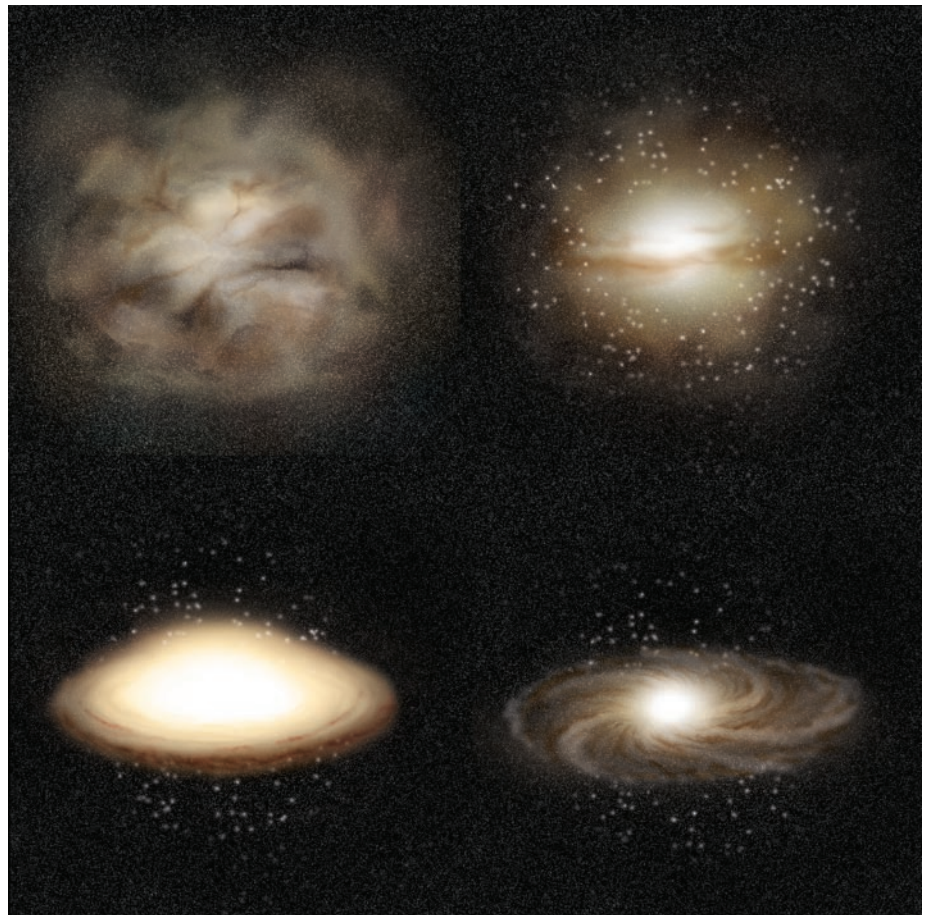
Hubble's first measurement of the expansion of the Universe in 1929 also resulted in an embarrassing contradiction: Working backward, on the basis of the expansion rate he measured, and assuming that the expansion has been decelerating since the Big Bang—as one would expect given the attractive nature of gravity—allowed one to put an upper limit on the age of the Universe since the Big Bang of 1.5 billion years ago (Ga). Even in 1929 this age was grossly inconsistent with well-accepted lower limits on the age of Earth. Although this contradiction evaporated as further measurements of the expansion rate of the Universe yielded a value that was up to an order of magnitude less than Hubble's estimate, much of the subsequent history of 20th-century cosmology has involved a continued tension between the so-called Hubble age—derived on the basis of the Hubble expansion—and the age of individual objects within our own galaxy.

Of special interest in this regard are perhaps the oldest objects in our galaxy, called globular clusters. Compact groups of 100,000 to 1 million stars with dynamical collapse times of less than 1 million years, many of these objects are thought to have coalesced out of the primordial gas cloud that only later collapsed, dissipating its energy and settling into the disk of our Milky Way Galaxy (see Fig. 1). Those globular clusters that still populate the halo of our galaxy are thus among the oldest visible objects within it, a fact confirmed by measuring the abundance of heavy elements such as iron in stars within

such clusters. This abundance can be less than one-hundredth of that measured in the Sun, which suggests that the gas from which these objects coalesced had not previously experienced significant star formation and

evolution. Thus, an accurate determination of the age of the oldest clusters can yield one of the most stringent lower limits on the age of our galaxy, and thus the Universe.

