The Ages of Stars
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Relative and absolute ages of Galactic globular clusters

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Abstract. We present a review of the latest work concerned with the relative and absolute ages of the Galactic globular clusters (GCs). Relative age-dating techniques generally divide into two types - those that measure a magnitude difference between two features in the color-magnitude diagram (i.e. Vertical Methods) and those that rely on color differences in the color-magnitude diagram (i.e. Horizontal Methods). Both types of diagnostics have been successfully applied and generally reach the same conclusions. Galactic GCs exhibit a mean age range of ∼3 Gyr, smaller (or nonexistent) for metal-poor clusters and larger (as much as 6 Gyr) for metal-rich ones. Generally speaking, the inner-halo GCs are older and more uniform in age as compared with those outside of the solar circle. Furthermore, the tendency of GCs with predominantly red horizontal branches (HBs) located in the outer halo to be preferentially younger than those with bluer HBs closer to the Galactic center suggests that age is the second parameter which, in addition to metal abundance, controls the HB morphology. In particular, we present additional compelling evidence supporting this assertion using a detailed examination of new photometry for the classic second-parameter cluster pair NGC 288 and NGC 362. Moving on to the absolute ages, we note that the absolute ages of the most metal-poor Galactic GCs sets a lower limit on the age of the Universe. The preferred age indicator for absolute ages is the luminosity of the main-sequence turnoff because most theoretical models agree on the onset of hydrogen exhaustion in the cores of low-mass stars. Based on the technique of main-sequence fitting to field subdwarfs with *Hipparcos* parallaxes, we find an age of $11.6^{+1.4}_{-1.1}$ Gyr for four metal-poor GCs with deep color-magnitude diagrams on a consistent photometric scale; this age is consistent with the results of a number of previous investigations.

Keywords. Hertzsprung-Russell diagram, stars: Population II, Galaxy: formation, globular clusters: general, globular clusters: individual (NGC 288, NGC 362, NGC 5466, NGC 6341 (M92), NGC 5053, NGC 5024 (M53)), Galaxy: halo,

1. Introduction

Authors often state that the Galactic globular clusters (GCs) represent the 'fossil record' of the formation process that created the Milky Way halo. One could argue that this analogy is flawed because, while fossils represent plants and animals that are now dead, the GCs are still alive and continuing to evolve. However, it is important to realize that the Galactic GCs (and the metal-poor field stars) are the only signatures we have remaining of the early epochs of star formation in the Milky Way. Certainly, in this sense, the 'fossil record' analogy is a valid one to employ.

What can we learn by studying the ages of the Galactic GCs? The relative ages and their behavior with chemical composition, Galactocentric distance, and horizontal branch (HB) morphology provide insight into the formation chronology of the Milky Way's halo. The absolute ages of the oldest globular clusters sets a lower limit on the age of the Universe. This therefore provides another constraint for the process of galaxy formation in the early Universe and implications for the broader questions of cosmology.

2. Relative ages

Techniques to estimate relative ages fall into two broad categories - those that rely on the measurement of magnitude differences in the color-magnitude diagram (CMD), also known as Vertical Methods (e.g. ΔV Method), and those that use color differences, similarly known as Horizontal Methods (e.g. Δ(B–V) Method). The Vertical method, which dates back to the work of Sandage (1981) and Iben & Renzini (1984), typically involves the measurement of the horizontal branch (HB) level, which can include the mean magnitude of the RR Lyrae variables, combined with the magnitude of the main sequence turnoff (MSTO). While this method is largely sound within a theoretical framework (see Sec. 3), problems occur in the identification of the MSTO's precise location given its vertical morphology. This inherent flaw can lead to an uncertainty of ∼0.1 mag in the level of the MSTO which translates to an uncertainty of ∼1 Gyr in the age of a cluster. In contrast, the horizontal method (Sarajedini & Demarque 1990; VandenBerg *et al.* 1990), which relies on the color difference between the MSTO and the red giant branch (RGB) is relatively straightforward to measure but suffers from theoretical uncertainties that arise from our limited knowledge of the model T_{eff} scale and the color-T_{eff} relation for stellar isochrones.

