The Age of the Universe

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Abstract

A minimum age of the universe can be estimated directly by determining the age of the oldest objects in the our Galaxy. These objects are the metal-poor stars in the halo of the Milky Way. Recent work on nucleochronology finds that the oldest stars are \(15.2 \pm 3.7\) Gyr old. White dwarf cooling curves have found a minimum age for the oldest stars of \(8\) Gyr. Currently, the best estimate for the age of the oldest stars is based upon the absolute magnitude of the main sequence turn-off in globular clusters. The oldest globular clusters are \(11.5 \pm 1.3\) Gyr, implying a minimum age of the universe of \(t_{\text{universe}} \geq 9.5\) Gyr (95% confidence level).

1 Introduction

A direct estimate for the minimum age of the universe may be obtained by determining the age of the oldest objects in the Milky Way. This direct estimate for the age of the universe can be used to constrain cosmological models, as the expansion age of the universe is a simple function of the Hubble constant, average density of the universe and the cosmological constant. The oldest objects in the Milky Way are the metal-poor stars located in the spherical halo. There are currently three independent methods used to determine the ages of these stars: (1) nucleochronology, (2) white dwarf cooling curves and (3) main sequence turn-off ages based upon stellar evolution models. In this review I will summarize recent results from these three methods, with particular emphasize on main sequence turn-off ages as they currently provide the most reliable estimate for the age of the universe.

2 Nucleochronology

Conceptually, the simplest way to determine the age of a star is to use the same method which have been used to date the Earth – radioactive dating. The age
of a star is derived using the abundance of a long lived radioactive nuclei with
a known half-life (see, for example the review [1]). The difficulty in applying
this method in practice is the determination of the original abundance of the
radioactive element. The best application of this method to date has been
on the very metal-poor star CS 22892 [2]. This star has a measured thorium
abundance (half-life of 14.05 Gyr), and just as importantly, the abundance of
the elements from $56 \leq Z \leq 76$ are very well matched by a scaled solar system
$r$-process\footnote{The $r$-process is the creation of elements heavier than Fe through the rapid capture
of neutrons by a seed nuclei.} abundance distribution. Thus, it is logical to assume that the
original abundance of thorium in this star is given by the scaled solar system
$r$-process thorium abundance. A detailed study of the $r$-process abundances
in CS 22892 lead to an age of $15.2 \pm 3.7$ Gyr for this extremely metal-poor
star [2]. This in turn, implies a $2\sigma$ lower limit to the age of the universe of
$t_{\text{universe}} \geq 7.8$ Gyr from nucleochronology. This is not a particularly stringent
constraint at present. However, the uncertainty in the derived age is due en-
tirely to the uncertainty in the determination of the thorium abundance in CS
22892. The determination of the abundance of thorium in a number of stars
with similar abundance patterns to CS 22892 will naturally lead to a reduction
in the error. If 8 more stars are observed, then the error in the derived age
will be reduced to $\pm1.2$ Gyr, making nucleochronology the preferred method
of obtaining the absolute ages of the oldest stars in our galaxy.

3 White Dwarf Cooling Curves

White dwarfs are the terminal stage of evolution for stars less massive than
$\sim 8 M_\odot$. As white dwarfs age, they become cooler and fainter. Thus, the
luminosity of the faintest white dwarfs can be used to estimate their age.
This age is based upon theoretical white dwarf cooling curves [3–5]. There
are a number of uncertainties associated with theoretical white dwarf models,
which have been studied in some detail. However, the effect of these theoretical
uncertainties are generally not included in deriving the uncertainty associated
with white dwarf cooling ages.

The biggest difficulty in using white dwarfs to estimate the age of the universe
is that white dwarfs are very faint and so are very difficult to observe. Most
studies of white dwarf ages have concentrated on the solar neighborhood, in
an effort to determine the age of the local disk of the Milky Way. Even these
nearby samples can be affected by completeness concerns. The age determina-
tion for these disk white dwarfs is complicated by the fact that the results are
sensitive to the star formation rate as a function of time [3]. A recent study
has increased the sample size of local white dwarfs and concluded that the lo-
The local disk of the Milky Way has an age of $t_{\text{disk}} = 9.5^{+1.1}_{-0.8}$ Gyr, where the quoted errors are due to the observational uncertainties in counting faint white dwarfs [6]. This implies a 2σ lower limit to the age of the local disk of $t_{\text{disk}} \geq 7.9$ Gyr.

