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THE AGE OF THE INNER HALO GLOBULAR CLUSTER NGC 6652[1]

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ABSTRACT

Hubble Space Telescope (V, I) photometry has been obtained for the inner halo globular cluster NGC 6652. The photometry reaches ∼4 mag below the turnoff and includes a well-populated horizontal branch. This cluster is located close to the Galactic center, at $R_{\rm GC} \simeq 2.0$ kpc, with a reddening of $E(V-I) = 0.15 \pm 0.02$, and has a metallicity of $[{\rm Fe/H}] \simeq -0.85$. Based upon $\Delta V_{\rm HB}^{\rm SGB}$, NGC 6652 is 11.7 ± 1.6 Gyr old. Using $\Delta V_{\rm HB}^{\rm SGB}$, precise differential ages for 47 Tuc (a thick disk globular cluster), M107, and NGC 1851 (both halo clusters) were obtained. NGC 6652 appears to be the same age as 47 Tuc and NGC 1851 (within ± 1.2 Gyr), while there is a slight suggestion that M107 is older than NGC 6652 by 2.3 ± 1.5 Gyr. As this is a less than 2 σ result, this issue needs to be investigated further before a definitive statement regarding the relative age of M107 and NGC 6652 may be made.

Key words: color-magnitude diagrams — Galaxy: formation — globular clusters: general — globular clusters: individual (NGC 6652)

1. INTRODUCTION

NGC 6652 is a compact globular cluster that is projected near the Galactic center at $l = 1\overset{\circ}{.}53$ and $b = -11\overset{\circ}{.}38$ (Harris 1996). A color-magnitude diagram (CMD) for this cluster was presented by Ortolani, Bica, & Barbuy (1994, hereafter OBB), who determined a number of cluster parameters, including $[{\rm Fe/H}] \approx -0.9$, $E(B-V) = 0.10 \pm 0.02$, $\langle V_{\rm HB} \rangle = 15.85 \pm 0.04$, and $\Delta V_{\rm HB}^{\rm TO} = 3.35 \pm 0.16$. The small value of $\Delta V_{\rm HB}^{\rm TO}$ suggested that NGC 6652 is younger than the average Galactic halo cluster. Adopting an absolute horizontal-branch (HB) magnitude of $M_V({\rm HB}) = +0.7$, OBB determined $R_{\rm GC} = 2.1$ kpc. Its proximity to the Galactic center, reasonably low metallicity, and small reddening make NGC 6652 somewhat unique. It is an inner halo globular cluster for which one can obtain an accurate relative age with respect to other halo clusters.

Based upon its metallicity, radial velocity, HB type, and position in the Galaxy, Zinn (1993) classified NGC 6652 as an old halo cluster. This is at odds with OBB's suggestion (based on the turnoff magnitude) that NGC 6652 is younger than the average halo cluster. Because NGC 6652 is a compact cluster located in a crowded field, the photometry near the turnoff obtained by OBB had a great deal of scatter, leading to a large error in the age determination. For this reason, we were granted *Hubble Space Telescope* (*HST*) time to obtain a deep CMD of NGC 6652, in order to clearly delineate the turnoff region and to obtain an accurate estimate of its age. The observations and data reduction procedure are presented in § 2, and the generation of the isochrones used to determine the age of NGC 6652 is discussed in § 3. The analysis of the CMD is presented in § 4, the discussion of the age of NGC 6652 is in § 5, and the summary of the results is in § 6.