Globular cluster age estimates in the 1980s fell in the range of 16 to 20 Ga (1–3), producing a new apparent incompatibility with the Hubble age, then estimated to be 10 to 15 Ga on the basis of an estimated lower limit on the Hubble constant  $H_0$  of 50 to 75  $\text{km s}^{-1} \text{Mpc}^{-1}$ . This provided one of the earliest motivations for reintroducing a cosmological constant into astrophysics. Such a term in Einstein's equations results in an increased Hubble age because it allows for a cosmic acceleration, implying a slower ex-



**Fig. 1.** The oldest globular clusters (compact collections of stars shown as bright dots in the figure) are thought to have coalesced early on from small-scale density fluctuations in the primordial gas cloud, which itself later coherently collapsed, dissipating its energy and settling into the disk of our Milky Way Galaxy. As a result, these objects populate a roughly spherical halo in our galaxy today. This sequence of events is shown schematically in four stages, from upper left to lower right.

<sup>1</sup>Departments of Physics and Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA. <sup>2</sup>Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755, USA.

\*To whom correspondence should be addressed. E-mail: lmk9@po.cwru.edu, chaboyer@heather.dartmouth.edu

pansion rate at earlier times. Thus, galaxies located a certain distance away from us today would have taken longer to achieve this separation since the Big Bang than they otherwise would have. However, as more careful examinations of uncertainties associated with stellar evolution were performed, as well as refined estimates of the parameters that govern stellar evolution, the lower limit on globular cluster ages progressively decreased, so that a wide range of cosmological models produced Hubble ages consistent with this lower limit (4–7).

In the interim, other classic cosmological tests [including cosmic microwave background (CMB) measurements and measurements of redshift versus distance for distant supernovae], when combined with mass estimates from large-scale structure observations, seem to point toward the need for something like a cosmological constant. It is thus timely to reexamine stellar age estimates in light of new data, in order to explore how this might complement these other cosmological constraints.

There are three independent ways to reliably infer the age of the oldest stars in our galaxy: radioactive dating, white dwarf cooling, and the main sequence turnoff time scale.

**Radioactive dating.** Recent observations of thorium and uranium in metal-poor stars (8, 9) now make it possible to determine ages of individual stars using the known radioactive half-lives of these elements ( $^{232}\text{Th}$  has a half-life of 14 billion years, whereas  $^{238}\text{U}$  has a half-life of 4.5 billion years), if one can estimate the initial abundance ratio of these two elements. There are two principal difficulties with radioactive dating: (i) Thorium and uranium have weak spectral lines in stars, and accurate abundance measurements of these elements is only possible if the stars have enhanced thorium and uranium abundances relative to lighter elements like carbon and nitrogen; and (ii) one must know how thorium and uranium are produced in order to calculate their initial abundance ratio. The first difficulty is overcome by surveying large numbers of metal-poor stars to find rare stars with enhanced abundances. The second difficulty is more problematic, because thorium and uranium are produced by rapid neutron capture (called the r-process) far from nuclear stability. This makes it difficult to estimate the systematic uncertainties associated with theoretical predictions of the initial abundance ratio of thorium and uranium.

At present, uranium has been definitively detected in only a single star: CS 31082-001 (8, 10). The computed production ratios give a quoted age for CS 31082-001 of  $14.0 \pm 2.4$  Ga (10). Uranium and a large number of other r-process elements, including thorium, have

been tentatively detected in the metal-poor star BD+17° 3248 (9). On the basis of the thorium and uranium abundance measurements and a comparison of these abundances to the abundance of other r-process elements, an age of  $13.8 \pm 4$  Ga is found for this star (9). Although these ages are in agreement, the uncertainty is large and depends critically on the theoretical calculation of the initial production ratio of thorium and uranium. Improving these age estimates will require further measurements of uranium and thorium in metal-poor stars, along with progress in understanding the r-process in general and the production ratio of thorium and uranium in particular.

**White dwarf cooling.** White dwarfs are the end stage of the evolution of stars with initial masses less than about eight solar masses. No nuclear energy generation is occurring in these white dwarfs, which are supported by electron degeneracy pressure. The white dwarf radiates energy into space, slowly cooling and becoming less luminous over time. As a result, the luminosity of the faintest white dwarfs in a cluster of stars can be used to estimate the age of the cluster by comparing the observed luminosities to theoretical models of how white dwarfs cool (11). However, calculation of the models for very old white dwarfs is complicated by complexities in the equation of state, uncertainties in the core composition of white dwarfs, and the cool temperatures at their surfaces, which require detailed radiative transfer calculations in order to estimate the flux emitted by these stars in the observed wavelength regions.