There are a number of other relative-age methods. Among these, the most common are Isochrone Fitting (VandenBerg 2000) and Main Sequence Fitting (Marin-Franch *et al.* 2009), both of which rely on estimating the distance to a cluster and then using the absolute magnitude of the MSTO to obtain an age. This process is more commonly used to infer absolute ages (Sec. 3) but it has seen limited application to relative ages as well. Other techniques that have seen limited use include one originally proposed by Paczynski (1984) and later advocated by Jimenez & Padoan (1996). This method involves matching theoretical luminosity functions (LF) to observed ones in order to infer an age. Jimenez & Padoan (1996) claimed to be able to measure ages to a precision of ∼0.2 Gyr. Another method, pioneered by Bergbusch & VandenBerg (1997), but that has not seen wide acceptance, is based on the construction of color functions in the magnitude range of the MSTO, subgiant branch (SGB), and lower RGB. The shape of the color function, which is the color histogram from the turnoff to the lower RGB, is sensitive to age and is used by comparisons with theoretical color-functions of known age and composition. One additional method that deserves comment is represented by the work of Sarajedini & Mighell (1996). They proposed the use of the magnitude difference between the unevolved main sequence and the subgiant branch. This method has multiple advantages such as ease of measurement and insensitivity to the metal abundance of the clusters being considered. However, it does require precise photometry that reaches ∼2 magnitudes below the MSTO and a knowledge of the relative reddenings of the clusters to better than ± 0.02 mag in E(B–V). Furthermore, it should be noted that all of these relative age methods can be combined in order to minimize their uncertainties and maximize their age sensitivity. Meissner & Weiss (2006) provide a detailed discussion of this topic.

Since the pioneering work of VandenBerg *et al.* (1990), it has become increasingly clear that the metal-poor globular clusters (i.e. $[Fe/H] \lesssim -1.5$) have the same age to within ∼1 Gyr. Furthermore, as metallicity increases, so does the age dispersion of the clusters. This trend has been confirmed by the results of Chaboyer *et al.* (1996), Rosenberg *et al.* (1999), Salaris & Weiss (2002), De Angeli *et al.* (2005), and Marin-Franch *et al.* (2009). This last study is based on imaging with the Advanced Camera for Surveys onboard the Hubble Space Telescope (HST) as part of the Galactic Globular Cluster Treasury project (GO-10775, hereafter referred to as GGCTP, see Sarajedini *et al.* 2007 for more details). The work of Marin-Franch *et al.* (2009) reinforces the results from many of these same papers with regard to the relation between age and Galactocentric distance (R_{GC}). In particular, it seems that old clusters dominate near the Galaxy's center with the age dispersion increasing for those in the middle and outer halo. This behavior favors the 'inside-out' formation scenario of the Milky Way halo (Kepner 1999, and references therein). In addition, a relation between age and metal abundance, with younger clusters being more metal-rich, is present for GCs that appear to have originated in disrupted dwarf satellites of the Galaxy. For example, Terzan 7, Terzan 8, Arp 2, M54, Palomar 12, and NGC 4147 trace their origins to the Sagittarius dwarf spheroidal galaxy and exhibit an age-metallicity relation.

