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THE RELATIVE AGE OF THE THIN AND THICK GALACTIC DISKS

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ABSTRACT

We determine the relative ages of the open cluster NGC 188 and selected *Hipparcos* field stars by isochrone fitting and compare them to the age of the thick-disk globular cluster 47 Tuc. The best-fit age for NGC 188 was determined to be 6.5 ± 1.0 Gyr. The solar-metallicity *Hipparcos* field stars yielded a slightly older thin-disk age, 7.5 ± 0.7 Gyr. Two slightly metal-poor ([Fe/H] = −0.22) field stars whose kinematic and orbital parameters indicate that they are members of the thin disk were found to have an age of 9.7 ± 0.6 Gyr. The age for 47 Tuc was determined to be 12.5 ± 1.5 Gyr. All errors are internal errors due to the uncertainty in the values of metallicity and reddening. Thus, the oldest stars dated in the thin disk are found to be 2.8 ± 1.6 Gyr younger than 47 Tuc. Furthermore, as discussed by Chaboyer, Sarajedini, & Armandroff, 47 Tuc has a similar age to three globular clusters located in the inner part of the Galactic halo, implying that star formation in the thin disk started within 2.8 ± 1.6 Gyr of star formation in the halo.

Subject headings: Galaxy: formation — globular clusters: general —
globular clusters: individual (47 Tucanae) —
open clusters and associations: individual (NGC 188)

1. INTRODUCTION

The dating of the oldest stars in the Milky Way allows us to infer the early history of star formation in our Galaxy and, hence, provides us with important information regarding the formation of the Milky Way. A great deal of attention has been paid to the ages of globular clusters (see, for example, the reviews by Stetson, VandenBerg, & Bolte 1996; Sarajedini, Chaboyer, & Demarque 1997) in the halo, and there have been a number of studies that determine the ages of the oldest open clusters in the thin disk (e.g., Carraro, Girardi, & Chiosi 1999; Chaboyer, Green, & Liebert 1999, hereafter CGL). Typically, there appears to be a gap of several Gyr between the ages of the globular clusters and the ages determined for the oldest stars in the thin disk. We have elected to investigate this further in order to quantify the age difference (if any) between the thin disk, the thick disk, and the halo of the Milky Way.

In recent years, numerous techniques have been employed to determine the ages of the oldest stars in the Galactic (thin) disk. Jimenez, Flynn, & Kotoneva (1998) examined the color-magnitude diagram (CMD) of *Hipparcos* field stars and arrived at a minimum disk age of 8 Gyr; Carraro et al. (1999) used isochrone fits to determine the ages of several old open clusters. Bergeron, Ruiz, & Leggett (1997) and Knox, Hawkins, & Hambly (1999) used observations of local white dwarfs and theoretical white dwarf cooling curves to determine a local disk age of 6.5–10 Gyr and 9–13 Gyr, respectively. Oswalt et al. (1996) also used observations of white dwarfs to place a minimum age of 9.5 Gyr on the Galactic disk. CGL studied the old open cluster NGC 6791 and determined an age of 8.0 ± 0.5 Gyr.

Globular clusters in the thick disk and halo have been the subject of a number of recent investigations. For example, Salaris & Weiss (1998) determined the ages of three thick-disk globular clusters, 47 Tuc, M71, and NGC 6352, and arrived at an age of 9.2 Gyr for all three. Harris et al. (1997) examined two halo clusters, NGC 2419 and M92, in order to determine their relative and absolute ages. Their study determined that the clusters had the same relative age to within 1 Gyr and an absolute age of 14–15 Gyr.

In this paper, the relative age of the thin and thick disks is measured, comparing the open clusters NGC 188 and NGC 6791 and selected *Hipparcos* field stars to the thick-disk globular cluster 47 Tuc. The results of this analysis are related to the results of Chaboyer, Sarajedini, & Armandroff (1999, hereafter CSA), in which the relative age of 47 Tuc to three halo clusters was determined using the same input physics as this study. Compared to other studies which have investigated the relative age of the thin disk and the halo (e.g., Carraro et al. 1999), this study has the advantage of using the same assumptions and methodologies in dating the thin and thick disks and the halo. This allows us to determine precise relative ages and to provide a reliable estimate of the error in the relative age estimates.

Section 2 of this paper will discuss the stellar model and isochrones used in this study. Section 3 details the age estimates for NGC 188 and the *Hipparcos* field stars (thin disk). The age of 47 Tuc (thick disk) is determined in § 4. The results are summarized in § 5, where the relative age between the thin and thick disks and the halo is discussed.

2. STELLAR MODELS AND ISOCHRONES

Stellar evolution tracks were constructed using Chaboyer's stellar evolution code (CGL) for a range of masses of 0.50–1.30 $M_\odot$, in increments of 0.05 $M_\odot$. The input physics, including low- and high-temperature opacities, nuclear reaction rates, helium diffusion coefficients, and the equation of state were identical to those described in CSA. The models were evolved in 6000 time steps from the zero-age main sequence through the red giant branch.

The values of [Fe/H] for each of set of stellar models were chosen to reflect the observed values in each of the clusters. To determine the uncertainty in the age due to the uncertainty in [Fe/H], stellar models were calculated for a

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range of [Fe/H] values, centered upon the preferred value for each of the clusters. Most of the models used a scaled solar heavy-element composition (Grevesse & Noels 1993). The models for 47 Tuc were calculated with $[\alpha/\mathrm{Fe}] = 0.0$ (scaled solar) and $[\alpha/\mathrm{Fe}] = +0.40$.

The calibrated solar model for this study had a helium mass fraction of $Y_{\odot} = 0.263$ and a heavy-element mass fraction of $Z_{\odot} = 0.0182$. The primordial helium abundance was taken to be $Y_p = 0.234$ (Olive, Steigman, & Skillman 1997), and the helium abundance for each model was calculated using the relation $Y = Y_p + (\Delta Y/\Delta Z)Z$ with $\Delta Y/\Delta Z = (Y_{\odot} - Y_p)/Z_{\odot}$.

The isochrones were constructed for ages between 5 and 14 Gyr, in 1 Gyr increments for each of the compositions. Color transformations to the observational plane were done in a manner identical to that described in CGL. Figure 1 compares the 10 Gyr isochrone for $[\mathrm{Fe/H}] = -0.70$ for both the α-enhanced and the non–α-enhanced cases. The resulting change in the isochrone corresponds to a change in [Fe/H] of nearly 0.20 dex. These results are similar to those found in Salaris & Weiss (1998).

Additional isochrones were generated in order to ascertain the effect that changes in the low-temperature opacities would have on the isochrones. Figure 2 plots the 10 Gyr isochrone for $[\mathrm{Fe/H}] = -0.70$ with Alexander & Ferguson (1994) opacities, as well as the 9, 10, and 11 Gyr isochrones with Kurucz (1991) opacities used in this study. This figure demonstrates that ages determined using isochrones generated with Kurucz opacities will indicate ages about 0.5 Gyr older than isochrones using Alexander & Ferguson opacities. This analysis was done in order to compare the age of NGC 6791 as found in CGL, which used Alexander & Ferguson opacities in its models, with the ages of the clusters in this study and CSA, which utilized Kurucz opacities. Kurucz (1991) opacities were used in this study and by CSA, as these opacities are available for both scaled solar and α-element–enhanced compositions. The Alexander & Ferguson opacities were only available to us for scaled solar compositions.

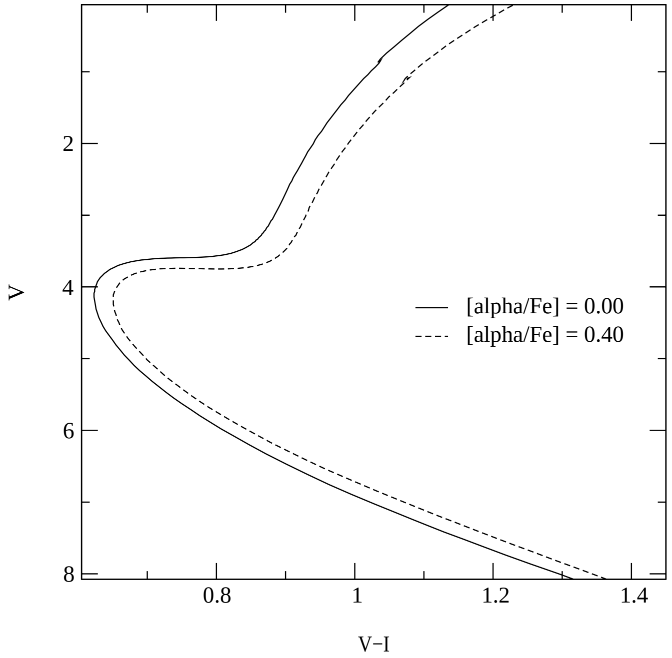

FIG. 1.—The 10 Gyr isochrones with $[\mathrm{Fe/H}] = -0.70$ for both the α-enhanced (0.40 dex) and the non–α-enhanced cases. The shift in the isochrone corresponds to a change in [Fe/H] of about 0.20 dex.