An initial attempt to observe the faintest white dwarfs in a globular cluster was made in 1995 with the Hubble Space Telescope (HST). These observations found white dwarfs at the limit of the photometry, which implied that the globular cluster M4 had a minimum age of 9 Ga (12). A much deeper exposure of M4 with HST (approximate exposure time 8 days) was obtained in 2001 (13), allowing observation of fainter white dwarfs. This study resulted in an estimated age for this cluster of  $12.7 \pm 0.7$  Ga (13). However, the quoted error in this age only takes into account the observational uncertainties and does not include the possible error introduced by uncertainties in the white dwarf cooling calculations. It is particularly difficult to estimate the complex equation of state of these stars, so that the systematic uncertainties are likely to be at least as large as, if not larger than, the quoted statistical errors.

Age estimates from both these techniques thus suggest a galactic age in excess of 10 Ga, which can marginally be accommodated in a flat, matter-dominated Universe, given current uncertainties in the Hubble constant. It is thus important to attempt to reduce the un-

certainties in age estimates, while also searching out other techniques whose independent uncertainties may be under better control if globular cluster ages are to be used to constrain the equation of state for a flat Universe.

### Main Sequence Turnoff Ages

Numerical stellar evolution models provide estimates of the surface temperature and luminosity of stars as a function of time. These can be compared to observations of stellar colors and magnitudes in order to determine, in principle, the age of an ensemble of stars in a globular cluster. As stars evolve, their location on a temperature-luminosity plot changes. Thus, the distribution on this plot for a system of stars of different masses (such as one finds in a globular cluster) matches the theoretical distribution at only one time. Although probing the entire distribution of stars would, in principle, provide the best constraint on the age of the system, in practice stellar models are best determined for main-sequence stars. The most robust prediction of the theoretical models is the time it takes a star to exhaust the supply of hydrogen in its core (4, 14), at which point the star leaves the main sequence (Fig. 2). Thus, absolute globular cluster age determinations with the smallest theoretical uncertainties are those that are based on the luminosity at this “main sequence turnoff” point.

The theoretical stellar isochrones used for comparison with observations are dependent on a variety of parameters that are used as inputs for the numerical codes used to model stars and compare them to observations. These input parameters are subject to various theoretical and experimental uncertainties. The one method that explicitly incorporates all of these in a self-consistent fashion uses Monte Carlo techniques (4). Input parameters can be randomly chosen from distributions fit to the inferred uncertainties from observations, allowing one to derive output distributions for stars to be compared to observed stellar distributions for low-metallicity globular clusters. It has been found that the uncertainty in translating magnitudes to luminosities (i.e., the uncertainties in deriving distances to globular clusters) is the chief source of uncertainty in globular cluster age estimates.

### Globular Cluster Distance Estimates

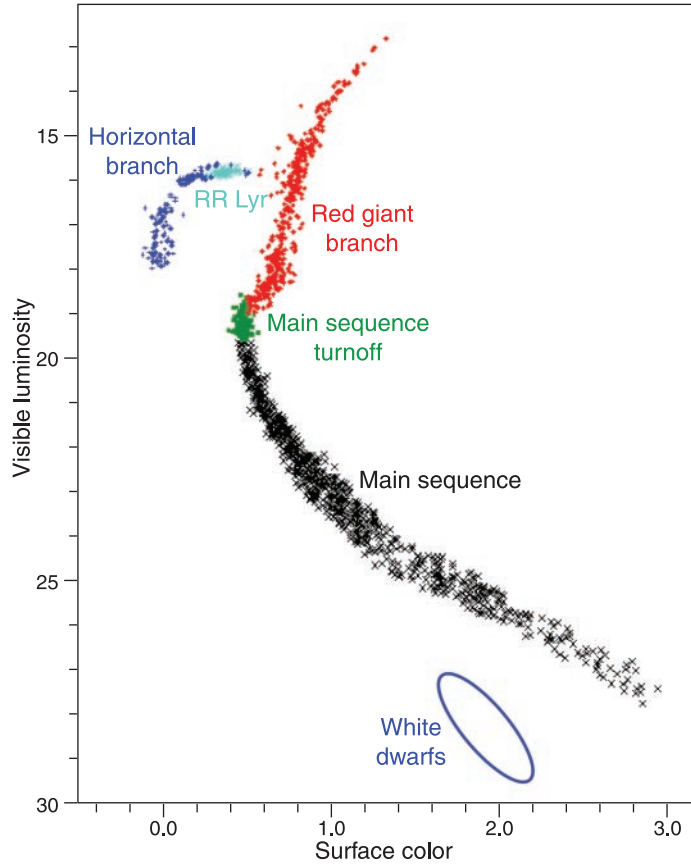
There are five main methods that can be used to estimate the distance to globular clusters. All of these methods rely on various assumptions or prior calibration steps. The most common technique involves what are called “standard candles.” This method assumes that some class of stars have the same intrinsic luminosity, regardless of their location in the Galaxy. One then observes the flux (apparent luminosity on the

