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A DISTANCE-INDEPENDENT AGE FOR THE GLOBULAR CLUSTER M92[1]

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ABSTRACT

We use deep Strömgren CCD photometry to determine the age of the globular cluster M92 (NGC 6341) from the $[(v-y)_0, c_0]$-diagram. Besides being completely independent of distance, this *color-color* plot has the further advantage that it is not very sensitive to the amount of foreground interstellar absorption. The main disadvantage of this approach is that it relies heavily on the accuracy of the $T_{\rm eff}$ and color scales of isochrones. As these aspects of the models continue to be uncertain, absolute ages cannot be derived in this way to within a few gigayears. For instance, while we obtain an age of 14.5 Gyr for M92 using the latest University of Victoria isochrones, an age as low as 12 Gyr or as high as 17 Gyr would be found if we adopted different zero points for the synthetic color–$T_{\rm eff}$ relations or an ad hoc shift of $\approx \pm 200$ K were applied to the models. However, much tighter constraints on the age may be obtained by invoking some additional constraints. To be specific, we find from the $(v-y, c_1)$-diagram that the extremely metal-deficient field halo stars are most likely coeval with M92 to within 1 Gyr (1 σ error bar) and that the properties of the well-observed [Fe/H] ≈ -2.5 *subgiant* HD 140283, which has $\sigma_\pi/\pi = 0.06$ from *Hipparcos*, imply $(m-M)_V \lesssim 14.60$ and an age $\gtrsim 16$ Gyr for M92. This, in fact, offers considerable support for the synthetic colors that we have used.

Key words: stars: abundances — stars: atmospheres — stars: evolution — stars: Population II

1. INTRODUCTION

The Milky Way globular clusters (GCs) are among the oldest identifiable objects in the universe, and indeed, they may have been among the first stellar systems to form after the big bang (Peebles & Dicke 1968). How their ages vary with metallicity and Galactocentric distance, as well as from cluster to cluster at a fixed [Fe/H]-value, provide vital constraints on the formation and early evolution of galaxies. Furthermore, because they contain typically $\sim 10^5$–10^6 stars, with significant numbers in advanced evolutionary stages, GCs serve as important objects for testing and improving the theory of stellar structure and evolution. For these reasons, globular cluster research has continued to be pursued actively for the nearly half century since the first observations of GC turnoff stars were made (Arp, Baum, & Sandage 1953; Sandage 1953).

Two main themes have developed in the study of cluster ages; namely, the determination of the *absolute* age of the oldest of the Galactic GCs (presumably one of the most metal-deficient systems) and the determination of the *distribution* of cluster ages. Neither issue has been settled. Mainly as a result of distance scale uncertainties, the upper limit to GC ages could be anywhere in the range from ≈ 12 Gyr (e.g., D'Antona, Caloi, & Mazzitelli 1997; Gratton et al. 1997; Chaboyer et al. 1998) to ≈ 17 Gyr (e.g., Layden et al. 1996; Fernley et al. 1998). Subdwarf analyses tend to favor ages near the lower end of this range, though it is clear that the number of metal-poor subdwarfs with sufficiently accurate parallaxes in the *Hipparcos* catalog is still too few, and the uncertainties in the available photometry, chemical abundance determinations, and the bias corrections are still too large, to reduce the error bars on the derived ages to below ~ 3 Gyr. High ages are implied by most estimates of RR Lyrae luminosities (see, e.g., Gratton 1998; Gould & Popowski 1998), though there are some notable counterexamples (Walker 1992; Sandage 1993; McNamara 1997).

Our inability to reach a consensus concerning relative cluster ages, as exemplified by the Stetson, VandenBerg, & Bolte (1996) and the Sarajedini, Chaboyer, & Demarque (1997) reviews, may well be due to the lack of sufficiently high-quality *C-M* diagrams for most GCs. As improved observations are becoming available (see, e.g., Ferraro et al. 1997; Grundahl 1999a; Rosenberg et al. 1999), the evidence is mounting in support of a relatively small dispersion in age ($\lesssim 1$–1.5 Gyr) at metallicities below [Fe/H] $= -1$, with no more than a small dependence of age on Galactocentric distance. Whether or not GC ages vary with [Fe/H] will not be known with any certainty until the distance scale problem is solved and until we have determined how the detailed run of heavy-element abundances (particularly that of oxygen) varies with iron content.

We have undertaken a study of several globular clusters using the Strömgren intermediate-band *uvby* system, which has many advantages over standard broadband *UBVRI* photometry. It can provide precise estimates of $T_{\rm eff}$, $\log g$, and [Fe/H] on a star-by-star basis, reveal the existence of variations in the atmospheric abundances of nitrogen in RGB stars (see Grundahl, vandenBerg, & Andersen 1998), and expose the effects of diffusive and radiative acceleration processes in hot HB stars (Grundahl et al. 1999b). But of

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particular relevance to the present investigation is the fact that the $[(v-y)_0, c_0]$-diagram $[c_0 = (u-v) - (v-b)$ for unreddened stars] offers the means to determine the ages of star clusters without needing to know their distances—thus eliminating the largest source of observational uncertainty in current age estimates. Working in this plane also minimizes the effects of reddening uncertainties. In this investigation, we derive the age of M92 using this distance-independent approach.

2. OBSERVATIONS AND DATA REDUCTION

The *uvby* observations for M92 (NGC 6341) reported in this work have been collected during five nights in 1998 June from the Nordic Optical Telescope (NOT) on the island of La Palma. Flat fields were obtained on each night during evening and morning twilight in four different instrument rotator positions in order to reduce effects due to scattered light on flat fielding (Grundahl & Sørensen 1996). Approximately 55 stars from the lists of Olsen (1983, 1984) and Schuster & Nissen (1988) were observed on four photometric nights to derive the transformation between the instrumental magnitudes and the standard *uvby* system.