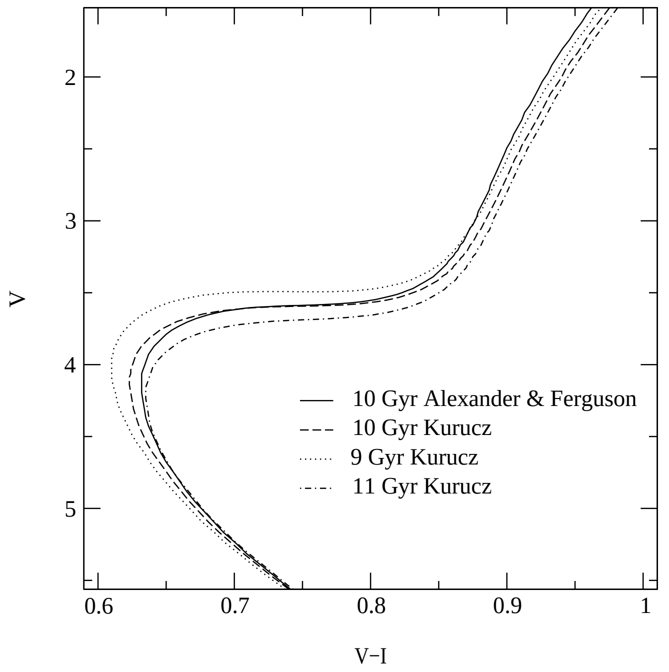

FIG. 2.—The 10 Gyr isochrone generated using Alexander & Ferguson opacities, with $[\mathrm{Fe/H}] = -0.70$. Also shown are the 9, 10, and 11 Gyr isochrones using Kurucz opacities.

3. THIN-DISK AGES

3.1. *NGC 188*

Isochrones were fit to the CMD for NGC 188 obtained from observations by Sarajedini et al. (1999, hereafter S99). The CMD was cross-correlated to include only cluster members with a greater than 75% membership probability (D. I. Dinescu 2000, private communication). Membership criteria were based upon a proper-motion study by Dinescu et al. (1996).

NGC 188 has $[\mathrm{Fe/H}] = -0.05$ based upon several determinations (Twarog, Ashman, & Anthony-Twarog 1997; Thogersen, Friel, & Fallon 1993; Hobbs, Thorburn, & Rodriguez-Bell 1990). Isochrones with $[\mathrm{Fe/H}] = -0.05$ were fit simultaneously in $B-V$ and $V-I$ using the main sequence, allowing the distance modulus to vary around the value established by S99. Figure 3 shows the 5, 6, and 7 Gyr isochrones fit to the observational data. The reddening was taken to be $E(B-V) = 0.09$ (S99) and transformed to $E(V-I)$ by $E(V-I) = 1.25E(B-V) = 0.1125$. The distance modulus, which yielded an excellent main-sequence fit, was $(m-M)_V = 11.43$, well within the error bars for the value determined by S99 of $(m-M)_V = 11.44 \pm 0.08$. The age indicated by both $B-V$ and $V-I$ fits was 6.5 Gyr.

Isochrones for a more metal-poor composition of $[\mathrm{Fe/H}] = -0.15$ were fit to the CMD, again assuming a reddening of $E(B-V) = 0.09$. The fits produced a distance modulus of $(m-M)_V = 13.34$, slightly less than S99, and an age of 7.5 Gyr. Figure 4 shows the 6, 7, and 8 Gyr isochrones for this lower metallicity fit to the observational data. Isochrones with a higher metallicity, $[\mathrm{Fe/H}] = +0.05$, were fit to the data as well and are shown in Figure 5, indicating $(m-M)_V = 11.48$ and an age of 5.5 Gyr.

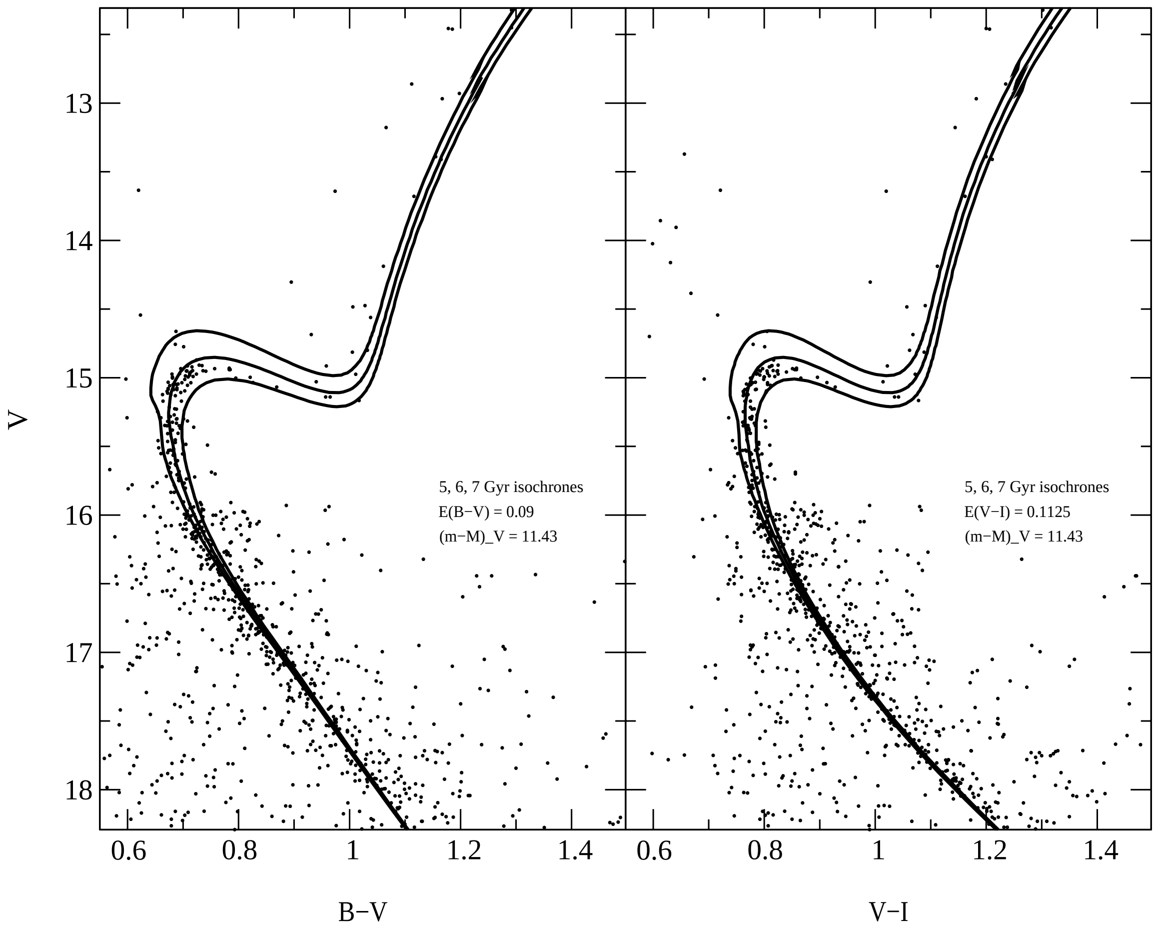

FIG. 3.—The 5, 6, and 7 Gyr isochrones with [Fe/H] $= -0.05$ fit simultaneously in $B-V$ and $V-I$ to the CMD for NGC 188. The photometric data were taken from Sarajedini et al. (1999).

However, it would appear unlikely that a younger age as a result of higher metallicity is the case, as the CMD does not show a hook at the main-sequence turnoff, which is seen in the isochrones.

In order to determine the uncertainty due to reddening, the [Fe/H] $= -0.05$ isochrones were fit for $E(B-V) = 0.07$ and 0.11. These fits indicate ages of 7.5 Gyr and 5.5 Gyr, respectively. The three sets of isochrone fits for NGC 188 are summarized in Table 1. The best age estimate was found to be 6.5 ± 1.0 Gyr, allowing for uncertainty in the metallicity and reddening of the cluster. This error estimate does not include the uncertainty in the input physics in the stellar models and isochrones, and so should be viewed as the error on the relative age of NGC 188.