2. OBSERVATIONS AND DATA REDUCTION

NGC 6652 was observed in 1997 September with the Wide Field Planetary Camera 2 (WFPC2) on *HST*. The cluster was centered on the PC1 chip. Observations were obtained with the F555W (V) filter (3 × 23 and 12 × 160 s) and the F814W (I) filter (3 × 20 and 12 × 160 s). The short exposure times were chosen to ensure good photometry at the level of the HB, while the long exposure times were picked to ensure good photometry around the turnoff and to allow for a good intercomparison between the long- and short-exposure frames. Figure 1 shows the averaged, long-exposure F555W image of the cluster. The WFPC2 images of NGC 6652 were divided into three sets of four long-exposure (160 s) F555W and F814W frames and one set of three short-exposure F555W (23 s) and F814W (20 s) frames. Each set of four long and three short exposures in a given filter was averaged using GCOMBINE in IRAF/STSDAS with cosmic-ray rejection enabled and the data-quality files used to flag defective pixels. This yielded a total of eight WFPC2 images, which were input into our photometric procedure.

We utilized the aperture photometry routines in DAOPHOT II (Stetson 1987, 1994), adopting an aperture radius of 2.5 pixels in the Planetary Camera and 2 pixels in the Wide Field Camera chips. Corrections from the small-aperture photometry to the standard 0″.5 radius were determined using 30 to 50 relatively uncrowded stars. These gave aperture corrections with typical standard deviations between 0.01 and 0.03 mag. The V and I instrumental mag-

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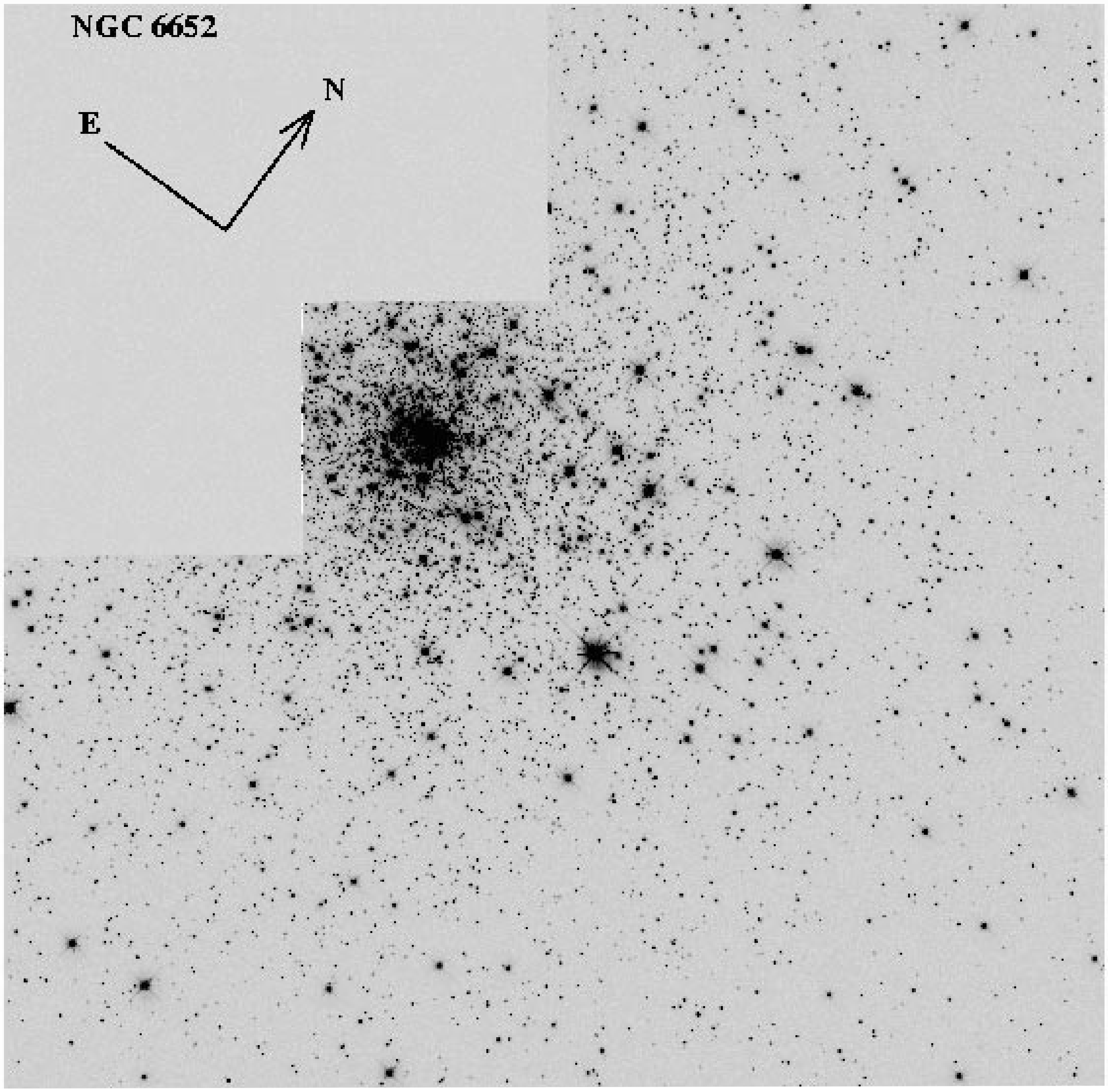