It is very important to note that the vast majority of papers that have examined the global properties of globular cluster ages have *excluded* the outer halo clusters - those beyond ~40 kpc from the Galactic center. These clusters include NGC 7006, Palomar 15, Pyxis, Palomar 3, Palomar 4, Palomar 14, Eridanus, and AM-1. Why are these clusters important in this regard? As noted by several authors, most notably Searle & Zinn (1978) and Lee *et al.* (1994), the so-called 'second parameter effect' is dependent on Galactocentric distance, being most extreme for clusters outside of R_{GC} ~40 kpc. This effect was first identified by Sandage & Wallerstein (1960) and describes the tendency of globular cluster HB morphologies at constant metallicity to become redder at larger values of R_{GC}. This therefore suggests that another parameter in addition to metal abundance is required to describe the HB and that the prominence of this parameter grows with R_{GC}. Therefore, as pointed out by Sarajedini *et al.* (1997), whatever this second parameter is, it must vary in a reasonable fashion on a global spatial scale, being negligible at small R_{GC} and overwhelming at large values of R_{GC}. Given this requirement, the leading second-parameter candidate ever since the seminal paper of Searle & Zinn (1978) has been cluster age. In this scenario, the mean age of the Galactic globular clusters should become younger as R_{GC} increases and the age dispersion should increase. As a result, any survey of Galactic globular cluster ages is incomplete unless the ages of the outer-halo clusters, which preferentially exhibit red HBs, are included.

Concerning the outer-halo clusters with red HBs, reliable relative ages have been published for Palomar 3, Palomar 4, Palomar 14, Eridanus, AM-1, and Pyxis. Stetson *et al.* (1999) used deep HST imaging with the Wide Field Planetary Camera 2 (WFPC2) to construct CMDs for Palomar 3, Palomar 4, and Eridanus. They compared these clusters to ground-based photometry for M5 and M3 and concluded that the outer-halo clusters are some 1.5 to 2 Gyr younger than the comparison clusters. A similar conclusion was reached by Dotter *et al.* (2008) in examining the ages of AM-1 and Palomar 14 as compared with M3 (see also Sarajedini 1997). Sarajedini & Geisler (1996) compared their CMD of Pyxis with that of NGC 362 and found them to be co-eval. Since it has long been established that NGC 362 is 1.5 to 2 Gyr younger than other GCs at its metallicity, it follows that the same is true for Pyxis.

This leads us to our next topic, which is concerned with the ages of the classic second-parameter pair NGC 362 and NGC 288. The former has a completely red HB while the latter has one that is predominantly blue and yet their metallicities are essentially identical to within 0.05 dex (De Angeli *et al.* 2005, and references therein). There is a substantial body of literature supporting the idea that NGC 288 is 2 to 3 Gyr older than NGC 362, precisely as implied by their HB morphologies if age were the second parameter which, in addition to metal abundance, influences the HB morphology (Bolte 1989; VandenBerg *et al.* 1990; Sarajedini & Demarque 1990; Green & Norris 1990; Rosenberg *et al.* 1999). However, a minority of authors (VandenBerg 2000; Stetson 2009) have recently pointed out that this conclusion is no longer on a firm footing.

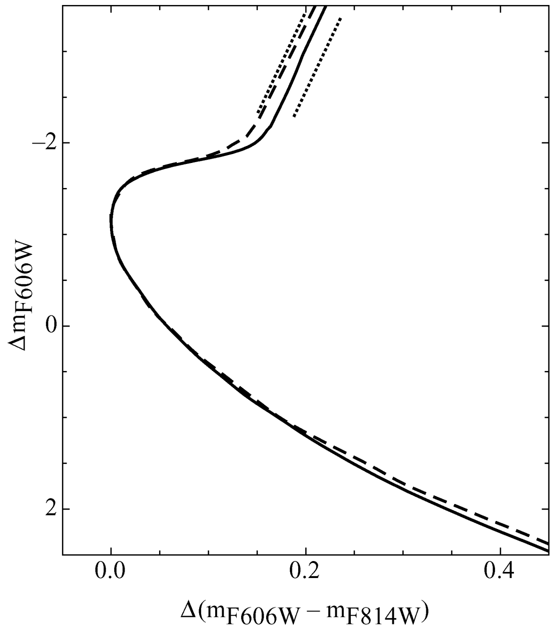

Figure 1. A comparison of the fiducial sequences of NGC 288 (dashed) and NGC 362 (solid line) as derived by Marin-Franch *et al.* (2009). They have been shifted using the prescription of VandenBerg *et al.* (1990) wherein the colors of the turnoffs and the magnitudes +0.05 mag redder than the turnoff are matched. The dotted lines represent age differences of ± 2 Gyr as determined from the isochrones of Dotter *et al.* (2007).