TABLE 1

ISOCHRONE FIT PARAMETERS FOR NGC 188

[Fe/H]	$(m-M)_V$	$E(B-V)$	$E(V-I)$	Age (Gyr)
−0.05……	11.43	0.09	0.1125	6.5
−0.15……	11.34	0.09	0.1125	7.5
+0.05……	11.48	0.09	0.1125	5.5
−0.05……	11.31	0.07	0.0875	7.5
−0.05……	11.52	0.11	0.1375	5.5

3.2. *Berkeley 17*

Berkeley 17 (Be 17) has been suggested to be the oldest open cluster (Phelps 1997). It has a metallicity of [Fe/H] $= -0.29 \pm 0.13$ from moderate-resolution spectroscopy (Friel et al. 1995), while Carraro et al. (1999) estimate [Fe/H] ~ -0.35 based upon the slope of the red giant branch in the infrared.[2]

Phelps (1997) obtained *BVI* photometry of this cluster which was used in our isochrone fits. A simultaneous fit to the $B-V$ and $V-I$ photometry was attempted, assuming $E(V-I) = 1.25E(B-V)$. We attempted to fit isochrones with [Fe/H] $= -0.10$, -0.24, and -0.40 with [α/Fe] $= +0.0$ and $+0.40$ (a total of six different compositions) without success. In all cases, the Be 17 main sequence was redder than our isochrones in $B-V$ and bluer than our isochrones in $V-I$. Our best attempt at a fit is shown in Figure 6. As this is clearly not an acceptable fit to the data, we are unable to assign an age to Be 17. There are a number of possible explanations for the inability of the isochrones to simultaneously fit the $B-V$ and $V-I$ data. These include (1) a nonstandard extinction law in the direction of Be 17 [i.e., $E(V-I) \neq 1.25E(B-V)$], (2) a helium abun-

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[2] We note that the *JK* photometry presented by Carraro et al. (1999) contains a great deal of scatter on the main sequence, so we are unable to use this data in our isochrone-fitting procedure.

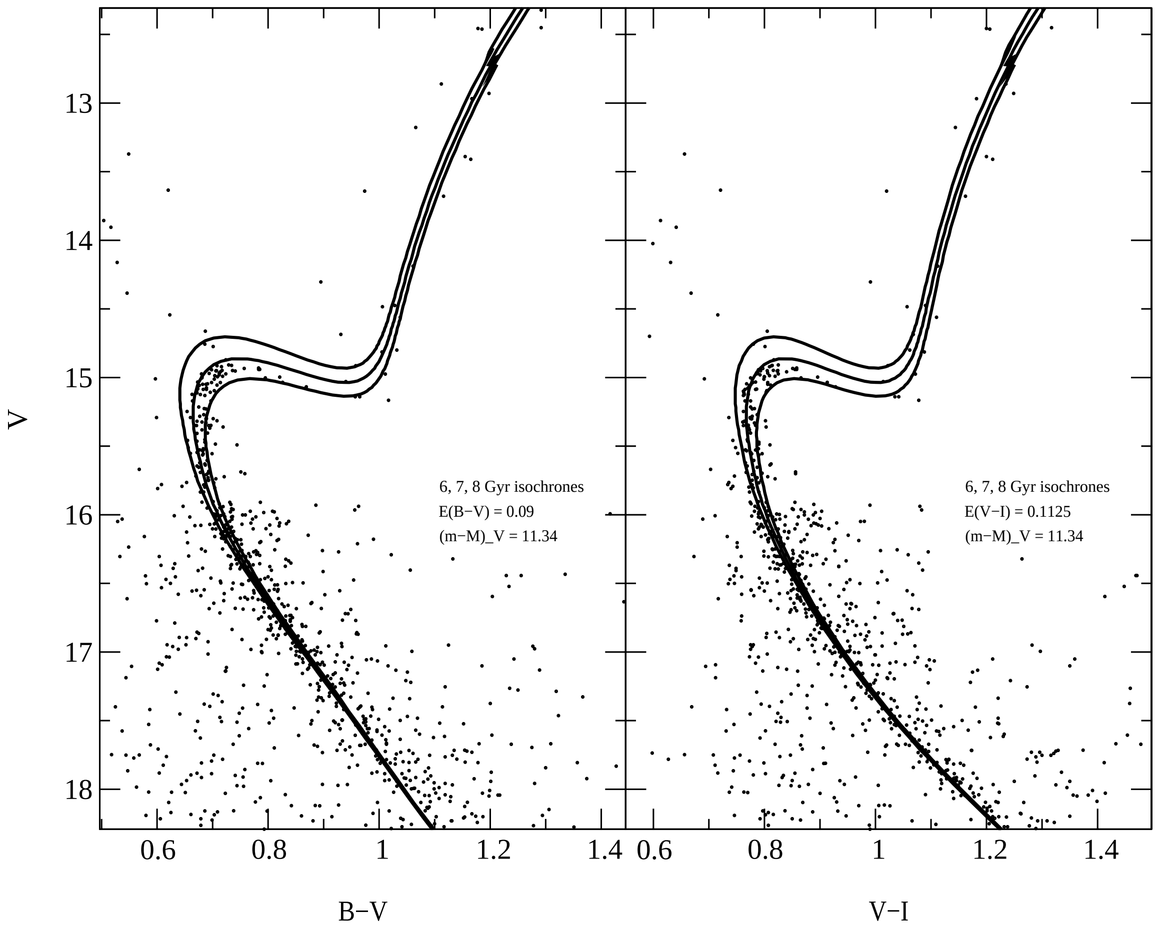

FIG. 4.—The 6, 7, and 8 Gyr isochrones with metallicity of [Fe/H] $= -0.15$ fit to NGC 188

dance significantly different than in our models, (3) errors in our isochrones, and (4) errors in the photometry (of order 0.05 mag in the color).

3.3. *Hipparcos Field Stars*

Open clusters are expected to dissipate/disrupt in the Galactic plane. Thus, only the most massive open clusters or those with orbits which keep them far away from the plane for most of their lifetimes are expected to survive for significant periods of time. For this reason, the age of the oldest field stars in the thin disk may provide a better estimate for the age of the thin disk than open clusters. An analysis of the age of oldest thin-disk stars in the solar neighborhood was made by comparing solar-metallicity isochrones to a selected sample of field stars from the *Hipparcos* database (ESA 1997).

The *Hipparcos* database was searched for single, nonvariable stars with good parallaxes ($\sigma_\pi/\pi < 0.12$). These stars were cross-referenced with the 1996 [Fe/H] catalog (Cayrel De Strobel et al. 1997) to find stars with [Fe/H] within 0.07 dex of solar. Choosing stars with metallicities near the solar value should ensure that these stars are members of the thin disk. In addition, choosing a relatively narrow metallicity range makes the age determination process simple. The selected stars were then plotted on a CMD and compared to solar-metallicity isochrones. As many of the stars do not have I-band photometry, the comparison to the isochrones was only done in $B-V$.

We are interested in determining the onset of star formation in the thin disk, and so concentrated our attention on the oldest stars in our sample for which it is possible to determine ages. These are the faintest stars in the main-sequence turnoff or subgiant branch regions of the CMD. There were 21 stars which appeared to be old in our search of the *Hipparcos* database. These 21 stars were checked for other published metallicities and space velocities. Some stars were omitted from the sample, which were shown in other sources to have metallicities of more than 0.07 dex from solar (Edvardsson et al. 1993; McWilliam 1990) or shown to have space velocities which are not characteristic of the thin disk (Eggen 1998; Edvardsson et al. 1993). The resulting sample of stars are shown in Figure 7, along with our zero-age main sequence and 6–8 Gyr isochrones (all with [Fe/H] $= 0.0$).

Figure 7*b* reveals that there are three stars which are much brighter/redder than our main-sequence isochrones. There are a few possible reasons for this discrepancy, including that these stars are binaries or are more metal-rich than indicated by the 1996 [Fe/H] catalog. We will not determine the age of these three stars.

An inspection of the oldest stars in the main-sequence turnoff and subgiant branch region in Figure 7*b* reveals that two stars lie on the 8 Gyr isochrone, four stars lie on or very near the 7 Gyr isochrone, and one star lies between the 7 and 8 Gyr isochrone. The derived ages for the stars in the turnoff region are quite sensitive to possible errors in the