FIG. 1.—Averaged long-exposure V frame of NGC 6652

nitudes were matched to form colors and corrected to a 0″.5 radius aperture. The total instrumental magnitudes were then adjusted for exposure time and placed on the standard VI system using the coefficients in Table 7 of Holtzman et al. (1995). A correction was also applied for the well-known charge transfer efficiency problem using the formulation of Whitmore, Heyer, & Casertano (1999). Magnitudes of stars in common between the long-exposure frames were averaged together, and only stars measured on all three frame pairs were retained. The final photometry file contains stars fainter than $V = 17$ from the long-exposure frames and stars brighter than $V = 17$ from the short exposures (4832 in total). In order to ensure that the long and short exposures' magnitudes were internally consistent, the magnitude of a number of stars (approximately 10 per chip) in common between the long and short exposures were compared and the average offset determined. This average offset (0.03 mag) was then applied to the short-exposure magnitudes, implying that all of the magnitudes are on the long-exposure scale. The photometry data are presented in Table 1.

Because of its compact nature, the inner regions of NGC 6652 are crowded on the PC1 chip. The faint (long

TABLE 1

PHOTOMETRIC DATA

Chip	X (pixels)	Y (pixels)	V (mag)	$V-I$ (mag)
PC1......	420.61	462.47	14.698	1.214
	665.83	481.91	14.852	1.434
	731.93	164.93	14.929	1.362
	415.13	514.46	14.969	1.347
	290.54	521.16	15.071	1.299
	277.56	709.88	15.174	1.322
	250.74	585.43	15.413	1.303
	382.62	258.89	15.489	1.256
	487.84	607.94	15.496	1.083
	390.07	525.26	15.560	1.260
	639.05	254.91	15.623	1.245
	269.85	435.04	15.651	1.102
	446.00	487.11	15.659	1.267

NOTE.—Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

exposure) photometry within $r < 11''.5$ (250 PC pixels) of the cluster center showed considerable scatter around the turnoff region. For this reason, the long-exposure photometry in our final CMD only includes stars with $r > 11''.5$ from the cluster center. This trimmed data set includes 3790 stars with good photometry.

A careful inspection of the photometry obtained with the different chips showed no difference [$\delta(V-I) < 0.005$] in the location of the principal features (i.e., the main sequence, subgiant branch, red giant branch, and the HB) in the CMD. This indicates that the aperture corrections (applied to each chip individually) are accurate, implying that the internal errors in the photometry are very small. The external errors are set by the accuracy of the Holtzman et al. (1995) transformations to the standard system.