With the advent of high-quality, deep photometry for a large set of clusters obtained as part of the GGCTP and the growing set of well calibrated GC photometry being made available by Stetson (2009), we can revisit the question of the age difference between NGC 288 and NGC 362 with renewed hope that a more definitive answer will emerge. First, we will employ the cluster fiducial sequences of the MS / SGB / lower RGB constructed by Marin-Franch *et al.* (2009) from the GGCTP data. Figure 1 shows these sequences for NGC 288 and NGC 362 registered using the prescription advocated by VanderBerg *et al.* (1990). In this method, which is a version of the Horizontal Method described above, the two fiducials are matched in color at the MSTO and in magnitude at a point +0.05 mag redward of the MSTO. Once shifted and matched in this way, older clusters will have RGBs that are bluer, and lower MSs that are redder, than those of younger clusters. This is precisely what is observed in Fig. 1. The dotted lines in Fig. 1 indicate the locations of RGBs for clusters that are 2 Gyr older (blueward) and younger (redward) than the comparison cluster. Therefore, the comparison shown in Fig. 1 suggests that NGC 288 is ~2 Gyr older than NGC 362. It should be emphasized that this result does not depend on distance or reddening, and that our value for the age difference agrees with the majority of previous investigators.

A second approach to the age difference between NGC 288 and 362 is illustrated in Fig. 2. We begin in the lower panel where we have adopted the reddenings for these two clusters from the maps of Schlegel *et al.* (1998). Note that NGC 288, being at $b = +89^o$, is very close to the north Galactic pole, making its reddening the smallest of any of the known Galactic GCs. After shifting the cluster fiducials in color to correct for reddening, we then offset them in magnitude in order to match their lower main sequences, under the constraint that their distance moduli differ by 0.03 mag, with NGC 288 having the

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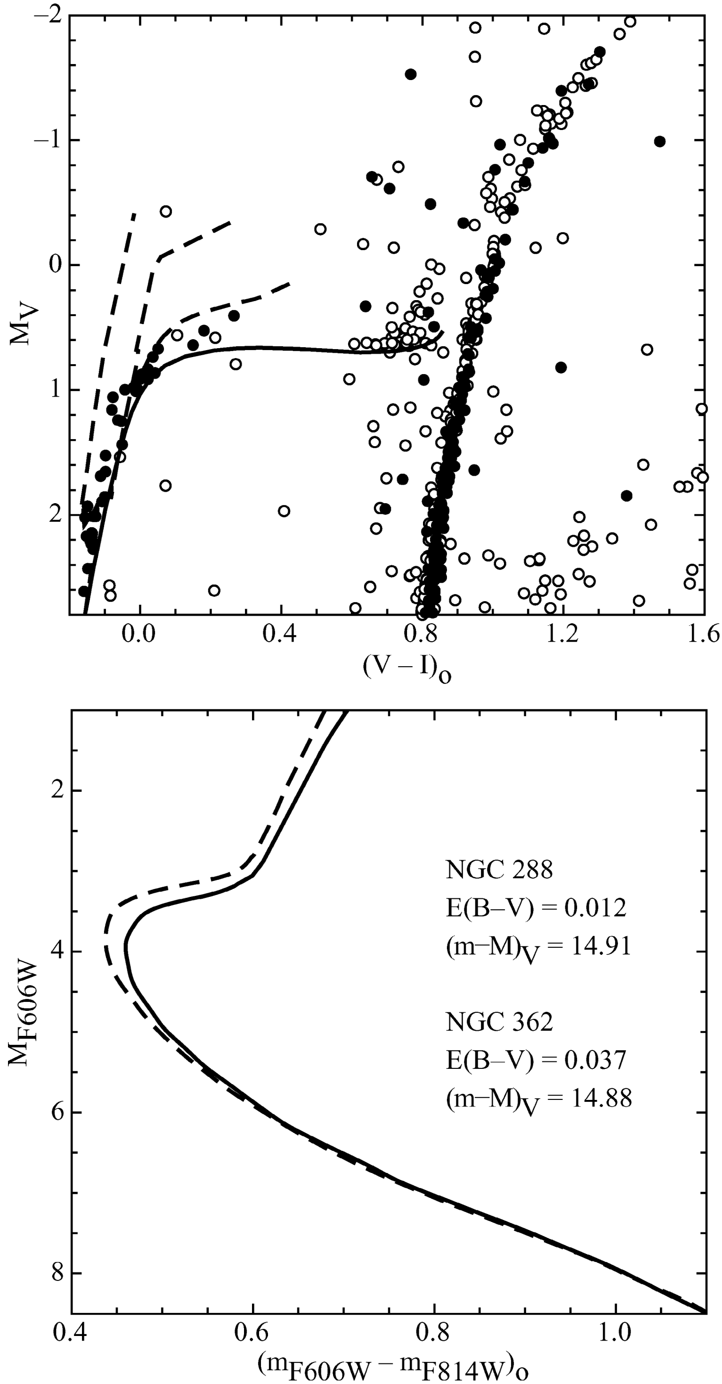