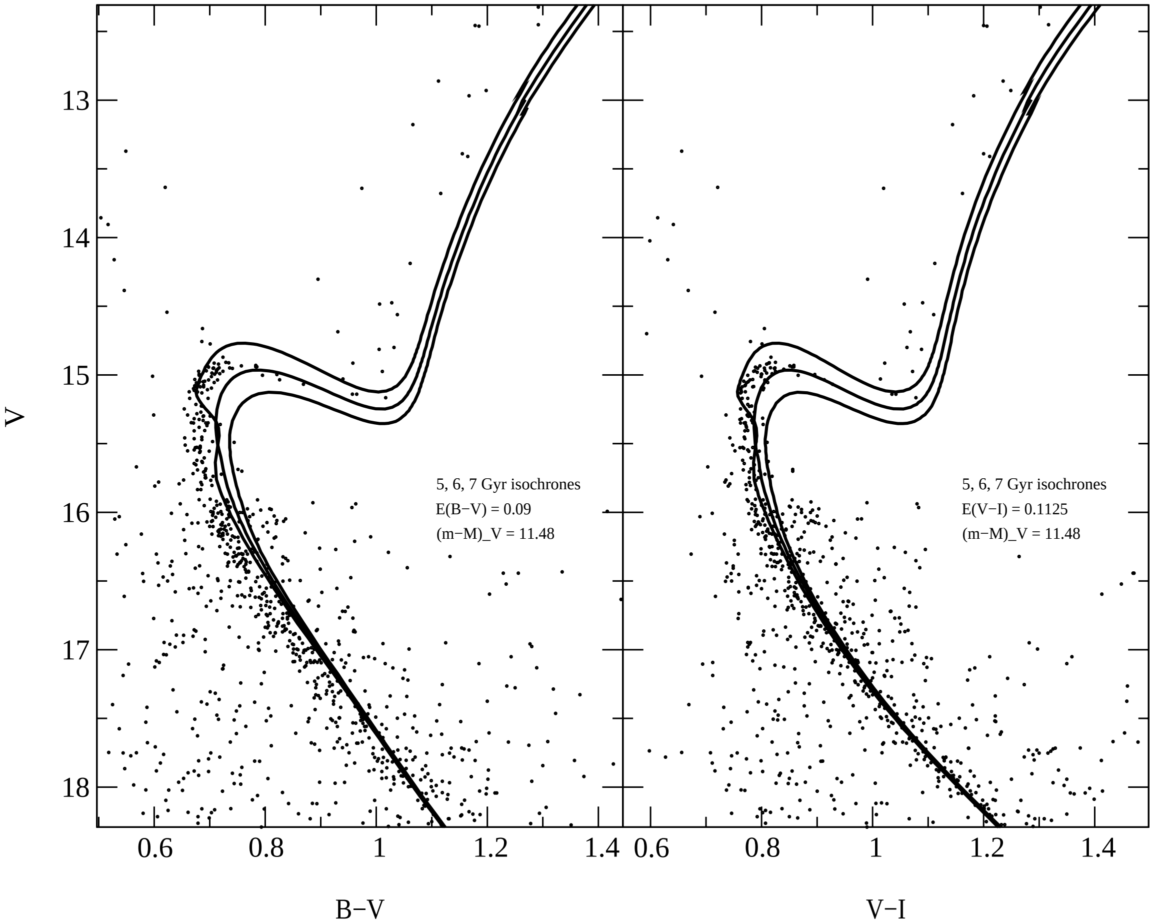

FIG. 5.—The 5–7 Gyr isochrones with metallicity of [Fe/H] $= +0.05$ fit to NGC 188

colors of the stars. For example, if the $B-V$ color of the 8 Gyr star with $M_V = 4.53$ were changed from $B-V = 0.670$ to $B-V = 0.655$, then its age would be changed to 7 Gyr. Given the uncertainties in the photometry, reddening, and in our color transformation, we are reluctant to base our estimate for the age of the oldest stars in the thin disk on just two stars. For this reason, we estimate that the oldest stars are 7.5 ± 0.5 Gyr old. Isochrones for [Fe/H] $= -0.05$ and $+0.05$ yielded ages of 8.0 Gyr and 7.0 Gyr, respectively, and we conclude that the oldest solar-metallicity stars in the thin disk have an age of 7.5 ± 0.7 Gyr. In determining this error, we simply added in quadrate the ±0.5 Gyr error due to the uncertainty in the metallicity of the stars to the ±0.5 Gyr uncertainty due to the photometry/reddening and color transformation.

There is a range in metallicities in the thin disk, and Edvardsson et al. (1993) found that (in the local solar neighborhood) the thin disk has metallicities ranging down to [Fe/H] $\simeq -0.20$. For this reason, we elected to search the *Hipparcos* database for single, nonvariable stars with good parallaxes ($\sigma_\pi/\pi < 0.12$) with $-0.08 \leq$ [Fe/H] ≤ -0.25 ([Fe/H] values from the 1996 [Fe/H] catalog; Cayrel De Strobel et al. 1997). This sample of stars allows us to determine the age of the somewhat metal-poor stars in the thin disk. In order to focus on the oldest stars, color and magnitude cuts were made in order to select stars with $3.4 < M_v < 5.0$ and $0.54 < B-V < 0.74$. These values were chosen based upon an inspection of our 7 Gyr and older isochrones with [Fe/H] $= -0.10$ and [Fe/H] $= -0.24$. These cuts were made rather generous to ensure that all potentially older stars are included in the sample. These cuts resulted in a sample of 21 stars which were plotted on a CMD with isochrones of appropriate metallicities. Stars which were less than ≈5 Gyr old were deleted from further study. This left a sample of 16 stars.

Basic data for each of these 16 stars was retrieved from the SIMBAD database at CDS. Four stars which were classified as variables or spectroscopic binaries were removed from the list, as it would not be possible to determine their ages. The derived ages are quite sensitive to the metallicity of the star. For this reason, the [Fe/H] references were checked for each star, and three stars whose recent (post-1995) [Fe/H] determinations were significantly different from those listed in the 1996 [Fe/H] catalog were removed from the list. The basic data for each of these stars are given in Table 2. The parallaxes, proper motions, and colors are from the Hippacos catalog. The [Fe/H] values are from Cayrel De Strobel et al. (1997), and the radial velocities were obtained from the SIMBAD database.

The age of each of these nine stars was determined from our isochrones (interpolating between the [Fe/H] $= -0.10$ and [Fe/H] $= -0.24$ isochrones). The error in the derived age of each star is due to the error in the absolute magnitude (due to the error in the parallax), an assumed color error of ±0.005 in $B-V$, and an assumed error in [Fe/H] of ±0.05 dex. The ages of these stars are given in Table 3, which also includes some derived kinematic data and orbital parameters for each star. The kinematic data and

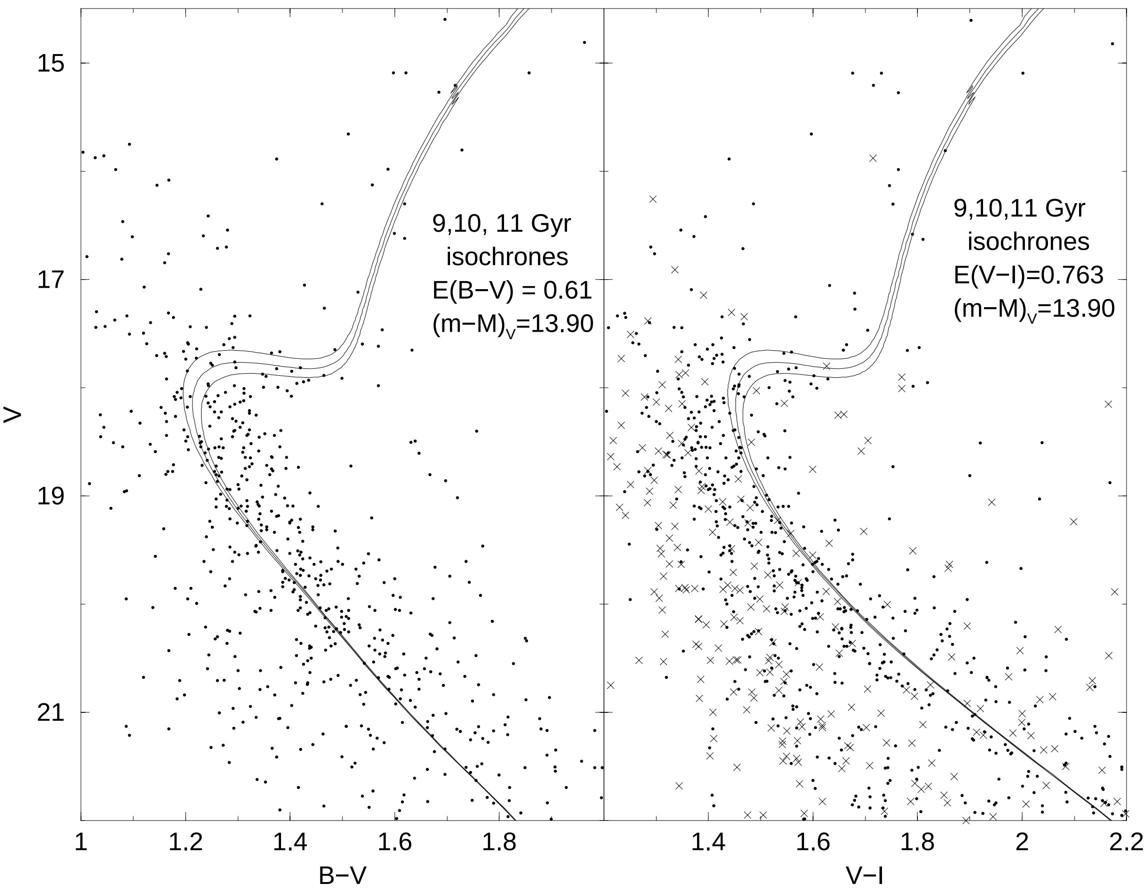

FIG. 6.—Best fit of our isochrones to Be 17. The Be 17 data is shown with filled circles, while the field stars (from a nearby field) are shown with crosses in the $V-I$ graph. This is clearly not a good fit, and, as a result, we are unable to assign an age to Be 17.

orbital parameters allow us to separate thin- and thick-disk stars.

The space motion of each star was calculated using a routine kindly provided to us by D. Dinescu. The motions were calculated in a cylindrical coordinate system (origin at the Galactic center) by adopting a solar radius of $R_\odot = 8.0$ kpc and a rotation velocity of the local standard of rest (LSR) of $\Theta_0 = 220$ km s^{-1}. In this coordinate system, the Π component is positive outward from the Galactic center, Θ is positive in the direction of Galactic rotation, and W is positive toward the north Galactic pole. Errors in the derived velocities include errors in the proper motions, radial velocities, and distances.