The data were obtained using a thinned AR coated 2048 × 2048 pixel CCD camera, with 0″.11 pixel size, covering approximately 3′.75 on a side. Most of the observations were obtained using tip/tilt corrections (the HiRAC camera) and the FWHM of nearly all our images ranged between 0″.5 and 1″.0. There was no significant variation of the point-spread function (PSF) over the field of view. We observed two overlapping fields in M92, one of which was centered on the cluster to ensure a large sample of horizontal-branch (HB) and red giant branch (RGB) stars. However, for the purposes of this paper, we will use only the data that were obtained for the field off the cluster center as they are deeper and more accurate.

All photometric reductions of the cluster frames were subsequently carried out using the suite of programs developed by P. B. S.: DAOPHOT, ALLSTAR, ALLFRAME, and DAOGROW (see Stetson 1987, 1990, 1994). Photometry for the defocused standard stars was derived using large-aperture photometry. Rather than transform the Strömgren indices $b-y$, m_1, c_1, and the y magnitudes to the standard system (as is customary for photoelectric *uvby* observations), we instead transformed each magnitude and used them to calculate V, $v-y$, and c_1. The residuals in the standard star transformation were 0.007 mag for V, 0.011 mag for $v-y$ and 0.017 mag for c_1. (For the indices, the errors associated with individual filters were combined in quadrature.) Illustrating the high precision of the photometry, we note that for stars located within 0.25 mag of the M92 turnoff in V, and with more than 10 y measurements and absolute values of the DAOPHOT parameter SHARP less than 0.05, the median errors in V, $v-y$, and c_1 for stars were found to be: 0.003, 0.005, and 0.009 mag, respectively.

3. CLUSTER PARAMETERS

The reddening of M92 appears to be very well established (e.g., see Harris 1996; Schlegel, Finkbeiner, & Davis 1998), and we adopt $E(B-V) = 0.023$ [i.e., $E(v-y) = 0.028$], as determined by Schlegel et al. At very low metallicities the Strömgren system does not provide good sensitivity to [Fe/H]; consequently, we will assume a reasonable compromise of published determinations. The Zinn & West (1984) scale, which is still widely used, gives [Fe/H] = −2.24 for M92. From high-resolution spectroscopy of cluster giants, the Lick–Texas group has obtained −2.25 (Sneden et al. 1991), whereas Carretta & Gratton (1997) have found −2.16, also on the basis of high-resolution, high signal-to-noise spectra of bright red giants. Taking a straight mean of these estimates yields [Fe/H] = −2.22.[8]

It is well known from theoretical stellar interior models (e.g., Salaris & Weiss 1998) that the abundances of α-elements must be known in order to obtain accurate ages, as an increase of 0.3 dex in [α/Fe] results in an approximately 1 Gyr decrease in the turnoff age (assuming a fixed distance). Most spectroscopic studies find [α/Fe] = 0.3–0.4 in metal-poor GCs (Kraft 1994; Carney 1996; McWilliam 1997), though it is presently unclear as to whether oxygen has the same enhancement, as indicated by the [element/Fe] ratio, as the other α-elements. Depending on whether the oxygen abundance is derived from the ultraviolet OH bands (Israelian, Garcia Lopez, & Rebolo 1998; Boesgaard et al. 1999) or from the [O I] lines at 6300, 6364 Å (Fulbright & Kraft 1999), the derived [O/Fe]-value can range from ∼0.3 to ≳1.0. Because ages depend quite sensitively on the oxygen abundance (e.g., VandenBerg 1985), it is obviously very important to understand why such discrepant results are obtained from the different spectral features and to adopt the correct oxygen abundance in stellar models. (An argument in favor of the lower oxygen abundances is that the [O I] lines are probably less susceptible to non-LTE effects than the *uv* OH bands. However, whether non-LTE effects are the entire explanation for the differences remains to be seen.) Of course, the abundances from both sets of lines also depend on the temperatures adopted for the stars. In addition, the normalization of OH gf-values carried out by some authors has been challenged by Balachandran & Bell (1998). As a further caution, we note that [O/Fe] ∼ 0.0 is found in some field halo stars (e.g., Nissen & Schuster 1997), as well as in some GCs (see the work on Pal 12 and Ruprecht 106 by Brown, Wallerstein, & Zucker 1997 and on M13 by Pilachowski & Armandroff 1996). Thus, it is entirely possible that the O/Fe number abundance ratio is much more variable than we presently appreciate. In any case, since [α/Fe] ≈ 0.3 seems to be found for *most* metal-poor cluster/field stars, including M92 (Sneden et al. 1991), this value is adopted here.

4. ANALYSIS

The isochrones used in this study have been derived from the VandenBerg et al. (2000) evolutionary tracks, using the Bergbusch & VandenBerg (1992) interpolation code. Surface gravities were determined at 100 K increments along the isochrones, with additional points being included near the turnoffs. Model atmospheres were calculated for these temperature and gravity values and synthetic spectra

[8] We note that King, Stephens, & Boesgaard (1998) have recently obtained [Fe/H] = −2.52 for M92 from Keck spectra of three subgiants near the cluster turnoff. It is not clear (see their discussion) why their derived iron abundance is a factor ≳2 lower than those obtained by Sneden et al. and Carretta & Gratton for the cluster giants. Also very puzzling is how the observed subgiants can have essentially the same colors and [Fe/H]-value as the field subgiant HD 140283 and yet have $T_{\rm eff}$'s, which are deduced from Fe I line analyses, that differ by ∼300 K. Further work is needed to resolve these issues.

were calculated using these models. The synthetic *uvby* colors of the models were then computed from the spectra using the sensitivity functions of Crawford & Barnes (1970). A discussion of model atmospheres, synthetic spectra, and synthetic color calculations as well as illustrations of the fits of synthetic and observed solar spectra are given by Bell, Paltoglou, & Tripicco (1994). As discussed in their paper, the zero points and scale factors needed to convert the synthetic colors to the observational Strömgren system must be determined. The zero points were set by making the synthetic colors of the Dreiling & Bell (1980, hereafter DB80) Vega model ($T_{\rm eff} = 9650$ K, $\log g = 3.9$, $[m/{\rm H}] = 0.0$) equal the observed colors of Vega. The zero point of c_1 is sensitive to the adopted $\log g$ of the Vega model, which is primarily determined from the profiles of the hydrogen lines. These do, however, give a reasonably precise estimate of $\log g$; namely, $\log g = 3.9 \pm 0.2$ (see DB80).