Figure 2. The lower panel shows the fiducial sequences of NGC 288 (solid) and NGC 362 (dashed) as derived by Marin-Franch *et al.* (2009) shifted as described in the text using the reddenings and distance moduli shown in the figure. The upper panel displays the high quality photometry for these two clusters (NGC 288: filled circles, NGC 362: open circles) from Stetson (2009) shifted using the same offsets as in the lower panel. The solid line is the theoretical zero age horizontal branch (ZAHB) from VandenBerg (2000) while the dashed lines are representative HB tracks from Dotter *et al.* (2007) showing the evolutionary paths of low mass HB stars from the ZAHB.

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Table 1. Stellar Evolution Models

Name	Nickname	Reference
Padova		Bertelli *et al.* (2008)
Dartmouth	'DSEP'	Dotter *et al.* (2007)
Teramo	'BaSTI'	Cordier *et al.* (2007)
Victoria-Regina	'VandenBerg'	VandenBerg *et al.* (2006)
Yale-Yonsei	'Y^2'	Yi *et al.* (2004)
Geneva		Lejeune & Schaerer (2001)

larger apparent modulus. This constraint is based on the results of Carretta *et al.* (2000) who derived distances for both of these clusters by fitting their fiducials to field subdwarfs with *Hipparcos* parallaxes. Once the fiducials have been matched using this procedure, we see in Fig. 2 that the lower main sequences line up beautifully as they should if the metallicities of the clusters are identical; furthermore, the relative locations of the MSTO / SGB / lower RGB regions suggest, once again, that NGC 288 is older than NGC 362.

To achieve consistency, we must also ensure that the same color and magnitude offsets that yield the comparison seen in the lower panel of Fig. 2 also provide a reasonable match of the brighter sequences in the CMD such as the HB and upper RGB. This comparison is displayed in the upper panel of Fig. 2 wherein the filled circles are NGC 288 and the open circles are NGC 362, both coming from the high-quality photometry of Stetson (2009). The solid line in Fig. 2 is a zero-age horizontal-branch (ZAHB) model from VandenBerg (2000) for [Fe/H] = –1.3 and [α/Fe] = +0.3, showing that the red HB of NGC 362 and the predominantly blue HB of NGC 288 are consistently located relative to each other. Furthermore, the dashed lines are post-ZAHB evolutionary tracks from Dotter *et al.* (2007) shifted to match the VandenBerg (2000) ZAHB locus. These tracks suggest that the HB stars at $M_V\sim+0.6$ and $(V-I)_o\sim0.2$ are above the ZAHB because they have evolved from the bluer portions of the HB.