Table 3 includes some basic orbital parameters based upon integration of the orbits in two models of the Galaxy's potential. These integrations were made by D. Dinescu, and full details of the integration routine may be found in Dinescu, Girard, & van Altena (1999). The orbits were integrated in Galactic potential models given by Johnston, Spergel, & Hernquist (1995) and Paczyński (1990). The two potentials yield similar orbital parameters, and only the orbital parameters from the Paczyński (1990) potential are shown in Table 3. The orbital parameters listed in Table 3 are L_z, the z-component of the angular momentum (a conserved quantity), pericentric ($R_{\rm per}$) and apocentric ($R_{\rm apo}$) radii, the maximum distance from the plane $z_{\rm max}$, the eccen-

TABLE 2

SOLAR NEIGHBORHOOD STARS: BASIC DATA

HD	[Fe/H]	$B-V$	π (mas)	M_V	$V_{\rm radial}$ (km s^{-1})	$\mu_\alpha \cos\delta$ (mas yr $^{-1}$)	μ_δ (mas yr^{-1})
11007.......	−0.18	0.57	36.65 ± 0.7	3.60 ± 0.04	−26.5	−166.73	297.35
15335.......	−0.22	0.59	32.48 ± 0.8	3.45 ± 0.06	40.3	−65.37	72.52
32923.......	−0.20	0.66	63.02 ± 0.9	3.91 ± 0.03	20.3	536.05	18.51
41330.......	−0.24	0.60	37.90 ± 0.8	4.01 ± 0.05	−11.8	−124.24	−295.30
52711.......	−0.15	0.60	52.37 ± 0.8	4.53 ± 0.03	21.8	155.73	−828.01
67458.......	−0.24	0.60	39.08 ± 0.8	4.76 ± 0.04	−17.6	339.59	−354.69
202628......	−0.14	0.64	42.04 ± 0.9	4.87 ± 0.05	10.7	242.07	21.98
207129......	−0.15	0.60	63.95 ± 0.8	4.60 ± 0.03	−7.0	165.64	−295.00
210918......	−0.18	0.65	45.19 ± 0.7	4.51 ± 0.03	−18.0	570.33	−791.08

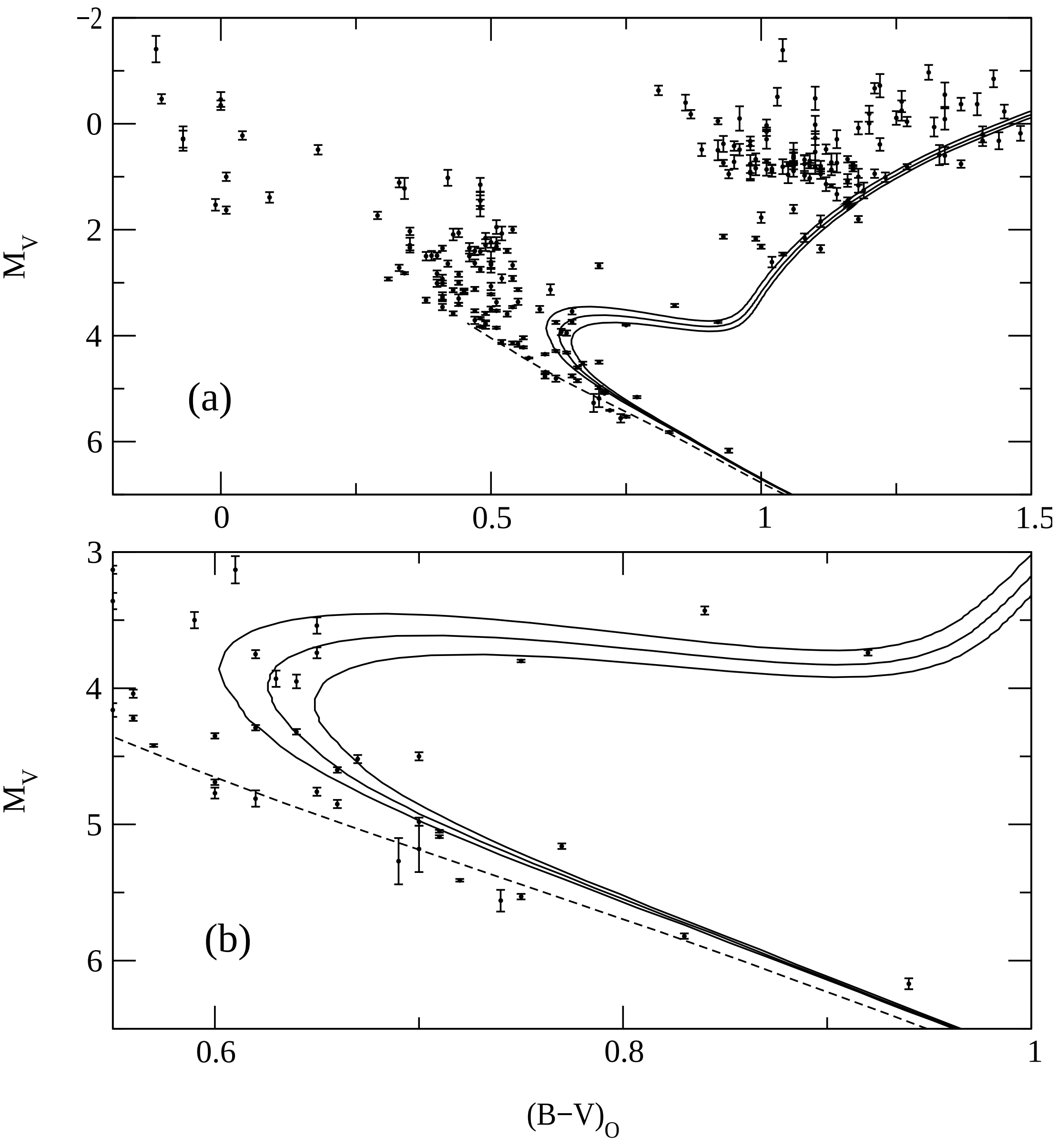

FIG. 7.—*Top*: *Hipparcos* field stars overlaid with the 6–8 Gyr solar-metallicity isochrones. *Bottom*: An enlargement of the turnoff region.

tricity of the orbits *e*, and the inclination angle with respect to the Galactic plane Ψ.

The stars in Table 3 all have $-0.14 \leq [\mathrm{Fe/H}] \leq -0.25$, and, in this metallicity range, one finds both thin- and thick-disk stars in the local solar neighborhood. The dispersion in the kinematics of the thin and thick disk make it impossible to definitively assign a single star to either the thin or thick disk. For example, in the thin disk $\sigma(W) = 20$ km s^{-1}, while

TABLE 3

SOLAR NEIGHBORHOOD STARS: DERIVED DATA

HD	Age (Gyr)	Π (km s^{-1})	Θ (km s^{-1})	W (km s^{-1})	L_Z (kpc km s^{-1})	R_{apo} (kpc)	R_{per} (kpc)	z_{max} (kpc)	e	Ψ (deg)	Population
11007	6.6 ± 0.5	-37.2 ± 1.3	250.8 ± 1.2	48.2 ± 1.1	2006.4	11.83	7.71	0.84	0.211	4.85	Thick disk?
15335	6.5 ± 0.5	14.3 ± 1.5	265.8 ± 1.0	-6.6 ± 1.0	2126.4	12.66	7.96	0.08	0.228	0.44	Thin disk
32923	10.0 ± 0.5	14.8 ± 0.9	210.1 ± 0.3	35.9 ± 0.5	1680.8	8.20	7.24	0.46	0.063	3.45	Thin disk
41330	9.3 ± 0.6	-17.4 ± 2.0	208.7 ± 0.6	-25.1 ± 0.8	1669.6	8.22	7.05	0.29	0.077	2.15	Thin disk
52711	6.7 ± 1.0	4.5 ± 1.9	156.9 ± 1.2	-2.7 ± 0.6	1255.2	8.00	4.26	0.02	0.306	0.22	Thick disk
67458	6.5 ± 1.0	-72.6 ± 1.1	227.8 ± 0.9	18.3 ± 0.2	1822.4	10.95	6.64	0.21	0.245	1.41	Thick disk?
202628......	6.3 ± 1.9	0.5 ± 1.5	235.8 ± 0.1	-19.5 ± 1.5	1886.4	9.39	8.00	0.23	0.080	1.51	Thin disk
207129......	6.2 ± 1.3	2.6 ± 3.2	211.9 ± 0.6	8.1 ± 3.8	1695.2	8.01	7.38	0.08	0.041	0.61	Thin disk
210918......	11.7 ± 1.1	37.0 ± 1.3	142.2 ± 1.7	-1.0 ± 1.7	1137.6	8.19	3.60	0.01	0.390	0.09	Thick disk

in the thick disk $\sigma(W) = 40$ km s^{-1} (Edvardsson et al. 1993). Thus, the W velocity of HD 41330 ($W = -25.1$ km s^{-1}) implies that it could be a member of the thick or thin disk. By considering all of the kinematic and orbital parameters (Π, Θ, W, L_z, e, and Ψ) one can classify a star as either a thin- or thick-disk star, bearing in mind that these classifications will never be 100% accurate. In general, thin-disk stars have small Π and W velocities, $\Theta \approx 220$ km s^{-1}, $L_z \approx 1700$ kpc km s^{-1}, $z_{\max} \lesssim 0.3$ kpc, $e \lesssim 0.2$, and small values of Ψ.