3. STELLAR MODELS AND ISOCHRONES

Stellar evolution tracks for masses in the range 0.50–1.1 $M_\odot$ (in 0.05 $M_\odot$ increments) were calculated using the Yale stellar evolution code (Guenther et al. 1992). These models incorporate the following physics: high-temperature opacities from Iglesias & Rogers (1996); low-temperature opacities from Kurucz (1991); nuclear reaction rates from Bahcall & Pinsonneault (1992) and Bahcall (1989); helium diffusion coefficients from Michaud & Proffitt (1993); and an equation of state that includes the Debye-Hückel correction (Guenther et al. 1992). Note that this equation of state yields stellar models that are in good agreement with those derived using the OPAL equation of state (Rogers 1994; Chaboyer & Kim 1995). The surface boundary conditions were calculated using a gray T-τ relation. The stellar models employ a solar-calibrated mixing length ($\alpha_\odot = 1.78$). The models were typically evolved from the zero-age main sequence to the upper giant branch (around $M_V \approx -1.0$) in 4000 time steps. In each time step, the stellar evolution equations were solved with a numerical accuracy exceeding 0.01%. The models did not include any overshooting beyond the formal edge of the convection zones.

The heavy-element composition of the models was chosen to reflect the observed abundance ratios in metal-poor stars (see, e.g., Lambert 1989). In particular, the α-capture elements (O, Mg, Si, S, and Ca) and Ti were enhanced by +0.4 dex, while Mn was made to be deficient by the same proportions. The solar abundances (before α-enhancement) were taken from Grevesse & Noels (1993). R. Kurucz (1999, private communication; low temperature) and C. Iglesias & F. Rogers (1999, private communication; high temperature) provided us with opacities for this specific mixture.

NGC 6652 has [Fe/H] = −0.96 on the Zinn & West (1984) scale and [Fe/H] = −0.85 on the Carretta & Gratton (1997) scale. Based upon the inclination of the red giant branch, OBB found that NGC 6652 was more metal-poor than 47 Tuc and concluded that [Fe/H] ≈ −0.9. In light of these abundance determinations, stellar models and isochrones were calculated for [Fe/H] = −1.20, −1.00, −0.85, and −0.70. The most metal-poor isochrone was calculated to facilitate an age comparison with somewhat more metal-poor halo clusters (see § 5.2). To explore the effect of the α-element enhancement, at [Fe/H] = −0.85, scaled solar-abundance models and isochrones were calculated in addition to the α-element–enhanced isochrones.

Our calibrated solar model had an initial solar helium abundance of $Y_\odot = 0.263$ and a heavy-element mass fraction of $Z_\odot = 0.0182$. Assuming a primordial helium abundance of $Y_p = 0.234$ (Olive, Steigman, & Skillman 1997), our calibrated solar model implies $\Delta Y/\Delta Z = 1.59$. Thus, the helium abundance for the models was determined using

$$Y = 0.234 + 1.59Z . \quad (1)$$

There is some evidence that 47 Tuc has a solar helium abundance (Salaris & Weiss 1998). As 47 Tuc is being used as a comparison cluster in this study, for [Fe/H] = −0.70 stellar models and isochrones were calculated for a solar helium abundance ($Y_\odot = 0.263$) in addition to the helium abundance implied by equation (1), $Y = 0.245$. The evidence for a solar helium abundance in 47 Tuc is not strong, and indeed Dorman, VandenBerg, & Laskarides (1989) found $Y \approx 0.24$ from fitting the HB morphology.

The isochrones were constructed by interpolating among the evolutionary tracks using the method of equal evolutionary points (Prather 1976) for the age range 6–18 Gyr, in 1 Gyr increments. The isochrones were transformed from the theoretical ($\log L$, $\log T_{\rm eff}$)-plane to observed colors and magnitudes using color transformations and bolometric corrections based on the Kurucz (1993) model atmospheres. The transformations used here were kindly supplied to us by S. Yi (1999, private communication), who derived them for a wide range of metallicities, using a procedure similar to that described by Bessell, Castelli, & Plez (1998). At solar metallicities, the Yi tables agree with Bessell et al.'s Table 1 to within ∼0.007 mag in $B-V$ and ∼0.004 in $V-I$ over the range of colors appropriate for old clusters. In the Yi tables, the solar colors are $(B-V)_\odot = 0.670$ and $(V-I)_\odot = 0.718$. Bessell et al. (1998) extensively tested their Kurucz-based (ATLAS9) colors for solar metallicities and found that all indexes agreed extremely well with observations for $T_{\rm eff} > 4250$ K (corresponding to $V-I \simeq 1.3$ at [Fe/H] = −0.85).