It is very important to realize that the morphological differences between NGC 288 and NGC 362 in the region of the MSTO, as illustrated in Figs. 1 and 2, *cannot* be the result of differences in CNO or α-element abundances. For this to be the case, NGC 288 must have a higher CNO or α-element abundance than NGC 362. This would make the morphology of the NGC 288 HB redder than the RR Lyrae instability strip, which is inconsistent with the purely blue HB of NGC 288.

In the past, comparisons such as the one shown in Fig. 2 used an additional cluster, NGC 1851, as a 'bridge' to help clarify the interpretation of such a diagram (e.g. Stetson *et al.* 1996). It was argued that since NGC 1851 has a bi-modal HB with stars on both the blue and red side of the instability strip, it would help identify the expected locations of the blue HB of NGC 288 and the red HB of NGC 362 relative to each other. However, the recent discovery by Milone *et al.* (2008) that NGC 1851 exhibits two subgiant branches throws significant doubt on its utility in comparisons of NGC 288 and NGC 362. The origin of the two SGBs is unclear but it certainly underscores the fact that NGC 1851 is not a 'simple' stellar populaton and therefore disqualifies it from being used as such.

3. Absolute ages

There are three ingredients required in the determination of GC absolute ages. First, investigators have historically used the magnitude of the MSTO as an absolute age indicator because most theoretical models agree on the onset of hydrogen exhaustion in the cores of low-mass stars. High-quality precision photometry, well-calibrated to a standard system, is required to achieve the most reliable determination of the MSTO

Table 2. Metal-Poor Clusters

Cluster	$[Fe/H]_{CG}$	$E(B-V)_{SFD}$
NGC 5466	–2.20	0.017
NGC 6341 (M92)	–2.16	0.022
NGC 5053	–1.98	0.017
NGC 5024 (M53)	–1.86	0.021

magnitude. Next, the apparent magnitude of the MSTO must be converted to an absolute magnitude and this, of course, requires knowledge of the cluster distance. Lastly, the absolute magnitude of the MSTO [$M_V(TO)$] is converted to an age using theoretical stellar-evolutionary models. A range of models are available from several different groups, and these are listed in Table 1, wherein a representative reference is also given. The procedure outlined above has been followed by a number of investigators with very similar results. The first paper to apply the 'new and improved' *Hipparcos* parallaxes of field subdwarfs to the problem of the absolute ages of GCs was that of Reid (1997). He used 15 of the nearest subdwarfs and fit the fiducial sequences of 7 Galactic GCs to the main sequence defined by these stars. Surprisingly, Reid (1997) concluded that the GCs are closer and therefore younger than previously thought; in particular, he claimed that the age of the most metal-poor GCs is between 11 and 13 Gyr. Chaboyer *et al.* (1998) also present an analysis of the absolute ages of the oldest Galactic GCs but with a new and important wrinkle. They constructed Monte Carlo simulations in which they vary the theoretical inputs into the models over a reasonable range for each parameter. Each set of inputs then results in a specific isochrone, of which there are over 10,000 realizations. They applied these simulations to the ΔV values of 17 metal-poor GCs in order to derive a distribution of ages for these clusters, which yields a mean age of 11.5 ± 1.3 Gyr.

This result was echoed by the work of Carretta *et al.* (2000); however, they discovered that their mean age for the oldest Galactic GCs and the associated distance scale resulted in a distance modulus for the Large Magellanic Cloud that is too large by $\sim$0.1 mag. After adjusting their distance scale to an adopted value of $(m-M)_o = 18.54 \pm 0.07$ for the LMC, they find a mean age of 12.9 ± 1.5 Gyr for the oldest Galactic GCs.

We have performed our own analysis of the absolute ages of the metal-poor GCs, using fiducial sequences from the GGCTP. Table 2 lists the four GCs we have selected, based on their similarly low metallicities (all on the scale of Carretta & Gratton (1997)) and low reddenings, all taken from Schlegel *et al.* (1998). Among these, NGC 5024 (M53) has been selected as a reference cluster because its metal abundance overlaps the range of values for field subdwarfs with well-measured parallaxes from *Hipparcos*. For the other three clusters, we have shifted their $(m_{F606W} - m_{F814W})$ VegaMAG fiducials in the color direction to account for reddening and for the metallicity difference with M53 and then in magnitude to match the unevolved main sequence of M53. The sensitivity of the fiducial color to metal abundance has been established using the isochrones of Dotter *et al.* (2007). For each cluster, this process yields a distance modulus relative to M53. The four independent measures of the MSTO mag are shifted to the distance scale of M53 and averaged together.