As we have deep, precise, and accurately calibrated *uvby* photometry for M92, we can use the distance-independent $[(v-y)_0, c_0]$-diagram to determine its age. Figure 1 illustrates the result of *overlaying* the isochrones for the indicated parameters onto the cluster observations. We see that there is no need to apply ad hoc shifts to the model colors to match the observed main-sequence locus. The large scatter in c_1 along the giant branch, which is very similar to that found in M13 (see Grundahl et al. 1998), is due to star-to-star differences in the abundance of nitrogen (also see Grundahl 1999a, especially his Fig. 4).

It turns out that the adopted [Fe/H] for M92 (see § 3) is midway between two of the [Fe/H]-values (-2.31 and -2.14) that were assumed in the VandenBerg et al. (2000) grids: we have simply opted to compare the data with the models for the higher of these two metallicities. Judging from the relative positions of the predicted and observed turnoff points, the $[{\rm Fe/H}] = -2.14$, $[\alpha/{\rm Fe}] = 0.3$ isochrones indicate an age near 14.5 Gyr for M92—the error in this estimate is discussed below. Had we used the isochrones for $[{\rm Fe/H}] = -2.31$ (and the same α-element enhancement) the derived age would increase by $\lesssim 0.5$ Gyr. Note that, as shown by VandenBerg et al. (also see Chaboyer, Sarajedini, & Demarque 1992), it is possible to mimic isochrones for $[\alpha/{\rm Fe}] > 0.0$ by those for $[\alpha/{\rm Fe}] = 0.0$ simply by requiring the total mass-fraction abundance of the metals, Z, to be the same (provided that $[{\rm Fe/H}] \lesssim -0.8$). Hence, the estimated age in the case that $[{\rm Fe/H}] = -2.31$ and $[\alpha/{\rm Fe}] = 0.3$, for which $Z = 1.69 \times 10^{-4}$, would be very similar to that obtained for $[{\rm Fe/H}] = -2.10$ and $[\alpha/{\rm Fe}] = 0.0$, which has the same Z.

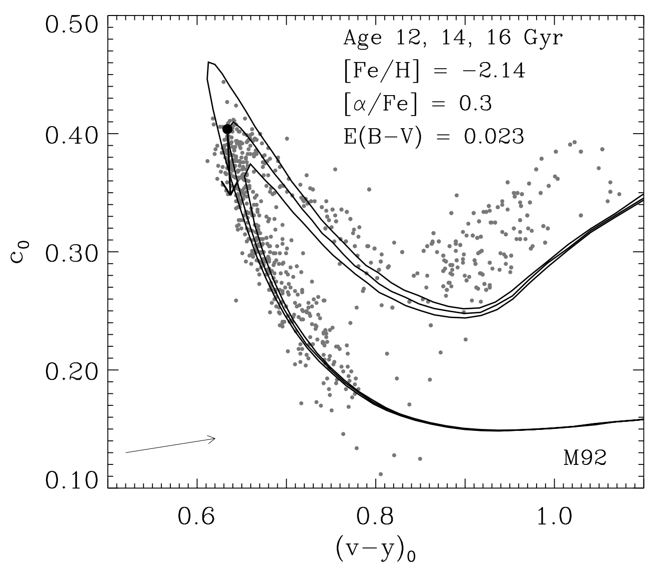

FIG. 1.—$[(v-y)_0, c_0]$ plot for M92 with isochrones for the indicated chemical abundances overplotted. From the resultant overlay in the vicinity of the turnoff, the inferred cluster age is found to be near 14.5 Gyr. The stars with $V > 18$ [those with $(v-y)_0 \lesssim 0.8$] have absolute values of the DAOPHOT parameter SHARP less than 0.04, at least 10 measurements in the y filter, and $\sigma(c_1) < 0.025$. To increase the sample of giants, all stars brighter than $V = 18$ with an absolute value of the SHARP parameter <0.1 were included. The reddening vector, which has a slope of 0.12, is shown in the lower left-hand corner. The large arrow attached to the turnoff of the 14 Gyr isochrone indicates how the location of that point would change if the predicted turnoff $T_{\rm eff}$ were decreased by 0.01 in the log (amounting to 155 K in this case): to maintain the same turnoff luminosity, $\delta(\log g) = 0.04$ was also assumed in the recalculation of synthetic colors.

Given the high precision of our photometry the corresponding (internal) uncertainty in age (using c_0) is $\pm$ 0.5 Gyr. It is worth emphasizing again that this age estimate does not depend in any way on the cluster distance. Furthermore, as can be seen from the reddening vector that has been plotted in Figure 1, an error of 0.05 mag in $E(v-y)$, corresponding to an error of 0.042 mag in $E(B-V)$, results in an error in c_0 of only 0.006 mag. This translates into an error in the estimated age of <0.3 Gyr. Hence, for clusters with low and/or well-determined reddenings, the effects of errors in the adopted reddenings are completely negligible. This represents a huge advantage over the classical main-sequence fitting technique, where a 0.01 mag error in $E(B-V)$ produces an $\approx 5\%$ error in the derived age. Provided that the photometry is well calibrated, the *only* significant uncertainty on the observational side lies with the determination of the detailed chemical abundances (particularly oxygen) in the cluster stars. But the main uncertainty in deriving ages from the $[(v-y)_0, c_0]$-diagram clearly rests with the models—in particular, with their $T_{\rm eff}$ and color scales.