Recently, with the Hubble Space Telescope it has become possible to observe white dwarfs in nearby globular clusters\(^2\). These observations are not deep enough to observe the faintest white dwarfs and can only put a lower limit to the age of the white dwarfs. Observations of the globular cluster M4 found a large number of white dwarfs, with no decrease in the number of white dwarfs at the faintest observed magnitudes [7]. Based upon the luminosity of the faintest observed white dwarfs, a lower limit to the age of M4 was determined to be $t_{\text{glob}} \gtrsim 8$ Gyr [7]. When the advanced camera becomes operational on HST (scheduled to occur in the year 2000), it will be possible to obtain considerably deeper photometry of M4, leading to an improved constraint on the age of M4 from white dwarf cooling curves.

4 Main Sequence Turn-off Ages

Theoretical models for the evolution of stars provide an independent method to determine stellar ages. These computer models are based on stellar structure theory, which is outlined in numerous textbooks [8,9]. One of the triumphs of stellar evolution theory is a detailed understanding of the preferred location of stars in a temperature-luminosity plot (Figure 1).

A stellar model is constructed by solving the four basic equations of stellar structure: (1) conservation of mass; (2) conservation of energy; (3) hydrostatic equilibrium and (4) energy transport via radiation, convection and/or conduction. These four, coupled differential equations represent a two point boundary value problem. Two of the boundary conditions are specified at the center of the star (mass and luminosity are zero), and two at the surface. In order to solve these equations, supplementary information is required. The surface boundary conditions are based on stellar atmosphere calculations. The equation of state, opacities and nuclear reaction rates must be known. The mass and initial composition of the star need to be specified. Finally, as convection

\(^2\) Globular clusters are compact stellar systems containing $\sim 10^5$ stars. These stars contain few heavy elements (typically 1/10 to 1/100 the ratio found in the Sun) and are spherically distributed about the Galactic center. Together, these facts suggest that globular clusters were among the first objects formed in the Galaxy. There is evidence for an age range among the globular clusters, so the tightest limits on the minimum age of the universe are found when only the oldest globular clusters are considered. These are typically the globular clusters with the lowest heavy element abundances (1/100 the solar ratio).
Fig. 1. A color-magnitude diagram of a typical globular cluster, M15 [10]. The vertical axis plots the magnitude (luminosity) of the stars in the V wavelength region, with brighter stars having smaller magnitudes. The horizontal axis plots the color (surface temperature) of the stars, with cooler stars towards the right. All of the stars in a globular cluster have the same age and chemical composition. Their location in the color-magnitude diagram is determined by their mass. Higher mass stars have shorter lifetimes and evolve more quickly than low mass stars. The various evolutionary sequence have been labeled. Most stars are on the main sequence (MS), fusing hydrogen into helium in their cores (for clarity, only about 10% of the stars on the MS have been plotted). Slighter higher mass stars have exhausted their supply of hydrogen in the core, and are in the main sequence turn-off region (MSTO). After the MSTO, the stars quickly expand, become brighter and are referred to as red giant branch stars (RGB). These stars are burning hydrogen in a shell about a helium core. Still higher mass stars have developed a helium core which is so hot and dense that helium fusion is ignited. This evolutionary phase is referred to as the horizontal branch (HB). Some stars on the horizontal branch are unstable to radial pulsations. These radially pulsating variable stars are called RR Lyrae stars, and are important distance indicators.

can be important in a star, one must have a theory of convection which determines when a region of a star is unstable to convective motions, and if so, the efficiency of the resulting heat transport. Once all of the above information has been determined a stellar model may be constructed. The evolution of a star may be followed by computing a static stellar structure model, updating the composition profile to reflect the changes due to nuclear reactions and/or mixing due to convection, and then re-computing the stellar structure model.