Weiss & Salaris (1999) recently studied the issue of color transformations for isochrones in the VI plane. They concluded that on the main sequence the color transformations based on the ATLAS9 models were a good choice. For the giant branch, Weiss & Salaris preferred to use empirical color relations. However, an inspection of their Figure 5 indicates that the color transformation based upon the ATLAS9 models is in good agreement with the empirical relations preferred by Weiss & Salaris (1999). Thus it appears that our choice of the Yi color table is a reasonable one, in good agreement with presently available data.

Figure 2 displays the 12 Gyr isochrones for the different compositions used in this paper. It is interesting to note that changing the helium abundance from $Y = 0.245$ (given by eq. [1]) to the solar value ($Y_\odot = 0.263$) has very little effect on the isochrone. Thus, the exact choice of Y will not affect the derived ages. In contrast, changing the [α/Fe] ratio by 0.4 dex has a substantial effect on the isochrones (larger than changing [Fe/H] by 0.15 dex), and so the uncertainty in the actual value of [α/Fe] in NGC 6652 will lead to a substantial uncertainty in the derived age.

In § 5.1, the isochrones are fitted to the CMD of NGC 6652. This fitting procedure assumes that the location of the unevolved main sequence predicted by the theoretical isochrones is accurate. To test this assumption, the *Hipparcos* Catalogue was searched for stars that (1) have $\sigma_\pi/\pi < 0.10$, (2) are fainter than $M_V \simeq 5.5$, and (3) are not known or suspected *Hipparcos* binaries or variables. This resulted in a

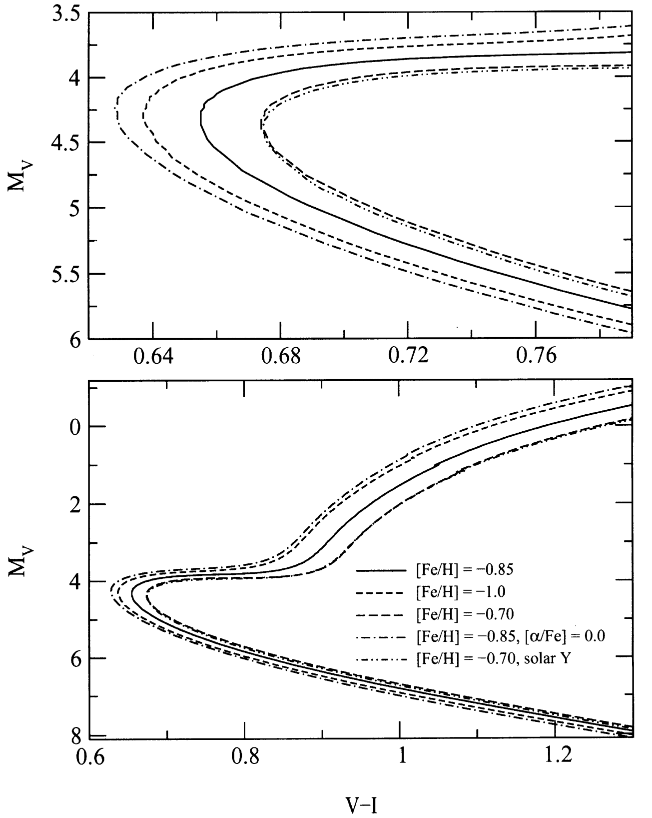

FIG. 2.—The $(M_V, V-I)$ CMD of the 12 Gyr theoretical isochrones used in this paper. Except as noted in the key, the isochrones have $[\alpha/\mathrm{Fe}] = +0.4$ and a helium mass fraction Y given by eq. (1). The bottom panel shows the isochrones over the entire range of validity of the color transformation ($V-I \leq 1.3$), while the top panel is an expanded view near the turnoff.