In Table 3 we have indicated the most probable classification of each star (thin or thick disk) *based on the kinematic and orbital parameters alone.* HD 52711 and 210918 are prototypical thick-disk stars, with rotation (Θ) velocities significantly different than the LSR, a low z-component to their orbital angular momentum (L_z), and a high eccentricity. In contrast, HD 207129 is a prototypical thin-disk star with a rotation velocity and L_z similar to the LSR, a low eccentricity, a small $z_{\max}$, and a small angle to the Galactic plane.

Three stars that are likely thin-disk stars (HD 15335, 202628, and 207129) have similar ages of $\simeq 6.4$ Gyr. The oldest stars which appear to be thin-disk stars are HD 32923 (10.0 ± 0.5 Gyr) and HD 41330 (9.3 ± 0.6 Gyr). Both of these stars have rotation velocities and L_z similar to the LSR and low eccentricities. The $z_{\max}$ of these stars is not too large (0.46 and 0.29 kpc), given that thin-disk stars have ≥ 0.325 kpc scale height exponentials (Majewski 1993). The angle of their orbits to the Galactic plane ($\Psi = 3^\circ.45$ and $2^\circ.14$) are somewhat larger than typical for thin-disk stars but not extremely so. As a result, we believe that it is likely that at least one of these two stars is a true member of the thin disk. These stars are located in a region of the CMD where the derived ages are relatively insensitive to the metallicities, colors, and absolute magnitudes. Consequently, the derived ages have very small error bars. Averaging the ages of these two stars together we find that the oldest, somewhat metal-poor thin-disk stars in the solar neighborhood have an age of 9.7 ± 0.6 Gyr.

The two stars with kinematic and orbital parameters most representative of the thick disk (HD 52711 and 210918) have quite different ages of 6.7 ± 1.0 Gyr and 11.7 ± 1.1 Gyr. The older age is similar to 47 Tuc (see below) while the younger age would suggest that there is a considerable overlap in the ages of the thin and thick disks. However, we are reluctant to reach such a conclusion based only on one star. Two other stars which might be thick-disk stars (HD 11007 and 67458) are also fairly young (6.6 ± 0.5 and 6.5 ± 1.0). However, one could argue that the kinematics and orbital parameters of these two stars are not too different from the thin disk, and so their identification as thick-disk stars is debatable. Further age determinations of more metal-poor stars ([Fe/H] < -0.25) are needed before one can conclude that their is a significant spread in the age of the thick disk.

4. 47 TUC

4.1. *Isochrone Fitting Ages*

Isochrone fitting ages were determined for the thick-disk globular cluster 47 Tuc. The photometric data for the cluster were obtained from Kaluzny et al. (1998). Heavy-element abundances in the literature indicate values of [Fe/H] $= -0.70 \pm 0.07$ (Carretta & Gratton 1997) and [Fe/H] $= -0.81$ (Brown & Wallerstein 1992). Additionally, Brown & Wallerstein (1992) indicate an enhancement in α-capture elements of [α/Fe] $= 0.22$. However, for the stellar models used in this study, opacities were available only for [α/Fe] $= 0.00$ and 0.40. Thus, isochrones were fit for abundances of [Fe/H] $= -0.70$ and -0.80, both with [α/Fe] $= 0.40$.

Isochrones were fit in a manner identical to NGC 188, simultaneously in $B-V$ and $V-I$. The value of reddening was fixed at $E(B-V) = 0.04$ (Harris 1996) and $E(V-I) = 1.25E(B-V) = 0.05$. The distance modulus was varied around $(m-M)_V = 11.37$ (Harris 1996) in order to obtain a good main sequence fit. Figure 8 shows the isochrone fits for [Fe/H] $= -0.70$ and [α/Fe] $= 0.40$. The poor simultaneous fit is likely due to the difference in α-enhancement by nearly 0.2 dex between the literature value and the models. The fits for [Fe/H] $= -0.80$ and [α/Fe] $= 0.40$, shown in Figure 9, likewise indicate a poor simultaneous fit to $B-V$ and $V-I$. In order to better reflect the total heavy-element abundance (Z) in the cluster, isochrones were generated with [Fe/H] $= -0.95$ and [α/Fe] $= 0.40$. This abundance was chosen to match the heavy element mass fraction for the values of [Fe/H] and [α/Fe] found in Brown & Wallerstein (1992), corresponding to $Z = 0.0040$. The result, shown in Figure 10, was an acceptable fit which indicated an age of 12.5 ± 0.5 Gyr for a reddening of $E(B-V) = 0.04$ and distance modulus of $(m-M)_V = 11.35$. Both the reddening and distance modulus were in good agreement with the values quoted in Harris (1996). Uncertainty due to reddening was determined by producing fits with $E(B-V) = 0.03$ and 0.05. These fits indicated ages of 14 ± 0.5 and 11.5 ± 0.5 Gyr, respectively. Table 4 summarizes the isochrone sets and parameters used in fitting to 47 Tuc. The age used for comparison to the other clusters and field stars was 12.5 ± 1.5 Gyr, as indicated and includes the uncertainty due to reddening.

4.2. $\Delta V_{\rm HB}^{\rm BTO}$ *Ages*

Age determinations were also made using the $\Delta V_{\rm HB}^{\rm BTO}$ method described in CSA. The $\Delta V_{\rm HB}^{\rm BTO}$ determination method is theoretically robust but requires a well-defined horizontal branch not present in the CMDs of open clus-

TABLE 4

ISOCHRONE FIT PARAMETERS FOR 47 TUC

[Fe/H]	[α/Fe]	$(m-M)_V$	E$(B-V)$	E$(V-I)$	Age (Gyr)
-0.80......	0.40	13.45	0.04	0.05	No simultaneous fit
-0.70......	0.40	13.40	0.04	0.05	No simultaneous fit
-0.95......	0.40	13.50	0.04	0.05	12.5 ± 0.5
-0.95......	0.40	13.28	0.03	0.0375	14 ± 0.5
-0.95......	0.40	13.42	0.05	0.0625	11.5 ± 0.5

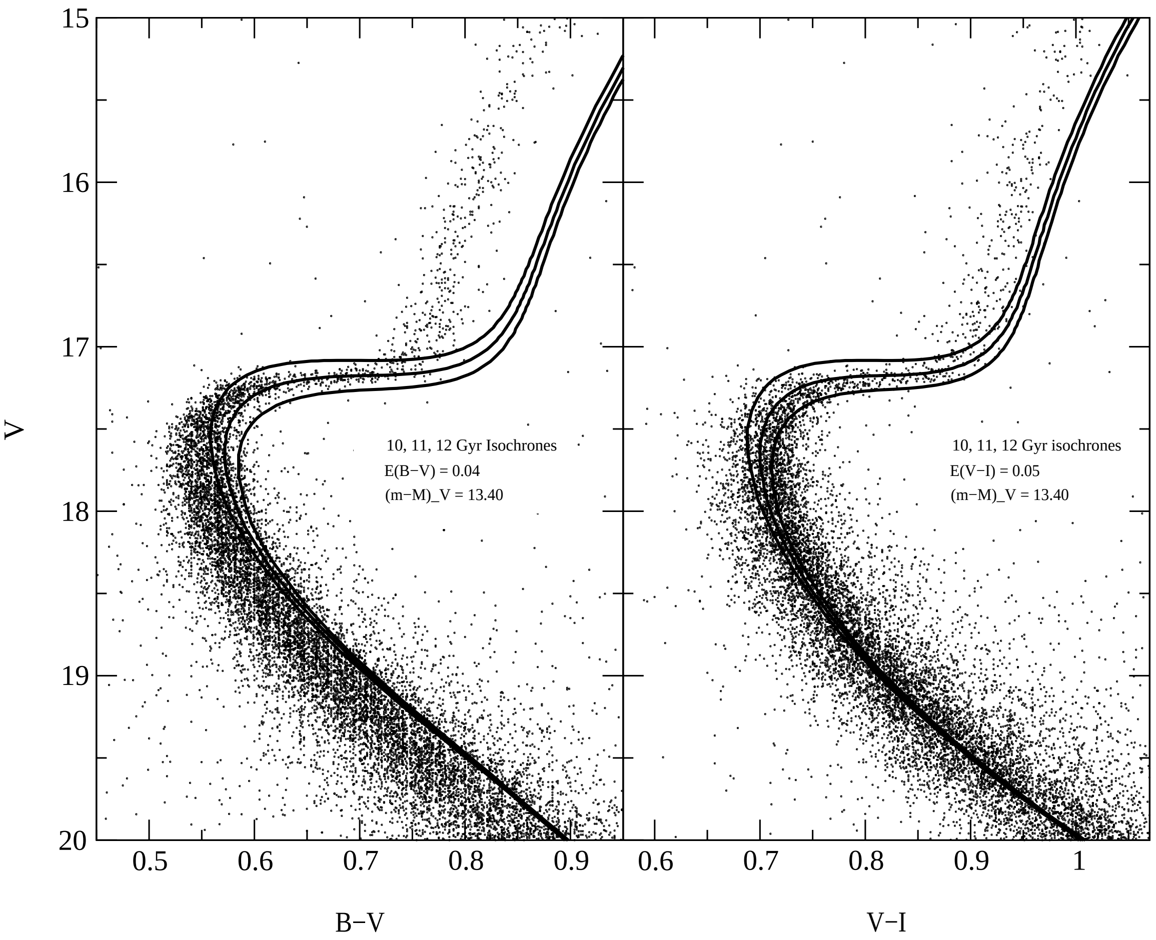

FIG. 8.—The 10, 11, and 12 Gyr isochrones with [Fe/H] = -0.70 and [α/Fe] = $+0.40$ fit to the CMD for 47 Tuc