As a check on our ability to calculate accurate Strömgren colors, we have studied the subdwarf Groombridge 1830 (HD 103095), the turnoff star HD 84937, and the subgiant HD 140283: these are among the best observed of the field Population II stars with accurate parallax-based distances. The photometry and derived reddening for the metal-poor stars employed in our analysis are taken from the Schuster & Nissen (1988) study, unless otherwise noted. An early analysis of Gmb 1830 by Tomkin & Bell (1973) yielded $[{\rm Fe/H}] = -1.3$ and $[{\rm C/Fe}] \approx -0.15$, on the assumption of $T_{\rm eff} = 5000$ K and a gravity corresponding to $\log g = 4.70$. More recent work, such as that by Balachandran & Carney (1996), confirms this temperature and Fe abundance but finds $[{\rm C/Fe}] = -0.3$ and $[{\rm O/Fe}] = +0.2$. We also note that Alonso, Arribas, & Martínez-Roger (1996a) found a temperature of 5029 ± 65 K using the infrared flux method (IRFM). Our $[{\rm Fe/H}] = -1.3$, $[\alpha/{\rm Fe}] = 0.3$ isochrones (for any age in the range 8–18 Gyr) predict $\log g \approx 4.70$ at $T_{\rm eff} = 5000$ K. These isochrones also give $M_V = 6.95$, 6.86, and 6.74, in turn, for $[\alpha/{\rm Fe}] = 0.0$, 0.3, and 0.6. As the observed parallax and V magnitude imply $M_V = 6.77$, we believe that the derived $\log g$–value is quite accurate.

The results of *uvby* (and *BV*) calculations for models in which the chemical abundance parameters and $T_{\rm eff}$ are varied are given in Table 1. Note that we use m_0 and c_0 to indicate observed indices corrected for interstellar reddening—for unreddened stars $m_0 = m_1$ and $c_0 = c_1$.

TABLE 1

OBSERVED AND PREDICTED *uvby* AND *BV* COLORS FOR NEARBY FIELD POPULATION II STARS

$b-y$	m_0	c_0	$v-y$	$B-V$	T_{eff}	$\log g$	Comments
HD 103095:							
0.484......	0.219	0.167	1.187	0.75			Intrinsic colors, assuming $E(b-y)=0.0$
0.487......	0.196	0.162	1.170	0.77	5000	4.7	Model A: N(He) = 11.0, [m/H] = −1.3
0.487......	0.195	0.163	1.169	0.77	5000	4.7	Model B: N(He) = 10.9, [m/H] = −1.3
0.486......	0.183	0.168	1.155	0.76	5000	4.7	Model C: N(He) = 10.9, [α/Fe] = 0.3
0.484......	0.190	0.156	1.158	0.74	5000	4.7	Model D: [C/Fe] = −0.3, [O/Fe] = +0.2
0.486......	0.183	0.168	1.155	0.76	5000	4.7	Model E: [C/Fe] = −0.1
0.461......	0.152	0.165	1.074	0.72	5100	4.7	Model F: N(He) = 11.0, [m/H] = −1.3
HD 84937:							
0.290......	0.060	0.351	0.640	0.38			Intrinsic colors, assuming $E(b-y)=0.013$
0.308......	0.050	0.354	0.666	0.41	6250	3.96	N(He) = 11.0, [m/H] = −2.0
0.303......	0.051	0.409	0.657	0.37	6350	3.96	N(He) = 11.0, [m/H] = −2.0
0.291......	0.050	0.358	0.632	0.38	6314	4.10	Nissen et al. (1997)
HD 140283:							
0.360......	0.039	0.280	0.759	0.46			Intrinsic colors, assuming $E(b-y)=0.019$
0.374......	0.036	0.242	0.784	0.50	5700	3.65	N(He) = 11.0, [m/H] = −2.5
0.383......	0.032	0.242	0.798	0.51	5700	3.65	N(He) = 10.9, [m/H] = −2.5
0.375......	0.037	0.242	0.787	0.50	5700	3.65	N(He) = 10.9, [α/Fe] = 0.3, [Fe/H] = −2.5
0.342......	0.037	0.320	0.721	0.45	5850	3.50	N(He) = 11.0, [m/H] = −2.5
0.354......	0.041	0.259	0.749	0.46	5850	3.80	N(He) = 11.0, [m/H] = −2.5
0.354......	0.041	0.243	0.749	0.47	5779	3.79	Nissen et al. (1997)

We reiterate that the zero points for the synthetic colors are based on the model for Vega, as discussed above. Model A (our reference model) has $T_{eff} = 5000$ K, $\log g = 4.70$, and $[m/H] = -1.3$ (where "m" is used to indicate the abundance of any metal.) Model B has a lower helium abundance, equivalent to a mixture having $X = 0.7595$ and $Y = 0.2396$, which are close to the values used in the isochrone calculations. Model C has enhanced α-process element abundances (including oxygen) whereas Models D and E explore the consequences of varying C and O (as noted). These abundance changes affect both line and continuous absorption in our models, which include bound-free absorption by both OH and CH. Model F illustrates the effects of varying the assumed T_{eff}, and it is readily apparent from this entry that a temperature as high as 5100 K is too hot. All of the other models give rather good agreement between the observed (after correction for reddening) and calculated $b-y$ and c_1 colors of HD 103095. In particular, there is no clear evidence of any significant variation of c_1 with the different abundance choices. However, we cannot explain the difference of ~ 0.025 mag between the observed and calculated m_1 indices, although we note that better agreement is obtained in the case of more metal-poor stars (see below). (At metallicities near one-tenth solar, our calculations indicate that a 0.1 dex increase in [Fe/H] produces a ~ 0.01 mag increase in m_1.)

The basic physical properties that have been derived for HD 84937 and HD 140283 have varied considerably over the years—see, e.g., Nissen (1997) and Nissen, Høg, & Schuster (1997) for discussions of pre- and post-*Hipparcos* results. In particular, the improved parallax measurements have implied somewhat higher gravities, with substantially higher precision: $\log g = 4.10 \pm 0.08$ for HD 84937 and 3.79 ± 0.06 for HD 140283 (see Nissen et al. 1997). Recent spectroscopic (e.g., Fulbright 1999) and photometric (see Nissen, Høg, & Schuster 1997) determinations of their iron abundances appear to be in very good agreement, with both approaches yielding an [Fe/H]-value near -2.1 for HD 84937 and ≈ -2.5 for HD 140283. On the basis of the infrared flux method, Alonso et al. (1996a) determined the effective temperatures of HD 84937 and HD 140283 to be 6330 ± 120 K and 5691 ± 84 K, respectively.