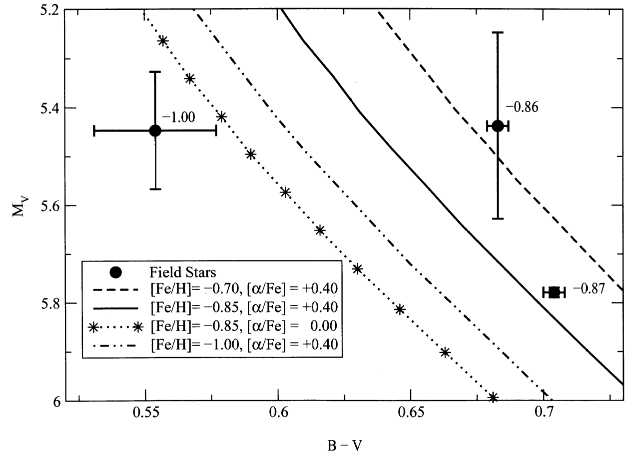

FIG. 3.—Comparison of unevolved, single stars in the *Hipparcos* Catalogue (with $-1.05 \leq [\mathrm{Fe/H}] \leq -0.65$ and good parallaxes, $\sigma_\pi/\pi < 0.10$) with the isochrones presented in this paper. Each of the stars (HD 6582, 193901, 216179) has been labeled with its [Fe/H] value determined from high-dispersion spectroscopy.

list of 2618 stars, of which the great majority have near-solar metallicity. As we are interested in stars with a similar metallicity to NGC 6652's, we require stars with $-1.05 \leq [\mathrm{Fe/H}] \lesssim -0.65$. To identify these metal-poor stars in the *Hipparcos* sample, we have cross identified the above *Hipparcos* subsample with the 1996 high-resolution spectroscopic catalog of Cayrel de Strobel et al. (1997), and more recent papers that give high-dispersion abundance analyses of metal-poor stars: Reid (1998), Clementini et al. (1999), Tomkin & Lambert (1999), and Carretta, Gratton, & Sneden (2000). Any stars that were known or suspected binaries and whose companions would contribute a significant flux in the *BVI* passbands were removed from our final list. In total, only three stars in the *Hipparcos* Catalogue pass our stringent selection criteria. A comparison between these stars and our isochrones is shown in Figure 3. Unfortunately, we were unable to locate Kron-Cousins $V-I$ colors for these stars, so the comparison is only shown in $B-V$. The small number of stars prevents us from reaching any definitive conclusions based upon this comparison. However, we note that the star with the most accurate parallax (with $[\mathrm{Fe/H}] = -0.87$) lies close to our $[\mathrm{Fe/H}] = -0.85$ isochrone. Given the typical uncertainties in the abundance determinations, $\sigma_{[\mathrm{Fe/H}]} \approx 0.08$ dex, it appears that our isochrones correctly predict the location of the unevolved main sequence around $[\mathrm{Fe/H}] = -0.85$.

Further support that our isochrones correctly predict the location of the unevolved main sequence comes from the following additional tests: (1) A comparison between single field stars with good parallaxes from *Hipparcos* and our isochrones found good agreement in the range $-1.5 \leq [\mathrm{Fe/H}] \leq -1.0$ (Chaboyer et al. 1998). This study was interested in metal-poor globular clusters and so did not consider stars with $[\mathrm{Fe/H}] > -1.0$. (2) With no adjustable parameters, our isochrones provide a good match to the main sequence of the Hyades ($[\mathrm{Fe/H}] = +0.15$) derived from *Hipparcos* parallaxes (Chaboyer, Green, & Liebert 1999). (3) We are using a solar-calibrated mixing length, which implies that our models are in good agreement with main-sequence solar-metallicity stars. Clearly, these tests are not definitive, as the number of single, metal-poor stars with well-determined parallaxes is relatively small. However, these tests do show that the isochrones are not in gross disagreement with the observations, and they suggest that at the level of approximately ± 0.10 mag, the isochrones correctly predict the location of the unevolved main sequence in relatively metal-poor stars ($-1.5 \leq [\mathrm{Fe/H}] \leq 0.65$).