sky) of the same class of stars in a globular cluster and determines the distance to the globular cluster by comparing the observed flux to the assumed intrinsic luminosity of the star. Classes of stars used to determine the distances to globular cluster stars include white dwarfs (15), main-sequence stars (16), horizontal branch (HB) stars (17), and RR Lyrae stars (a subclass of HB stars) (18). Details regarding these different types of stars are found in Fig. 2 and its caption. The key to the success of this approach involves the accuracy in determining the intrinsic luminosity of the standard candle. This can be done by using theoretical models, or by directly measuring the distance to a nearby standard candle star using trigonometric parallax. This distance estimation can be combined with a measurement of the star's flux to determine the intrinsic luminosity of that standard candle.

Studies of the internal dynamics of the stars within a globular cluster provide an independent method for determining the distance to a globular cluster. The dynamical distance estimate compares the relative motion of globular cluster stars in the plane of the sky (proper motion) to their motions along the line of sight to the star (radial velocities). The measured radial velocities are independent of distance, whereas the measured proper motions are smaller for more distant objects; hence, a comparison of the two observations allows one to estimate the distance to a globular cluster.

As these discussions make clear, the distance determination for globular clusters is subject to many uncertainties. However, our knowledge of the distance scale is evolving rapidly. Many of the distance indicators to globular clusters make use of HB stars. Our knowledge of the evolution of HB stars continues to advance through the use of increasingly more realistic stellar models. Studies of the evolution of HB stars and their use as distance indicators have shown that the luminosity of the HB stars depends not only on metallicity, but also on the evolutionary status of the stars on the HB in a given globular cluster (19, 20).

To compare different distance indicators, it is convenient to parameterize the distance estimate by what it implies for the



**Fig. 2.** A schematic color-magnitude diagram for a typical globular cluster (33) showing the location of the principal stellar evolutionary sequences. This diagram plots the visible luminosity of the star (measured in magnitudes) as a function of the surface color of the star (measured in B-V magnitude). Hydrogen-burning stars on the main sequence eventually exhaust the hydrogen in their cores (main sequence turnoff). After this, stars generate energy through hydrogen fusion in a shell surrounding an inert hydrogen core. The surface of the star expands and cools (red giant branch). Eventually the helium core becomes so hot and dense that the star ignites helium fusion in its core (horizontal branch). A subclass is unstable to radial pulsations (RR Lyrae). When a typical globular cluster star exhausts its supply of helium, and fusion processes cease, it evolves to become a white dwarf.

visual (V) magnitude of an RR Lyrae star,  $M_v(\text{RR})$ . The results are summarized in Table 1 for the different distance indicators. There are three new features of this compilation, as compared to those associated with previous analyses: (i) Hipparcos parallaxes for metal-poor, blue HB stars in the field to calibrate the globular cluster distance scale are included (17); (ii) the statistical parallax results on field RR Lyrae stars are included; (iii) a new HST parallax for the star RR Lyrae itself is included, which is considerably more accurate than the Hipparcos parallax (18); and (iv) only distance estimates for systems with  $[\text{Fe}/\text{H}] < -1.4$  are included.

To compare the different distance estimates, these  $M_v(\text{RR})$  values must be translated to a common  $[\text{Fe}/\text{H}]$  value. For this, an  $M_v(\text{RR})-[\text{Fe}/\text{H}]$  slope of  $0.23 \pm 0.06$  is used, as suggested by models (19). We used  $[\text{Fe}/\text{H}]$

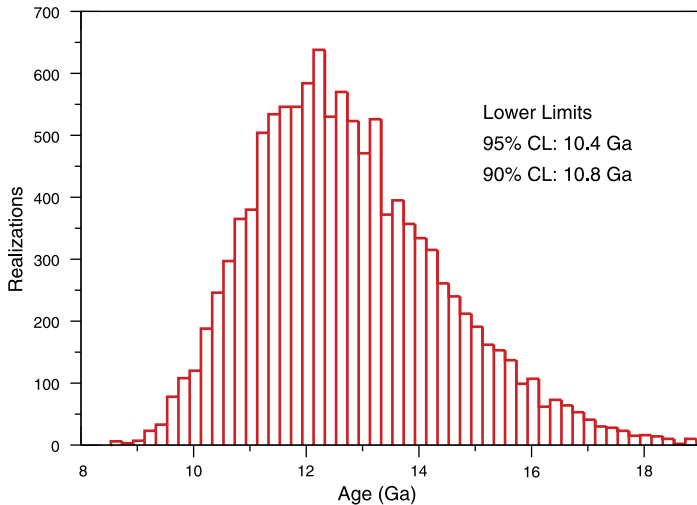
$= -1.9$ , as this is the mean of the globular clusters whose average age will be determined. Because the different distance estimates span a relatively modest range in  $[\text{Fe}/\text{H}]$  (0.54 dex), the exact value of the  $M_v(\text{RR})-[\text{Fe}/\text{H}]$  slope has only a minor effect in our resultant distance scale. The weighted mean value of the absolute magnitude of the RR Lyrae stars at  $[\text{Fe}/\text{H}] = -1.9$  is  $M_v(\text{RR}) = 0.46$  mag.