The last step involves measuring the distance of M53. We proceeded by first selecting from Table 2 of Carretta *et al.* (2000) the subdwarfs with *Hipparcos* parallaxes and with absolute magnitudes in the range $5 < M_V < 8$. We avoided all suspected binaries, yielding a total of 21 subdwarfs. We compared the *Hipparcos* V–I colors to the B–V values from Carretta *et al.* (2000) and found a tight relation, with three stars appearing as outliers in this plot - HIP 46120, 57939, and 79537. The V–I colors of these stars were offset by –0.07 mag to bring them onto the relation defined by the remaining 18 stars. We then

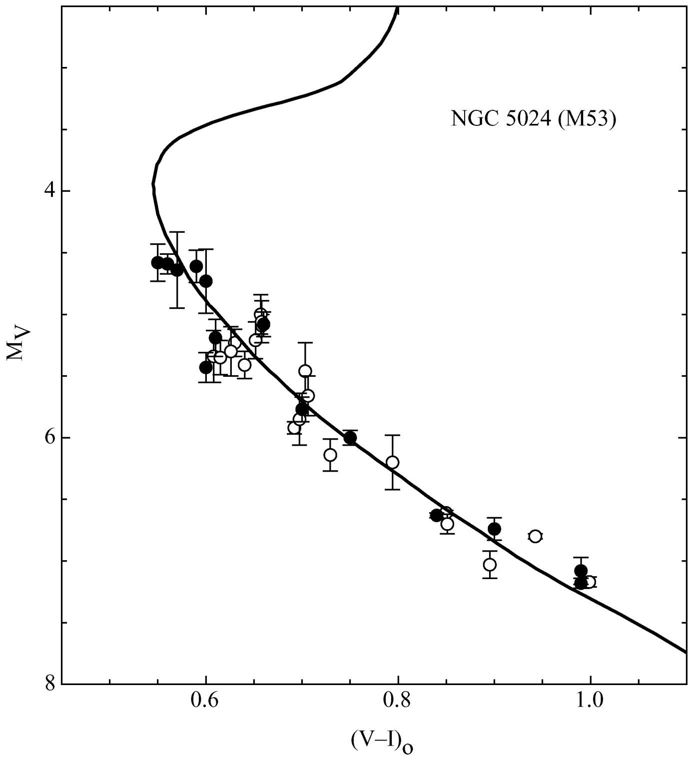

Figure 3. The solid line represents the fiducial sequence of NGC 5024 (M53) from the work of Marin-Franch *et al.* (2009). This has been fitted to the open circles which are field subdwarfs with *Hipparcos* parallaxes as detailed in the text. For comparison, the filled circles are the subdwarfs from the work of Sandquist *et al.* (1999) scaled to a metal abundance of [Fe/H] = –1.91.