However, at very low metallicities, the color-T_{eff} relations derived by Alonso et al. (1996a, 1996b) show nonphysical trends (see, e.g., Ryan, Norris, & Beers 1999), which casts some doubt on their reliability at very low Z. In fact, it seems likely that HD 140283 is somewhat hotter than ≈ 5700 K. For instance, when Nissen et al. used the Alonso et al. (1996b) *calibration* of $b-y$ as a function of T_{eff} and [Fe/H] to derive the temperature of HD 140283, they obtained 5779 K on the assumption that $E(b-y) = 0.0$. Had they adopted a reddening amounting to 0.019 mag in $b-y$, which we consider to be a better estimate, Nissen et al. would have obtained a higher temperature by ~ 120 K. In addition, Fuhrmann, Axer, & Gehren (1994) derived an effective temperature of 5814 ± 44 K for HD 140283 from the profiles of the Balmer lines. Finally, we note that temperatures near 5850 K and 6320 K (in excellent agreement with the Alonso et al. determination) are inferred for HD 140283 and HD 84937, respectively, from our color transformations when the aforementioned estimates of [Fe/H] and $\log g$ are assumed. (These relations are the ones used to transform the isochrones from the theoretical to the observed plane.)

Table 1 lists the results of a number of calculations that have been carried out to try to match the observed colors of HD 84937 and HD 140283. There is clearly excellent consistency between the predicted and observed color indices of HD 84937[9] when very close to the Alonso et al. (1996a) effective temperature for this star, the *Hipparcos*-based gravity, and the current best estimate of its [Fe/H]-value are assumed: see the entry labelled "Nissen et al. (1997)." (As in the case of HD 140283, Nissen et al. would have obtained a somewhat higher T_{eff} for HD 84937 had they

[9] The reddening of $E(b-y) = 0.013$ reported by Schuster & Nissen for this star is barely significant, as discussed in their paper.

adopted $E(b-y) = 0.013$ instead of assuming it to be unreddened.) It also seems clear from the synthetic colors that the temperature derived for HD 140283 by Alonso et al. is too low. To match the observed color indices of this star, a temperature close to 5850 K and a gravity slightly less than $\log g = 3.8$ (but within the error bars of the *Hipparcos*-based estimate) are indicated, if $[Fe/H] = -2.5$ is assumed.

We conclude from our examination of the three field halo stars that the predicted and observed colors match very well for current best estimates of their [Fe/H], $\log g$, and T_{eff}-values. It is worth emphasizing that this good agreement is obtained on the assumption of a temperature scale which is very close to that derived from the infrared flux method: only in the case of HD 140283 do we require a significantly hotter T_{eff}, but as noted above, the calibration of the Alonso et al. (1996a, 1996b) IRFM color-T_{eff} relations is suspect at extremely low metallicities. As shown by Bell & Gustafsson (1989) and by Houdashelt, Bell, & Sweigart (2000), measured angular diameters of near–solar-abundance giants are in excellent agreement with those predicted if the IRFM temperatures are assumed for them. Our expectation was that the temperatures derived for Population II stars from the IRFM method should also be quite good, and it is encouraging to find that this is indeed the case. [Although there is not perfect consistency with the predicted T_{eff} scale of our isochrones (see VandenBerg et al. 2000), the fits to the M92 *C-M* diagram given below suggest that errors in either the temperatures or colors cannot be very large. Reference should be made to the VandenBerg et al. study for an extensive discussion of this issue.]

In view of these results, there is some justification for believing that the comparison shown in Figure 1 may be quite accurate. However, an age of ≈ 14.5 Gyr for M92 (see Fig. 1) is higher than most estimates based on fits of the cluster *C-M* diagram to local Population II subdwarfs (e.g., Reid 1997; Gratton et al. 1997): of the initial investigations that used *Hipparcos* results in main-sequence fits of globular cluster fiducials to local calibrators, only Pont et al. (1998) obtained a relatively short distance modulus (and moderately high age) for M92. However, we can offer what we consider to be quite a strong argument in support of ages $\gtrsim 15$ Gyr for the most metal-deficient field and cluster stars.

Consider, first, the left-hand panel of Figure 2, in which the $[Fe/H] < 2.0$ field halo stars from the Schuster & Nissen (1988, 1989) studies are overplotted on the M92 observations. We see that the cluster turnoff apparently lies at a higher c_0-value (by ~ 0.03 mag) than the field stars, suggesting that the latter are ~ 2 Gyr older than the cluster. However, the location of HD 140283 (the point with the lowest c_0-value and an attached error bar) is problematic. This is mainly for the reason that, at the color of the field star, c_0 is predicted to have only a slight dependence on age. That is, the difference in c_0 between HD 140283 and the cluster subgiants having the same $(v-y)_0$ color is difficult to understand.