The statistical parallax technique yields values for  $M_v(\text{RR})$  that are larger (i.e., fainter) than the other distance techniques. When statistical parallax results are included in the weighted mean, the standard deviation about the mean is 0.13 mag. When the statistical parallax results are not included in the analysis, the mean becomes  $M_v(\text{RR}) = 0.44$  and the standard deviation about the mean drops to 0.07 mag. In earlier analyses, the statistical parallax data were not included (5), because there were suggestions that some systematic differences might exist between RR Lyrae stars in the field and those in globular clusters. However, subsequent investigations have shown that this is not the case (21).

Using the  $\pm 0.13$  mag standard deviation results in a long tail at low values of  $M_v(\text{RR})$ . It is inappropriate to include this spurious low tail when quoting an allowed range. An asymmetric Gaussian distribution  $M_v(\text{RR}) = 0.46^{+0.13}_{-0.09}$  mag has a low range consistent with that derived when the statistical parallax result is not included, but has a mean and high range equivalent to the value derived by including the statistical parallax result in a straightforward way. This is the distribution that will be used to derive the allowed distance scale for metal-poor globular clusters.

### Stellar Evolution Input Parameters

Seven critical parameters used in the computation of stellar evolution models have been identified whose estimated uncertainty can significantly affect derived globular cluster age estimates (5). In order of importance, they are (i) oxygen abundance  $[\text{O}/\text{Fe}]$  (22), (ii) treatment of convection within stars, (iii) helium abundance, (iv)  $^{14}\text{N} + \text{p} \rightarrow ^{15}\text{O} + \gamma$  reaction rate, (v) helium diffusion, (vi) transformations from

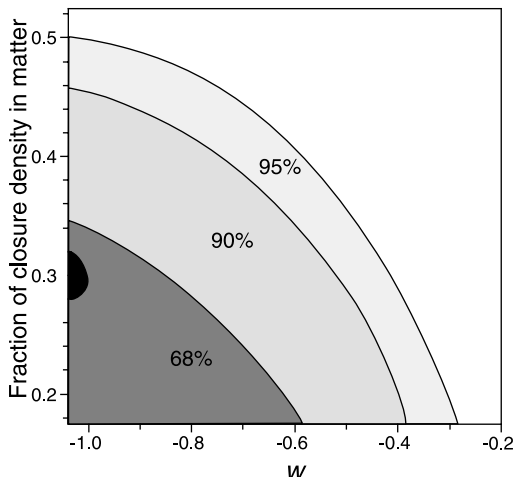


**Fig. 3.** Histogram representing results of Monte Carlo presenting 10,000 fits of predicted isochrones for differing input parameters to observed isochrones to determine the age of the oldest globular clusters.

theoretical temperatures and luminosities to observed colors and magnitudes, and (vii) opacities below  $10^4$  K. Table 2 details the range of these parameters used in a Monte Carlo simulation to evaluate the errors in the globular cluster age estimates. The ranges for the oxygen abundance, the primordial helium abundance, and the helium diffusion coefficients have changed as a result of recent observations.

### The Age and Formation Time of Globular Clusters and Constraints on the Cosmic Equation of State and Mass Density

Using the estimates for the parameter ranges for the variables associated with stellar evolution (4, 5), we have determined the age of the oldest Galactic globular clusters with a Monte Carlo simulation (Fig. 3). Taking a one-sided 95% range, one finds a lower bound of 10.4 Ga. This



**Fig. 4.** Range of allowed values for the dark energy equation of state versus the matter density, assuming a flat Universe, for the lower limit derived in the text for the age of the Universe, and for  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

lower bound is more stringent than previous estimates because of a confluence of factors; the new  $M_V(\text{RR})$  distance estimates contributed 60% of the increase relative to previous estimates. The best-fit age has also increased and is now 12.6 Ga. Moreover, we also find the 95% confidence upper limit on the age to be 16 Ga. To use these results to constrain cosmological parameters, one

needs to add to these ages a time that corresponds to the time between the Big Bang and the formation of globular clusters in our galaxy.