compared the V–I colors from *Hipparcos* to those from Sandquist *et al.* (1999). For the seven stars in common between them, we find a constant offset of 0.10 ± 0.01 mag in the sense that the *Hipparcos* V–I colors are too blue. In this way, we have generated a set of 21 single-star subdwarfs with well-determined V–I colors, along with absolute magnitudes, reddenings, and metallicities from Table 2 of Carretta *et al.* (2000). The colors of these stars are adjusted to the metal abundance of M53 ([Fe/H] = −1.86) as shown in Figure 3 using an equation derived from the isochrones of Girardi *et al.* (2000). As a consistency check, the filled circles in Figure 3 are the subdwarfs used by Sanquist *et al.* (1999) at a metal abundance of [Fe/H] = –1.91. The penultimate step involves shifting the M53 V–I fiducial in color, to account for the reddening, and then in magnitude, to fit the subdwarfs in order to determine the distance modulus. We find $(m-M)_V = 16.37 \pm 0.05$ for M53. Applying this to the relative distances of the other three clusters yields a mean MSTO magnitude of $\langle M_V(TO) \rangle = 3.967 \pm\ 0.064$. The final step then requires us to use this MSTO magnitude along with the metallicity of M53 and equation (3) of Chaboyer *et al.* (1998), which includes the results of their isochrone Monte Carlo simulations, to calculate the mean age of these four metal-poor clusters. This procedure yields an age of $11.2^{+1.4}_{-1.1}$ Gyr. The Chaboyer *et al.* (1998) models include the full effects of Helium diffusion, which spectroscopic evidence suggests is an overestimate of reality (Korn *et al.* 2007). Chaboyer *et al.* (2001) note that ages from isochrones that include full diffusion are about 4% lower than isochrones with diffusion inhibited in the surface layers. As a result, our absolute age for the four GCs in Table 2 turns out to be $11.6^{+1.4}_{-1.1}$ Gyr.

4. Acknowledgments

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Discussion

C. Gallart: You have shown just in passing a result that I think is amazing, which is the fact that you find a flat age-metallicity relation for the majority of clusters and that the “outliers” of younger age seem to be related to disrupted dwarfs. This would point to a basically instantaneous formation of the Galactic halo, and then a mysterious age-metallicity relation for the accreted clusters. How do you interpret the latter?

A. Sarajedini: The ages of the clusters in our sample and how they vary with metallicity and Galactocentric distance suggest two modes of cluster formation. First, a group that formed via “rapid hierarchical collapse” which resulted in a small age range and no age-metallicity relation. Second, a group that formed via a slower hierarchical process that resulted in a range of ages and an age-metallicity relation. The latter appear to be associated with disrupted dwarf satellites of the Milky Way. It is not immediately clear how to interpret the age-metallicity relation other than to say that we need to measure ages in other ways to confirm this.

J. Kaluzny: I would like to point out that yet another method for determination of globular cluster ages was proposed by Pacynski. It is based on eclipsing detached binaries as age and distance indicators. With this method, masses and luminosities of turn-off stars can be determined directly. A practical application of this idea is presented in a poster by Thompson *et al.*

A. Sarajedini: Thank you for pointing this out. I have not covered this method in my talk because I decided to discuss methods that have been applied to many clusters, in a survey approach, so as to derive the global properties of the Milky Way clusters as they pertain to their ages.

J. Melbourne: I was wondering about the correction of the distance scale based on the LMC. Did you use this correction in your analysis and should we be using the LMC for this?

A. Sarajedini: No, I have not used this correction to the LMC in my absolute-age analysis. I think we should insist on consistency between nearby distance indicators and more distant ones. At the moment, there is enough uncertainty in the LMC distance that I would not use it to anchor the subdwarf distance scale.

M. Catelan: I just wanted to mention that NGC 5286 is another cluster that has been associated with the Canis Major dwarf spheroidal. We’ve recently studied its CMD and determined an age for the cluster (see paper by Zorotovic *et al.* 2008, arXiv:0810.0682), finding it to be about 2 Gyr older than M3. This seems to deviate from the trend that you’ve shown for other Canis Major globulars. My question: Do you think Canis Major is indeed a dwarf spheroidal?

A. Sarajedini: I don’t think I’m in a position to answer your question with any certainty. Your age result on NGC 5286 seems to be verified by our HST Treasury data (GO-10775). We need to revisit the question of the relative cluster ages using other techniques.

J. Christensen-Dalsgaard: The mixing-length parameter is of course only a simplistic way to parameterize our ignorance about convection. However, we are getting to the point where hydrodynamical simulations can determine the properties of corrective envelopes, for a variety of stellar parameters.

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A. SARAJEDINI: This is very good news, and I look forward to more significant advance in this area.

Ata Sarajedini

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