A plausible cause of this discrepancy is that M92 has significantly lower CNO abundances than the field stars, but we are unaware of any evidence to support this possibility. What seems to be the most likely explanation is that there is a small zero-point problem with our u photometry. This is suggested by the fact that fits of the M92 *C-M* diagram to HD 140283 (e.g., see Fig. 2, *right-hand panel*) yield exactly the same distance modulus irrespective of whether b, v, or y (which is the same as V) are used as the ordinate. However, when u is employed, a 0.04 mag discrep-

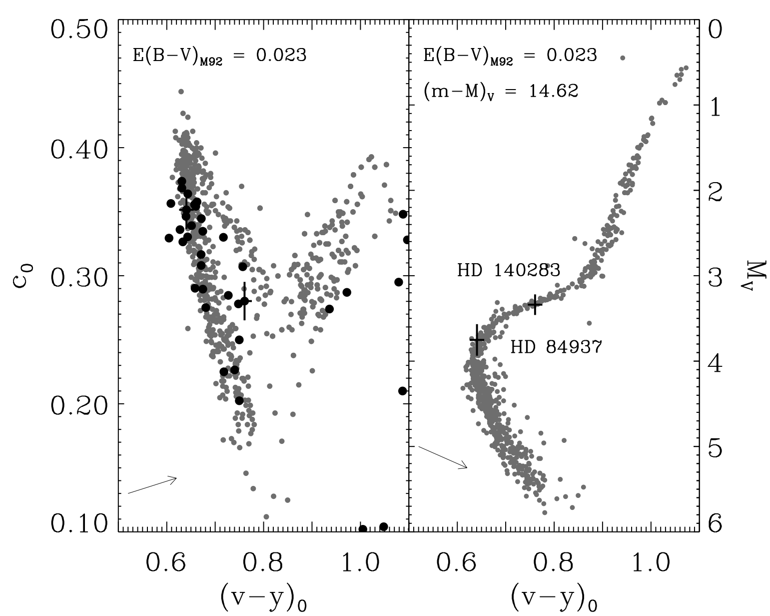

FIG. 2.—Comparison of our M92 data with local metal-poor stars with $[Fe/H] < -1.9$ from Schuster & Nissen (1988, 1989). The two well-studied stars HD 84937 and HD 140283 are overplotted as plus signs (symbol size indicates the error bars). The reddenings of the field stars were estimated by Schuster & Nissen from $uvby\beta$ photometry, and we have adopted their values. Note, in the left-hand panel, that the field star turnoff appear to be located at a lower c_1-value than the cluster TO, indicating that they are ≈ 2 Gyr older than the cluster. We believe, however, that the inconsistent positions of HD 84937 in the two panels (relative to the M92 turnoff) are indicative of a small zero-point error in our M92 u photometry—in the sense that our observed c_1-values should be ~ 0.04 mag smaller (see footnote 10). *If* this is indeed the case, then the field and cluster populations are coeval. The location of HD 140283 is also much improved if there is a problem with our u photometry. The right-hand panel shows a "fit" of M92 to HD 140283, on the assumption that the field subgiant has a reddening $E(b-y) = 0.019$ mag, which is consistent with current best estimates. The derived $(m-M)_V$-value for M92 is 14.62, which is arguably an upper limit to the cluster distance modulus if HD 140283 has a lower metallicity than M92 by ~ 0.3 dex and the two objects have very similar ages.

ancy is found in the sense that our observed *u* magnitudes are too faint, which would imply that the cluster c_0-values are too large (by the same amount). (We have not been able to locate the source of this problem, but we suspect that the steep gradient in the CCD sensitivity over the *u* bandpass may be to blame. The resolution of this difficulty will require further observations.)

The implications of such an error are obvious. If a 0.04 mag adjustment were applied to the M92 photometry in the left-hand panel of Figure 2, then there would be not be an inconsistency between the properties of the field and cluster subgiants (and the resultant overlay of the turnoff stars in the two samples would indicate that both populations have very similar ages). Moreover, the corrected version of Figure 1 would imply an age that is consistent with the distance modulus obtained from the $[M_V, (v-y)_0]$ plane (see Fig. 2, *right-hand panel*). (Isochrone fits to the cluster *C-M* diagram are presented at the end of this section.) We emphasize that the short distance modulus which is derived from the absolute magnitude of HD 140283 is very robust given that it is obtained using either *b*, *v*, or *y* (and the difference in the inferred modulus using *u* is only 0.04 mag). Although HD 84937 does not provide a strong constraint on the distance of M92, because it is located so near to the cluster turnoff, it is encouraging that it does fit almost perfectly on the cluster locus (see Fig. 2, *right-hand panel*) when the best estimate of its properties and the indicated M92 distance are assumed.[10]

We recall that Stetson & Harris (1988) obtained exactly the same distance modulus as we have found, but using main-sequence fits to local subdwarfs. However, their result was based on pre-*Hipparcos* parallaxes, and a number of publications based on this improved database have led to substantially higher distance moduli—14.99 by Reid (1997) and 14.80 by Gratton et al. (1997). One of the reasons why Pont et al. (1998) obtained $(m-M)_V = 14.67 \pm 0.08$ mag for M92 was that they included nearby subgiants in their distance determination. However, all of these estimates, including that subsequently obtained by Carretta et al. (2000), who found a modulus of 14.72, are based wholly or partly on main-sequence fits using *B* and *V* photometry which results in a very steep main sequence. As a consequence, uncertainties in reddening and the gathering of photometry from different sources can be a potential problem. In this study, the photometric standards and the photometry for the metal-poor subdwarfs come from the *same* sources (Schuster & Nissen 1988 and Olsen 1983, 1984): the data from these investigations are very well calibrated to the standard *uvby* system.

Because of its location on the *C-M* diagram, HD 140283 provides an especially important constraint on the age of M92 (see, e.g., Pont et al. 1998; VandenBerg 1999). Given that most investigators have found this star to be ≈0.2–0.3 dex more metal-poor than the cluster, the distance that we have derived for M92 is arguably an *upper* limit (if the cluster and field subgiant have nearly the same age). For instance, Figure 3 shows a fit of isochrones for [Fe/H] = −2.14 and [α/Fe] = 0.3 to the M92 fiducial on the $[(B-V)_0, M_V]$-plane—on the assumption that cluster subgiants possessing the same intrinsic color as HD 140283 also have the same absolute visual magnitude.[11] It turns out that we obtain a slightly larger distance modulus for M92 (by ≈0.02 mag) in Figure 3 than in the right-hand panel of Figure 2. It is not uncommon for independent investigations to have photometric zero points that differ by 0.01–0.03 mag, and it is possible that the fiducial derived by Stetson & Harris is slightly too faint along the subgiant branch because relatively few stars in this phase of evolution were observed in their investigation (see their Figs. 15–16). This small offset is not a serious concern for our purposes: if a slightly shorter distance modulus, as suggested by Figure 2, is more appropriate, then our estimate of the age of M92 should be increased by a small amount.