Observations of large-scale structure, combined with numerical simulations and CMB measurements of the primordial power spectrum of density perturbations, have now established that structure formation occurred hierarchically in the Universe, with galaxies forming before clusters. Moreover, observations of galaxies at high redshift definitively imply that gravitational collapse into galaxy-size halos occurred at probably less than 1.5 Ga, and definitely less than 5 Ga, after the Big Bang. Although this puts a firm upper limit of 21 Ga on the age of the Universe, the task of putting a lower limit on the time in which galaxies like ours formed is somewhat more subtle.

Fortunately, this is an area in which our observational knowledge has increased in recent years. In particular, recent studies using observations of globular clusters in nearby galaxies and measurements of high-redshift Lyman  $\alpha$  objects all independently put a limit  $z < 6$  for the maximum redshift of structure formation on the scale of globular clusters (23–26).

To convert the redshifts into times, it is generally necessary to know the equation of state of the dominant energy density in order to solve Einstein's equations for an expanding Universe. However, the age of the Universe as a function of redshift is insensitive to the cosmic equation of state today for redshifts greater than about 3 to 4. This is because for these early times the matter energy density would have exceeded the dark energy density because such energy, by violating the strong energy condition, decreases far more slowly as the Universe expands than does matter.

This can be seen as follows. For a flat Universe with fraction  $\Omega_0$  in matter density and  $\Omega_x$  in radiation at the present time, the age  $t_{z'}$  at redshift  $z'$  is given by

$$H_0 t_{z'} = \int_{z'}^{\infty} \frac{dz}{(1+z)[\Omega_0(1+z)^3 + \Omega_x(1+z)^{3(1+w)}]^{1/2}} \quad (1)$$

where  $w$ , the ratio of pressure to energy density for the dark energy, represents the equation of state for the dark energy (assumed here for simplicity to be constant). For  $w < -0.3$ , as required in order to produce an accelerating Universe, and for  $\Omega_0 \approx 0.3$  and  $\Omega_x \approx 0.7$  as suggested by observations (27–29), the  $\Omega_x$  term is negligible compared to the  $\Omega_0$  term for all redshifts greater than about 4.

This relation implies that the age of the Universe at a redshift  $z = 6$  was greater than about 0.8 Ga, independent of the cosmological model. Using this relation and the estimates given above, we find, on the basis of main sequence turnoff estimates of the age of the oldest globular clusters in our galaxy, a 95% confidence level lower limit on the age of the Universe of 11.2 Ga, and a best fit age of 13.4 Ga.

These limits can be compared with the inferred Hubble age of the Universe, given by Eq. 1 for  $z' = 0$ , for different values of  $w$ , and for different values of  $H_0$  today. CMB determinations of the curvature of the Universe suggest that we live in a flat Universe [i.e., (30)]. When we combine the CMB result with these age limits on the oldest stars, some form of dark energy is required. The Hubble Key Project (31) estimated range for  $H_0$  is  $72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (note that this estimate is based on an estimate of  $M_V(\text{RR})$  that is consistent with our estimates). Figure 4 displays the allowed range of  $w$  versus matter energy density for the case  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . In this case, for  $\Omega_0 > 0.25$ , as suggested by large-scale structure data,  $w < -0.7$  at the 68% confidence level, and  $w < -0.45$  at the 95% confidence level.

Although the precise limits and allowed parameter range are sensitive to the assumed value of the Hubble constant, the lower limit on globular cluster ages presented here definitively rules out a flat, matter-dominated (i.e.,  $w = 0$ ) Universe at the 95% confidence level for the entire range of  $H_0$  determined by the Key project. Interestingly, for the best fit value of the Hubble constant, globular cluster age limits also put strong limits on the total matter density of the Universe. In order to achieve consistency, if  $w > -1$ ,  $\Omega_0$  cannot exceed 35% of the critical density at the 68% confidence level and 50% of the critical density at the 95% confidence level.

One might wonder whether the upper lim-

Table 1. Estimates of  $M_v(\text{RR})$ .