There are a number of uncertainties associated with stellar evolution models,
and hence, age estimates based on the models. Probably the least understood aspect of stellar modeling is the treatment of convection. Numerical simulations hold promise for the future [11,12], but at present one must view properties of stellar models which depend on the treatment of convection to be uncertain, and subject to possibility large systematic errors. Main sequence, and red giant branch globular cluster stars have surface convection zones. Hence, the surface properties of the stellar models (such as its effective temperature, or color) are rather uncertain. Horizontal branch stars have convective cores, so the predicted luminosities and lifetimes of these stars are subject to possible systematic errors.

Given the known uncertainties in the models, the luminosity (absolute magnitude) of the main-sequence turn-off has the smallest theoretical errors, and is the preferred method for obtaining the absolute ages of globular clusters (e.g. [13,14]). The theoretical calibration of age as a function of the luminosity of the main-sequence turn-off has changed somewhat over the last several years. It has long been realized that diffusion (the settling of helium relative to hydrogen) could shorten the predicted main sequence lifetimes of stars [15]. However, it was not clear if diffusion actually occurred in stars, so this process had been ignored in most calculations. Recent helioseismic studies of the Sun have shown that diffusion occurs in the Sun [16,17]. The Sun is a typical main sequence star, whose structure (convective envelope, radiative interior) is quite similar to main sequence globular cluster stars. Thus, as diffusion occurs in the Sun, it appears likely that diffusion also occurs in main sequence globular cluster stars. Modern calculations find that the inclusion of diffusion lowers the age of globular clusters by 7% [18]. The recent use of an improved equation of state has led to a further 7% reduction in the derived globular cluster ages [19]. The equation of state now includes the effect of Coulomb interactions [20]. Helioseismic studies of the Sun find that there are no significant errors associated with the equation of state currently used in stellar evolution calculations [21]. Together, the use of an improved equation of state and the inclusion of diffusion in the theoretical models have lead to a ~ 2 Gyr (14%) reduction in the estimated ages of for the oldest globular clusters. The excellent agreement between theoretical solar models and the Sun (see Figure 2) suggest that future improvements in stellar models will likely lead to small (less than ~ 5%) changes in the derived ages of globular cluster stars.

A detailed Monte Carlo study found that the uncertainties in the theoretical models led to an 1-σ error of 7% in the derived globular cluster ages [22]. This study considered errors associated with 15 different parameters used in the construction of theoretical stellar models and isochrones. The parameter which lead to the largest uncertainty in the derived age of the globular clusters was the abundance of the α-capture elements (oxygen is the most important α-capture element) in globular cluster stars. It is difficult to determine the abundance of oxygen observationally [23,24], with estimates of the oxygen
Fig. 2. The difference between the squared sound speed between a theoretical solar model and the actual Sun \((c_{\text{model}}^2 - c_{\text{Sun}}^2)/c_{\text{model}}^2\), as a function of radius of the model. The sound speed of the Sun is obtained from helioseismology — observations of the solar \(p\)-modes, whose frequencies depend on the sound speed. Note that the maximum difference between the model and the Sun is less than 0.5%, a level of accuracy rarely seen in astronomy. The best solar models constructed in the early 1990’s lead to squared sound speed differences of order 3%.

abundance varying by up to a factor of 3. When extreme values for the oxygen abundance are used in the theoretical calculations, the derived globular cluster ages change by 8%.

The use of the luminosity of the main sequence turn-off as an age indicator requires that the distance to the globular cluster be known. Determining distances is one of the most difficult tasks in astronomy, and is always fraught with uncertainty. The release of the Hipparcos data set of parallaxes to nearby stars \([25]\) has suggested that a revision in the conventional globular cluster distance scale is necessary. Hipparcos did not directly determine the distance to any globular clusters, but did provide the distance to a number of nearby metal-poor main sequence stars. Assuming that globular cluster stars have identical properties to these nearby stars, the nearby stars can serve as calibrators of the intrinsic luminosity of metal-poor main sequence stars and the distance to a globular cluster determined. This technique is referred to as main sequence fitting. There have been a number of papers which have used the Hipparcos data set to determine the distance to globular clusters using main sequence fitting \([22,26–28]\). Three of these papers conclude that globular clusters are further away than previously believed, leading to a reduction in the derived ages. The remaining paper \([28]\) concluded that the Hipparcos data did not lead to a revision in the globular cluster distance scale. However, this work incorrectly included binary stars in the main sequence fitting \([22]\). When the known binaries are removed from the fit (a case which is also considered in \([28]\)), then all four papers are in agreement — the Hipparcos data yields
Table 1