ters. In order to compare the $\Delta V_{\rm HB}^{\rm BTO}$ ages in CSA with the isochrone fitted ages in this paper, the age of 47 Tuc was determined using both methods, and all ages were calculated relative to 47 Tuc. The observed value for $\Delta V_{\rm HB}^{\rm BTO}$ in the CMD for 47 Tuc was 3.18 ± 0.04 mag. The theoretical value of $V_{\rm HB}$ was calculated using $M_v({\rm RR}) = 0.23([{\rm Fe/H}] + 1.6) + 0.56$ (CSA) and corrected for the fact that the HB was only apparent redward of the RR Lyrae instability strip in 47 Tuc. This correction was determined using the theoretical HB models of Demarque et al. (2000). Using the [Fe/H] = -0.95, [α/Fe] = $+0.40$ isochrones yielded an age of 13.5 Gyr. The [Fe/H] = -0.70, [α/Fe] = $+0.40$ isochrones yielded an age of 12.2 Gyr. 47 Tuc has [α/Fe] = $+0.22$ (Brown & Wallerstein 1992) and [Fe/H] = -0.70 ± 0.07 (Carretta & Gratton 1997), which gives a Z value intermediate between the above two isochrones sets. For this reason, we average the two ages and adopt an $\Delta V_{\rm HB}^{\rm BTO}$ age for 47 Tuc of 12.9 ± 0.7 Gyr.

The age determined from the $\Delta V_{\rm HB}^{\rm BTO}$ is 0.4 Gyr older than that determined from the isochrone fits. This small difference in age is well within the estimated error in our isochrone fit age. As the $\Delta V_{\rm HB}^{\rm BTO}$ age estimate is expected to yield more accurate absolute ages than isochrone fitting, we will assume an absolute age of 12.9 Gyr for 47 Tuc. However, when determining the relative age of 47 Tuc to the old thin disk, we will use the isochrone fitting age of 47 Tuc, as the open clusters and *Hipparcos* field stars had their ages determined using isochrone fitting.

5. SUMMARY AND DISCUSSION

The age of 47 Tuc (12.9 ± 0.7) Gyr provides a reliable estimate for the age of the thick disk. The results for the various relative stellar ages determined in this study are summarized in Table 5. This table includes the age for NGC 6791 from CGL and the ages of three inner halo globular clusters (NGC 6652, NGC 1851, and M107) investigated by CSA. The results from CSA indicate that star formation in the inner halo began roughly at the same time as the thick disk. All three of the studies discussed here (CSA, CGL, and this study) used the same input physics and distance scale, allowing for a relative age comparison between all clusters in the studies. The relative age between the thin-disk stars and 47 Tuc in this study and CGL was determined using the isochrone fitting ages. Relative ages between 47 Tuc and the inner halo were determined using the $\Delta V_{\rm HB}^{\rm BTO}$ method. The globular cluster 47 Tuc was used as a “ bridge ” between the studies, as its age was determined using both the isochrone fitting and $\Delta V_{\rm HB}^{\rm BTO}$ methods.

The relative ages determined in this paper indicate that NGC 188 was formed 6.0 ± 1.8 Gyr after 47 Tuc. The oldest solar-metallicity *Hipparcos* field stars were formed 5.0 ± 1.7 Gyr after 47 Tuc. Both of these results suggest that the solar-metallicity stars in the thin disk were formed significantly later than the thick disk. Simply averaging these results suggests that solar-metallicity stars (in the solar neighborhood) started to form 5.5 ± 1.2 Gyr after the thick

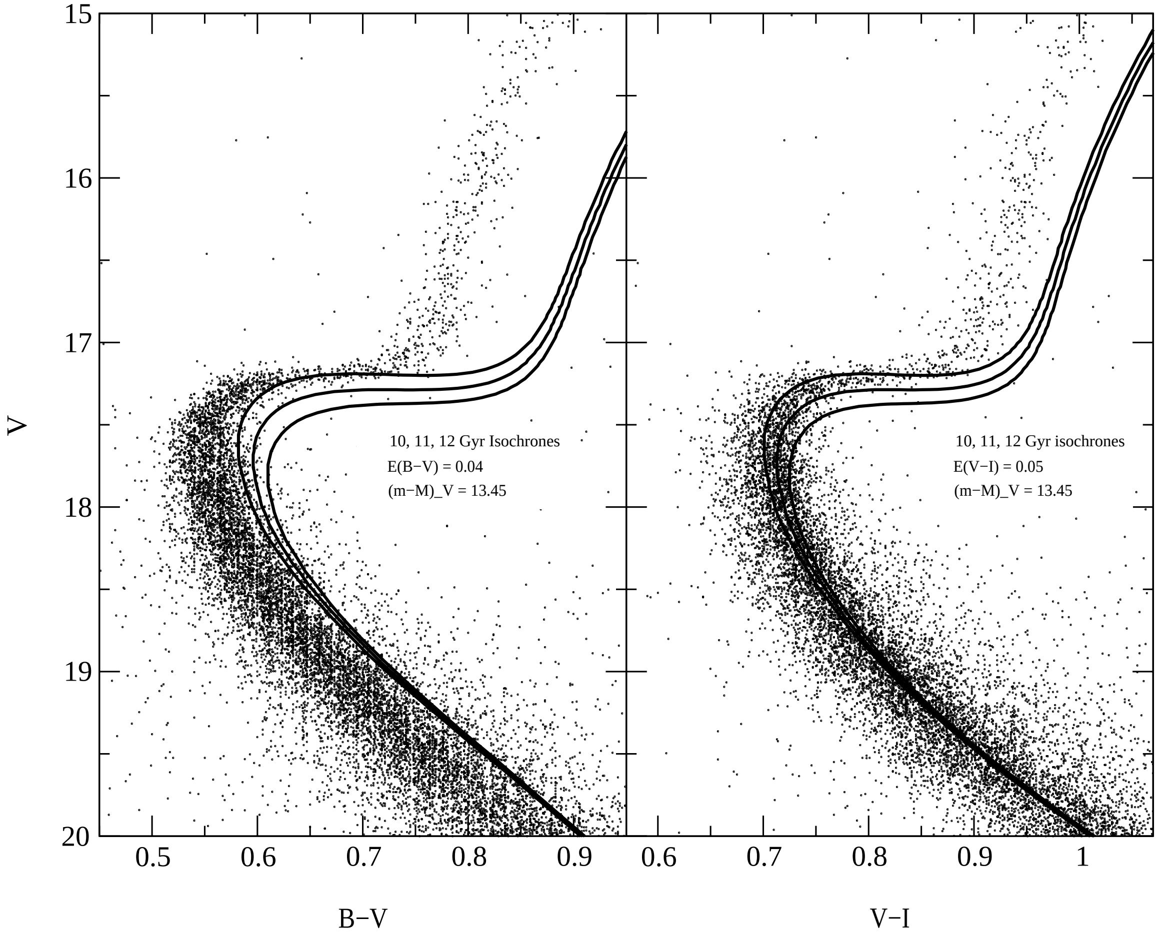

FIG. 9.—The 10, 11, and 12 Gyr isochrones with [Fe/H] = −0.80 and [α/Fe] = +0.40 fit to the CMD for 47 Tuc

disk. In contrast, the slightly metal-poor ([Fe/H] ≈ −0.22) solar neighborhood stars were formed 2.8 ± 1.6 Gyr after 47 Tuc. As this difference in age is less than 2 σ, it is conceivable that thin-disk stars were being born in the solar neighborhood at the same time, or shortly after, thick-disk objects like 47 Tuc were forming. The small relative ages between the thick disk and inner halo (Table 5) provide evidence that star formation in these regions began at roughly the same time. Figure 11 shows the relative ages versus metallicity of all the clusters discussed in this study.