Method	Objects	[Fe/H]	$M_v(\text{RR})$	$M_v(\text{RR})$ at [Fe/H] = -1.90
Theoretical HB models	Metal-poor blue HB clusters	-1.90	$0.35 \pm 0.10$	$0.35 \pm 0.10$ (79)
Main sequence fitting	M13, M68, M92, N6752	-1.83	$0.35 \pm 0.10$	$0.36 \pm 0.10$ (76)
White dwarf fitting	N6397	-1.42	$0.52 \pm 0.15$	$0.41 \pm 0.15$ (75)
LMC RR Lyr	RR Lyr in the LMC	-1.90	$0.44 \pm 0.10$	$0.44 \pm 0.10$ (34)
Trigonometric parallax	RR Lyrae	-1.39	$0.61 \pm 0.11$	$0.49 \pm 0.15^*$ (21)
Trigonometric parallax	Field halo HB stars	-1.51	$0.60 \pm 0.12$	$0.51 \pm 0.16^*$ (17)
Dynamical	M2, M13, M22, M92	-1.74	$0.59 \pm 0.15$	$0.55 \pm 0.15$ (76, 35)
Statistical parallax	Field RR Lyr	-1.60	$0.77 \pm 0.13$	$0.71 \pm 0.16^*$ (36)

\*Includes additional 0.10 mag uncertainty due to uncertain evolutionary status.

Table 2. Monte Carlo input parameters.

Parameter	Distribution	References
[O/Fe]	$0.45 \pm 0.25$ (uniform)	(37–41)
Convection: Mixing length	$1.85 \pm 0.25$ (uniform)	(5)
Helium abundance	$0.2475 \pm 0.0025$ (uniform)	(30, 42, 43)
$^{14}\text{N} + \text{p} \rightarrow ^{15}\text{O} + \gamma$ reaction rate	$1.00 \pm 0.12$ (uniform)	(5)
Helium diffusion	$0.50 \pm 0.30$ (uniform)	(44–47)
Color transformation	Binary	(48, 49)
Opacities below $10^4$ K	$1.0 \pm 0.3$ (uniform)	(5)

it on globular cluster ages can provide a lower bound on  $w$ . This would be of great interest, because we have no fundamental theoretical understanding of this quantity. In fact, however, this hope cannot be fulfilled. Assuming  $\Omega_0 > 0.2$ , which seems quite conservative, one can show that there is a maximum Hubble age (32), independent of  $w$ , of  $\sim 20$  Ga, for a Hubble constant of 72. Because the current upper limit we derive exceeds this value, no useful constraint on  $w$  can be derived. On the other hand, if one could definitively demonstrate an age limit from globular clusters that actually approached this upper limit, a serious inconsistency with the Hubble age might once again arise.

The results described in this review take us back full circle, implying that globular cluster ages are currently inconsistent with the determined age of the Universe unless some kind of dark energy dominates the energy density of the Universe. Whether this dark energy resides in the form of a cosmological constant ( $w = -1$ ) remains to be seen, although this value is certainly favored by age estimates. Indeed, it is remarkable that all fundamental independent observables in modern cosmology—including CMB measurements, measurements of large-scale

structure, measurements of the distance-redshift relation, and now measurements of the age of the Universe—all are consistent with a single cosmological model, involving a flat Universe with about 30% of its energy density due to nonrelativistic matter, and 70% of its energy due to something like a cosmological constant. Determining the specific nature of this exotic energy that dominates the Universe will require much observational and theoretical effort. Globular cluster ages at present give nontrivial but loose constraints. However, the recent progress in determining stellar ages gives cause for optimism that better limits may be possible in the near future.

References and Notes

1. K. Janes, P. Demarque, *Astrophys. J.* **264**, 206 (1983).
2. G. G. Fahlman, H. B. Richer, D. A. Vandenberg, *Astrophys. J. Suppl. Ser.* **58**, 225 (1985).
3. A. Chieffi, O. Straniero, *Astrophys. J. Suppl. Ser.* **71**, 47 (1989).
4. B. Chaboyer, P. Demarque, P. Kernan, L. M. Krauss, *Science* **271**, 957 (1996).
5. ———, *Astrophys. J.* **494**, 96 (1998).
6. E. Carretta, R. G. Gratton, G. Clementini, F. Fusi Pecci, *Astrophys. J.* **533**, 215 (2000).
7. F. Pont, M. Mayor, C. Turon, D. A. Vandenberg, *Astron. Astrophys.* **329**, 87 (1998).
8. R. Cayrel et al., *Nature* **409**, 691 (2001).
9. J. J. Cowan et al., *Astrophys. J.* **572**, 861 (2002).
10. V. Hill et al., *Astron. Astrophys.* **387**, 560 (2002).