| Age (Gyr)      | Distance determination                         | Reference |
|---------------|-----------------------------------------------|-----------|
| 11.5 ± 1.3    | 5 independent techniques                      | [22]      |
| 12 ± 1        | main sequence fitting (Hipparcos)             | [26]      |
| 11.8 ± 1.2    | main sequence fitting (Hipparcos)             | [27]      |
| 14.0 ± 1.2    | main sequence fitting (Hipparcos) including binaries | [28]      |
| 12 ± 1        | theoretical HB & main sequence fitting        | [29]      |
| 12.2 ± 1.8    | theoretical HB                                | [30]      |

larger distances (and hence, younger ages) for globular clusters. My analysis [22] considered four distance determination techniques in addition to using the Hipparcos data, and concluded that the five independent distance estimates to globular clusters all led to younger globular cluster ages.

A number of authors have recently examined the question of the absolute age of the oldest globular clusters. All of these works used the luminosity of the main sequence turn-off as the age indicator. The results are summarized in Table 1. Despite the fact that these investigators used a variety of theoretical stellar models (with differing input physics) and different methods to determine the distance to the globular clusters, the derived ages are remarkably similar, around 12 Gyr. These ages are ~ 3 Gyr younger than previous determinations, due to improved input physics used in the models, and a longer distance scale to globular clusters. My work [22] considered a variety of distance indicators and included a very detailed Monte Carlo study of the possible errors associated with the theoretical stellar models. For this reason, my preferred age for the oldest globular clusters is 11.5 ± 1.3 Gyr, implying a minimum age of the universe of $t_{\text{universe}} \geq 9.5$ Gyr at the 95% confidence level.

5 Summary

A direct estimate for the minimum age of the universe can be obtained by determining the age of the oldest objects in the galaxy. These objects are the metal-poor stars located in the halo of the Milky Way. There are currently three independent techniques which have been used to determine the ages of the metal-poor stars in the Milky Way: nucleochronology, white dwarf cooling theory, and main sequence turn-off ages. The best application of nucleochronology to date has been on the very metal-poor star CS 22892 which
has an age of $15.2 \pm 3.7$ Gyr [2], implying a $2\sigma$ lower limit to the age of the universe of $t_{\text{universe}} \geq 7.8$ Gyr. White dwarf cooling theory is difficult to apply in practice, as one needs to observe very faint objects. Currently, it is impossible to observe the faintest white dwarfs in a globular cluster, so white dwarf cooling theory can only provide a lower limit to the age of a globular cluster. Based upon the luminosity of the faintest observed white dwarfs, a lower limit to the age of M4 was determined to be $t_{\text{glob}} \geq 8$ Gyr [7]. Absolute globular cluster ages based upon the main sequence turn-off have recently been revised due to a realization that globular clusters are farther away than previously thought. The age of the oldest globular clusters is $11.5 \pm 1.3$ Gyr [22], implying a minimum age of the universe of $t_{\text{universe}} \geq 9.5$ Gyr (95% confidence level). At the present time, main sequence turn-off ages have the smallest errors of the available age determination techniques and provide the best estimate for the age of the universe.

To obtain the actual age of the universe, one must add to the above age the time it took for the metal-poor stars to form. Unfortunately, a good theory for the onset of star formation within the galaxy does not exist. Estimates for the epoch of initial star formation range from redshifts of $z \sim 5$ to 20. This corresponds to ages ranging from 0.1 to 2 Gyr, implying that the actual age of the universe lies in the range $9.6 \leq t_{\text{universe}} \leq 15.4$ Gyr. Tightening the bounds of this estimate will require a better understanding of the epoch of galaxy formation, along with improved stellar models and distance estimates to globular clusters.

Acknowledgment

The author was supported for this work by NASA through Hubble Fellowship grant number HF–01080.01–96A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5–26555.

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