It is interesting to note that the very metal-rich open cluster NGC 6791 is 4.0 ± 1.9 Gyr younger than 47 Tuc. This old open cluster has an orbit that makes its classification as a thin-disk object somewhat problematic. In particular, Scott, Friel, & Janes (1995) report that this cluster has a rotation velocity Θ that is 60 km s^{-1} lower than the thin disk, and it is moving radially outward with $\Pi = 100$ km s^{-1}, resulting in a orbit with a large eccentricity. However, this work assumed a considerably larger distance than was found by CGL (5.3 vs. 4.2 kpc). For this reason, we

TABLE 5

RELATIVE AGES BETWEEN OLD THIN, THICK DISK, AND HALO STARS

Object	Location	[Fe/H]	R_m (kpc)[a]	ΔAge (Gyr)	Method	Source
47 Tuc	Thick disk	−0.71	6.2	0	Isochrone fit, ΔV_{HB}^{BTO}	This paper
Field stars	Thick disk	−0.18	5.9	−0.8 ± 1.9	Isochrone	This paper
NGC 6791......	Thick disk?	+0.40	6.6	−4.0 ± 1.9	Isochrone fit	CGL
Field stars	Thin disk	−0.22	7.6	−2.8 ± 1.6	Isochrone	This paper
Field stars	Thin disk	0.00	8.0	−5.0 ± 1.7	Isochrone	This paper
NGC 188	Thin disk	−0.05	10.1	−6.0 ± 1.8	Isochrone fit	This paper
M107............	Inner halo	−1.04	2.8	+1.1 ± 1.3	ΔV_{HB}^{BTO}	CSA
NGC 1851......	Inner halo	−1.22	18.0	−2.5 ± 1.2	ΔV_{HB}^{BTO}	CSA
NGC 6652......	Inner halo	−0.96	(2.0)	−1.2 ± 1.7	ΔV_{HB}^{BTO}	CSA

[a] $R_m = (R_{apo} + R_{per})/2$ (median distance from the Galactic center), determined from the stellar orbits (§ 3.3 for the field stars; § 5 for NGC 6791; Dinescu et al. 1999 for the globular clusters; and Carraro and Chiosi 1994 for NGC 188). The numbers in parentheses for NGC 6652 is its R_{GC} value, as orbital information does not exist for this cluster.

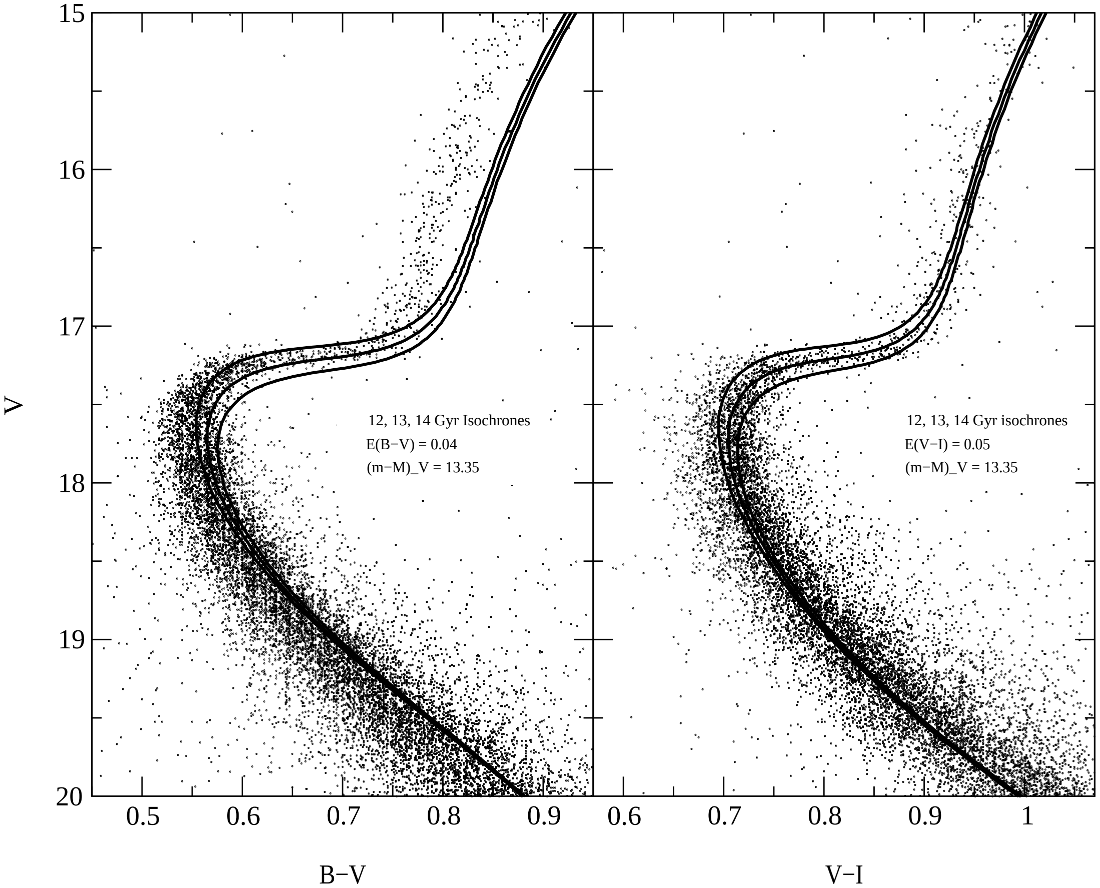

FIG. 10.—The 12, 13, and 14 Gyr isochrones with [Fe/H] = -0.95 and [α/Fe] = $+0.40$ fit to the CMD for 47 Tuc

have calculated the kinematic and orbital parameters of NGC 6791 using the distance found by CGL (4.2 kpc), the radial velocity from Peterson & Green (1998) (47 ± 1 km s^{-1}), and the preliminary proper motions from Cudworth (1994). We find the following: $\Pi = 88 \pm 14$ km s^{-1}; $\Theta = 165 \pm 10$ km s^{-1}; $W = -6 \pm 17$ km s^{-1}; $L_z = 1266$ kpc km s^{-1}; $R_{\rm apo} = 9.1$ kpc; $R_{\rm per} = 4.2$ kpc; $z_{\rm max} = 0.8$ kpc; $e = 0.37$; and $\Psi = 6\overset{\circ}{.}6$. The orbit is fairly eccentric, with a low rotation velocity and a reasonably large $z_{\rm max}$, suggesting that NGC 6791 is a thick-disk object. However, Scott et al. (1995) caution that clusters like NGC 6791 may simply be in the wings of the kinematic distribution of the thin disk, and its peculiar orbit is what has allowed it to survive.

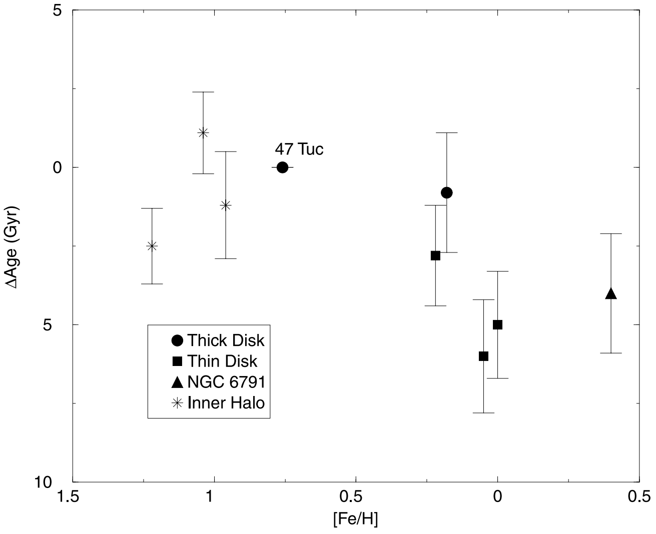

FIG. 11.—Ages relative to 47 Tuc as a function of metallicity for the stars and clusters discussed in this paper.

Table 5 includes the median distance of the stars/clusters from the Galactic center (R_m) based upon the orbits of the stars/clusters. We see that all of the thick-disk and thin-disk objects we have discussed in this paper cover a relatively modest range in their distance from the Galactic center (5.9 kpc $\leq R_m \leq$ 10.1 kpc). Thus, all of these objects were born at reasonably similar Galactocentric distances, so their ages reflect the star formation in small region of the galaxy. The three inner halo clusters discussed by CSA turn out to have a fairly wide range in R_m (2–18 kpc). The fact that the 47 Tuc has a similar age to these clusters suggests that globular cluster formation was occurring at about the same time over a wide range of Galactocentric distances.

There have been many proposed scenarios of galactic formation. These scenarios include the free-fall collapse of a protogalactic cloud, originally proposed by Eggen, Lynden-Bell, & Sandage (1962), and the merger of independently formed stellar systems (Searle 1977; Searle & Zinn 1978). Although no definitive conclusions about galactic formation can be drawn from the results of this study, some possibilities can be presented. The similarity in age between the inner halo and thick disk indicates that if the thick disk was formed from the gravitational collapse of the halo, this collapse occurred on short timescales (<1 Gyr). There is a clear age gap of several Gyr between solar-metallicity stars in the nearby thin disk and the thick disk (47 Tuc). The age gap between moderately metal-poor thin-disk stars and the thick disk is much smaller, and the present uncertainties in the age determinations allow for the possibility that the thin disk formed immediately after (<1 Gyr) after the thick disk and halo.

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