[10] Note that, for our adopted M92 distance, HD 84937 is slightly below the turnoff in left-hand panel of Fig. 2, but slightly above it in the right-hand panel. This inconsistency is removed if the *u*-band zero point is indeed 0.04 mag too faint in our M92 photometry. Furthermore, the relative location of HD 84937 and HD 140283 in the right-hand panel of Fig. 2 is consistent with the *Hipparcos* astrometry *and* their location in the $[(v-y)_0, c_0]$-diagram for the field stars, lending further support to our suspicion of the *u* zero-point error.

[11] We prefer to compare isochrones with the Stetson & Harris (1988) *BV* data for M92 than to fit them to the *C-M* diagram in the right-hand panel of Fig. 2, because the transformation to $B-V$ has been tested much more thoroughly than those to the various Strömgren indices. Indeed, the present investigation describes only one of several tests that we are carrying out to evaluate the accuracy of synthetic *uvby* magnitudes. As far as the $B-V$ transformations are concerned, they are precisely on the Bell & Gustafsson (1989) system (see, e.g., Fig. 9 in the study by VandenBerg 1992), and so represent a purely theoretical, but well-constrained, prediction of how this color index varies with log *g* and $T_{\rm eff}$ at low metallicity.

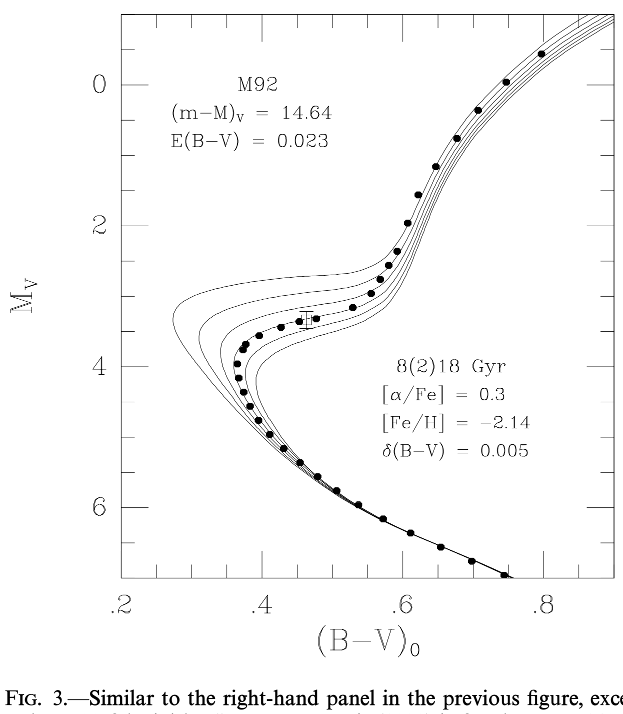

FIG. 3.—Similar to the right-hand panel in the previous figure, except that the M92 fiducial by Stetson & Harris (1988) is fitted to HD 140283 (*open square*) on the $[(B-V)_0, M_V]$-diagram. (The extension of the cluster fiducial to bright magnitudes was based, in part, on data provided by M. Bolte 2000, private communication; see VandenBerg 2000.) Isochrones for the indicated chemical composition and ages from 8 to 18 Gyr in 2 Gyr steps have been superposed on the data to show that the age of M92 is ≈14.5 Gyr, if the cluster distance modulus is $(m-M)_V = 14.64$. Given that HD 140283 is believed to be about 0.3 dex more metal-poor than [Fe/H] = −2.14, this estimate of the M92 distance is arguably an upper limit, if the field subgiant and the globular cluster are approximately coeval. Note that the isochrones had to be shifted to the red by only $\delta(B-V) = 0.005$ mag in order to achieve a good fit to the cluster turnoff.

The main point to be made concerning Figure 3 is the following. If HD 140283 is coeval with M92, then the distance modulus of the latter must be ~ 0.1 mag smaller than $(m-M)_V = 14.64$ to be consistent with the ≈ 0.3 dex difference in their [Fe/H]-values. As already noted (see Table 1 and the accompanying discussion), most photometric and spectroscopic studies obtain $[\mathrm{Fe/H}] \approx -2.5$ for HD 140283, whereas current best estimates of the iron content of M92 tend to lie between -2.16 (Carretta & Gratton 1997) and -2.25 (Sneden et al. 1991). It is certainly possible that HD 140283 is *somewhat* older than M92 (in which case the former becomes the object of choice for setting a lower limit on the age of the universe), but it seems unlikely that the difference in age can be more than ~ 1 Gyr. This is for the reason that the ages of globular clusters having $[\mathrm{Fe/H}] \lesssim -1.8$ show little or no dependence of age on metallicity (Rosenberg et al. 1999, VandenBerg 2000). An age of ≈ 14.5 Gyr (see Fig. 3) is arguably, therefore, a lower limit to the age of M92.

Suppose we do adopt a 0.1 mag smaller distance modulus for the globular cluster. As shown in Figure 4, we would obtain an age of 16 Gyr for M92 (which is approximately what we would find for HD 140283 were we to compare its location with isochrones for $[\mathrm{Fe/H}] = -2.5$). Note that the isochrones now match the entire *C-M* diagram of M92 exceedingly well. [A fit of comparable quality is also found if we were to assume $(m-M)_V = 14.60$ and $[\mathrm{Fe/H}] = -2.31$; see VandenBerg 2000.] Hence, one of the consequences of assuming that HD 140283 and M92 are essentially coeval is that the observed and predicted *C-M* diagrams come into nearly perfect alignment—which does provide some additional support for this scenario, though one cannot place too much reliance on isochrone shapes. In both Figures 3 and 4, small zero-point corrections were applied to the model colors in order match both the turnoff color of the most appropriate isochrone and the location of the unevolved main sequence at the adopted cluster distance. Such small adjustments are obviously well within the uncertainty of the synthetic color–T_{eff} relations.