11. B. M. S. Hansen, *Astrophys. J.* **520**, 680 (1999).
12. H. B. Richer et al., *Astrophys. J.* **484**, 741 (1997).
13. B. M. S. Hansen, *Astrophys. J.*, in press.
14. A. Renzini, in *Observational Tests of Cosmological Inflation*, T. Shanks, A. J. Banday, R. S. Ellis, Eds. (Kluwer, Dordrecht, Netherlands, 1991), pp. 131–141.
15. A. Renzini et al., *Astrophys. J.* **465**, L23 (1996).
16. B. Chaboyer, in *Globular Cluster Distance Determinations in Post-Hipparcos Cosmic Candle*, A. Heck, F. Caputo, Eds. (Kluwer, Dordrecht, Netherlands, 1998), pp. 111–124.
17. R. G. Gratton, *Mon. Not. R. Astron. Soc.* **296**, 739 (1998).
18. G. F. Benedict et al., *Astron. J.* **123**, 373 (2002).
19. P. Demarque, R. Zinn, Y. Lee, S. Yi, *Astron. J.* **119**, 1398 (2000).
20. F. Caputo, S. degl’Innocenti, *Astron. Astrophys.* **298**, 833 (1995).
21. M. Catelan, *Astrophys. J.* **495**, L81 (1998).
22. [O/Fe] is the oxygen abundance in a star relative to the iron abundance, in solar units, and is defined by the equation  $[\text{O}/\text{Fe}] = \log(\text{O}/\text{Fe})_{\text{star}} - \log(\text{O}/\text{Fe})_{\text{Sun}}$ . For example, a star with the same relative oxygen-to-iron ratio as the sun would have  $[\text{O}/\text{Fe}] = 0$ .
23. H. A. Kobulnicky, D. C. Koo, *Astrophys. J.* **545**, 712 (2000).
24. D. Burgarella, M. Kissler-Patig, V. Buat, *Astron. J.* **121**, 2647 (2001).
25. O. Y. Gnedin, O. Lahav, M. J. Rees, available at <http://arXiv.org/abs/astro-ph/0108034>.
26. S. van den Bergh, *Astrophys. J.* **559**, L113 (2001).
27. L. M. Krauss, *Astrophys. J.* **501**, 461 (1998).
28. S. Perlmutter et al., *Astrophys. J.* **517**, 565 (1999).
29. P. M. Garnavich et al., *Astrophys. J.* **509**, 74 (1998).
30. P. De Bernardis et al., *Astrophys. J.* **564**, 559 (2002).
31. W. L. Freedman et al., *Astrophys. J.* **553**, 47 (2001).
32. L. M. Krauss, available at <http://arXiv.org/abs/astro-ph/0212369>.
33. P. R. Durrell, W. E. Harris, *Astron. J.* **105**, 1420 (1993).
34. A. R. Walker, *Astrophys. J.* **390**, L81 (1992).
35. R. F. Rees, in *Formation of the Galactic Halo: Inside and Out*, H. Morrison, A. Sarajedini, Eds. (Astronomical Society of the Pacific, San Francisco, 1996), pp. 289–294.
36. A. Gould, P. Popowski, *Astrophys. J.* **508**, 844 (1998).
37. A. M. Boesgaard, J. R. King, C. P. Deliyannis, S. S. Vogt, *Astron. J.* **117**, 492 (1999).
38. E. Carretta, R. G. Gratton, C. Sneden, *Astron. Astrophys.* **356**, 238 (2000).
39. R. G. Gratton et al., *Astron. Astrophys.* **369**, 87 (2001).
40. J. Meléndez, B. Barbuy, F. Spite, *Astrophys. J.* **556**, 858 (2001).
41. G. Israelian et al., *Astrophys. J.* **551**, 833 (2001).
42. S. Bures, K. M. Nollett, M. S. Turner, *Astrophys. J.* **552**, L1 (2001).
43. T. M. Banks, R. T. Rood, D. S. Balsaer, *Nature* **415**, 54 (2002).
44. J. Christensen-Dalsgaard, C. R. Proffitt, M. J. Thompson, *Astrophys. J.* **403**, L75 (1993).
45. S. Basu, M. H. Pinsonneault, J. N. Bahcall, *Astrophys. J.* **529**, 1084 (2000).
46. B. Chaboyer et al., *Astrophys. J.* **562**, 521 (2001).
47. A. A. Thoul, J. N. Bahcall, A. Loeb, *Astrophys. J.* **421**, 828 (1994).
48. R. L. Kurucz, in *The Stellar Populations of Galaxies*, B. Barbuy, A. Renzini, Eds. (Kluwer, Dordrecht, Netherlands, 1992), pp. 225–232.
49. E. M. Green, P. Demarque, C. R. King, *The Revised Yale Isochrones & Luminosity Functions* (Yale Univ. Observatory, New Haven, CT, 1987).