4. ANALYSIS OF THE COLOR-MAGNITUDE DIAGRAM

The $(V, V-I)$ CMD for NGC 6652 obtained from the *HST* data is shown in Figure 4. As discussed in § 2, the data from the long exposures ($V \geq 17$) do not include stars with $r < 11''.5$. The CMD clearly delineates the major evolutionary sequences from ~ 4 mag below the turnoff to ~ 1.5 mag above the HB. An inspection of the CMD leads to the following values:

$$V_{\mathrm{ZAHB}} = 16.00 \pm 0.03 \;, \quad \langle V_{\mathrm{HB}} \rangle = 15.96 \pm 0.04 \;,$$

$$(V-I)_{\mathrm{TO}} = 0.818 \pm 0.004 \;,$$

$$V_{\mathrm{TO}} = 19.55 \pm 0.07 \;, \quad V_{\mathrm{SGB}} = 19.09 \pm 0.03 \;,$$

$$\Delta V_{\mathrm{HB}}^{\mathrm{TO}} = 3.59 \pm 0.08 \;, \quad \Delta V_{\mathrm{HB}}^{\mathrm{SGB}} = 3.13 \pm 0.05 \;.$$

All errors are estimated internal errors, which reflect the scatter of the photometry. The magnitude of the HB was estimated at the midpoint in the color of the HB (around $V-I \simeq 1.05$). The point V_{SGB} was defined by Chaboyer et al. (1996) to be the magnitude of the point on the subgiant branch (SGB) that is 0.05 mag redder than the turnoff. As discussed by Chaboyer et al. (1996), it is an excellent age