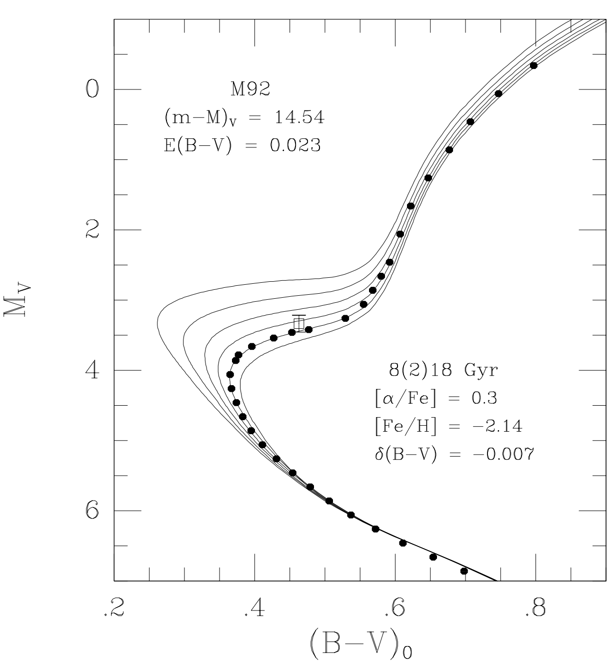

FIG. 4.—As in the previous figure, except that the distance modulus of M92 has been reduced by 0.1 mag to compensate for the difference in [Fe/H] between the cluster and HD 140283. This represents a more realistic fit of M92 to the field subgiant if both objects are coeval. Note, in this case, that the entire *C-M* diagram of M92 is well reproduced by the isochrones once a slight blueward shift is applied to the synthetic colors.

VandenBerg (2000) has argued that GC distances which are derived from fits of cluster *C-M* diagrams to local subdwarfs are not necessarily in conflict with those inferred from most *direct* measurements of RR Lyrae luminosities—i.e., from Baade-Wesselink (e.g., Fernley et al. 1998), statistical parallax (Layden et al. 1996; Gould & Popowski 1998), and *Hipparcos* trigonometric parallax (Gratton 1998) studies. The extremely metal-poor subgiant HD 140283 provides particularly strong evidence, in our view, in support of the short distance scale and fairly high cluster ages. To be sure, the uncertainties are such that the age of the oldest stars could be as low as ~ 13 Gyr or as high as ~ 18 Gyr, but estimates outside this range seem to us to be rather unlikely.

Although 16 Gyr appears to be our best estimate of the age of M92 and HD 140283, the models that we have used have not taken into account the effects of diffusion. Consequently, one would expect that this estimate is too high by about 10% as the result of this omission (e.g., Proffitt & VandenBerg 1991). However, it is not at all clear that diffusion operates in Population II stars at predicted rates, even though standard solar models apparently do a much better job of predicting the observed oscillation frequencies of the Sun if diffusion is treated (see the superb review by Christensen-Dalsgaard et al. 1999).

The main problem is that diffusive models are unable to explain the observed Li abundances in metal-poor stars (see, e.g., Swenson 1995). Lithium is predicted to settle just as rapidly as helium (Turcotte, Richer, & Michaud 1998), and as shown by Proffitt & VandenBerg (1991) helium should be almost completely depleted in the surface layers of extreme Population II stars due to the gravitational settling process. Li should therefore be similarly depleted to undetectable levels, and yet significant Li has been found in turnoff stars of NGC 6397 (Molaro & Pasquini 1994), which is one of the Galaxy's most metal-deficient GCs. In addition, one expects (see Proffitt & VandenBerg) that diffusion will have some effects on isochrone shapes, yet it is clear from Figure 4 that nondiffusive models are able to reproduce observed *C-M* diagrams extremely well. So we have an interesting puzzle that needs to be understood. Our expectation is that something does inhibit diffusion in the surface layers of the most metal-deficient stars, but that the age effect, which arises from the settling of helium (and metals) in the deep interior, is still present. However, we have no way of knowing one way or the other at this point in time. (For some interesting ideas on how this dilemma may be resolved, the reader is referred to Vauclair 1999.)

5. CONCLUSIONS

This investigation has used the well-observed nearby subgiant HD 140283, which has $M_V = 3.34 \pm 0.12$ from *Hipparcos* parallax measurements and an assumed $E(b-y) = 0.019$ mag, to derive $(m-M)_V \approx 14.6 \pm 0.12$ for M92. This implies an age of 16 ± 2 Gyr using isochrones based on the recent stellar evolutionary tracks by VandenBerg et al. (2000) for $[\alpha/\mathrm{Fe}] = 0.30$. (This estimate should probably be reduced by ~ 1–1.5 Gyr to take into account the effects of He diffusion, which was not treated in the models that we have used.) Provided that the adopted chemical abundances of M92 and HD 140283 are accurate, the derived cluster distance appears to be particularly well constrained. We emphasize that this estimate is not affected in any significant way by the possible zero-point error in our *u* photometry.

The other important finding of this study is that, when isochrones are superposed directly onto the cluster observations on the distance-independent $[(v-y)_0, c_0]$- diagram, we obtain an age of 14.5 Gyr, which is only 1.5 Gyr less than that derived using HD 140283. We have argued that this difference is likely due to a small zero-point problem with our *u* photometry for M92 and that the inferred age would rise to near 16 Gyr if our expected correction to the *u* magnitudes is applied. Further observations are needed to confirm our suspicions concerning this matter. However, whether or not future work shows that there is "perfect" consistency between color-color and color-magnitude diagrams, this work has provided encouraging support for both the T_{eff} scale of the VandenBerg et al. (2000) stellar models and the color transformations that we have used. With further improvements to both the observations and the theoretical models, it should be possible to derive ages for the most metal-poor clusters directly from the $(v-y, c_1)$-diagram and totally remove what has been, to date, the dominant uncertainty in the determination of globular cluster ages; namely, those associated with the cluster distances.

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