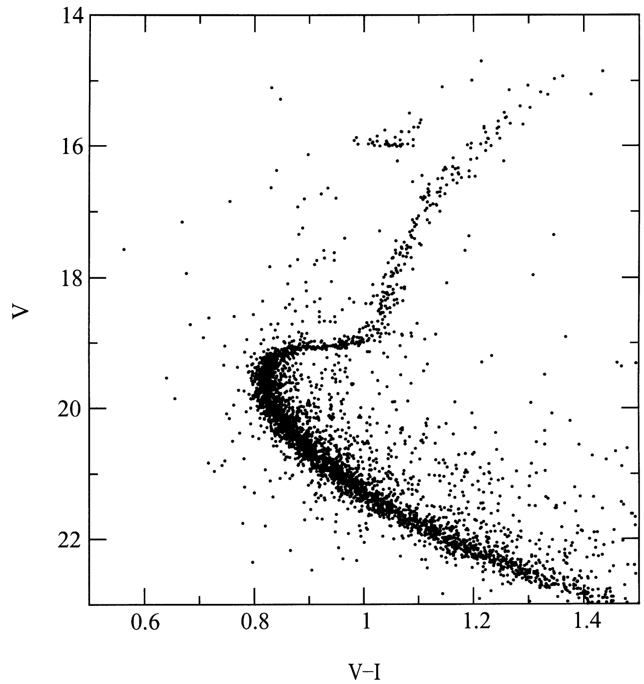

FIG. 4.—The $(V, V-I)$ CMD of NGC 6652

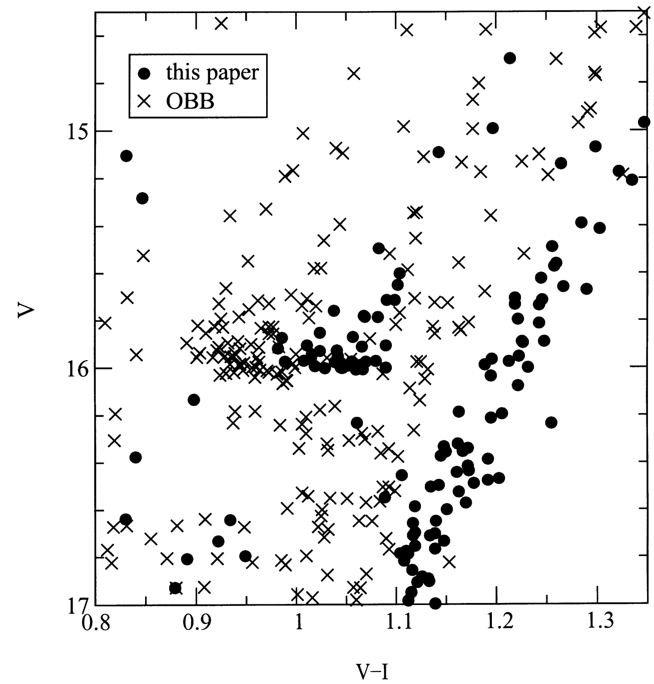

FIG. 5.—Comparison of the photometry near the HB presented in this paper with that presented by OBB.

indicator for old stellar systems. Recently, Ferraro et al. (1999) have presented a homogeneous catalog of HB parameters. They stress that as a result of the rapid evolution away from the zero-age horizontal branch (ZAHB), the observed lower envelope of the HB does not coincide with the ZAHB from theoretical models. The V_{ZAHB} level reported above is the lower envelope of the observations. Using their theoretical HB models, Ferraro et al. (1999) determined that a correction of approximately $+0.04$ mag needs to be applied to the observed lower envelope of the NGC 6652 horizontal branch. If such a correction is necessary in our data set, then $V_{ZAHB} = 16.04 \pm 0.03$ using the methodology of Ferraro et al. (1999).

The $(V, V-I)$ CMD of OBB shows considerable scatter around the turnoff, so it is difficult to compare our photometry with theirs at the fainter magnitudes. However, it is possible to compare our photometry around the level of the HB. This comparison is shown in Figure 5. From this figure, it is clear that the level of the ZAHB is 0.03 mag fainter in the photometry of OBB as compared with the photometry presented in this paper. In addition, the color of the red giant branch (RGB) at the level of the HB as found by OBB is 0.08 mag bluer than the RGB color in our photometry. The reason or reasons for these differences are unclear. The differences are considerably larger than our estimated errors because of the aperture corrections, and they are larger than the estimated errors in the *HST* $(V, V-I)$ calibration. To investigate this further, F439W and F555W (B, V) GO 6095 observations (Sosin et al. 1997) were retrieved from the *HST* archive, and the data were reduced in exactly the same manner as was done with our $(V, V-I)$ data. The results of this comparison are plotted in Figure 6. From this, one can see that the $B-V$ RGBs are in better agreement between the two data sets than those in $V-I$. There is a slight offset in the level of the ZAHB, with the OBB photometry being *brighter* than the *HST* photometry. From the OBB $B-V$ data, we obtained $\langle V_{HB} \rangle = 15.85$ and $(B-V)_g = 1.11$ (color of the RGB at the level of the HB). From the VI data presented by OBB, we find $\langle V_{HB} \rangle = 15.95$ and $(V-I)_g = 1.11$. The disagreement between the level of the HB in the $B-V$ and $V-I$ data sets suggests that the OBB data are not internally consistent. In the $B-V$ and $V-I$ *HST* data, the level of the HB agrees to within 0.01 mag. In addition, OBB found $(B-V)_g = (V-I)_g$. In general, the $V-I$ color is redder than the $B-V$ color. Our isochrones show this trend, as does the

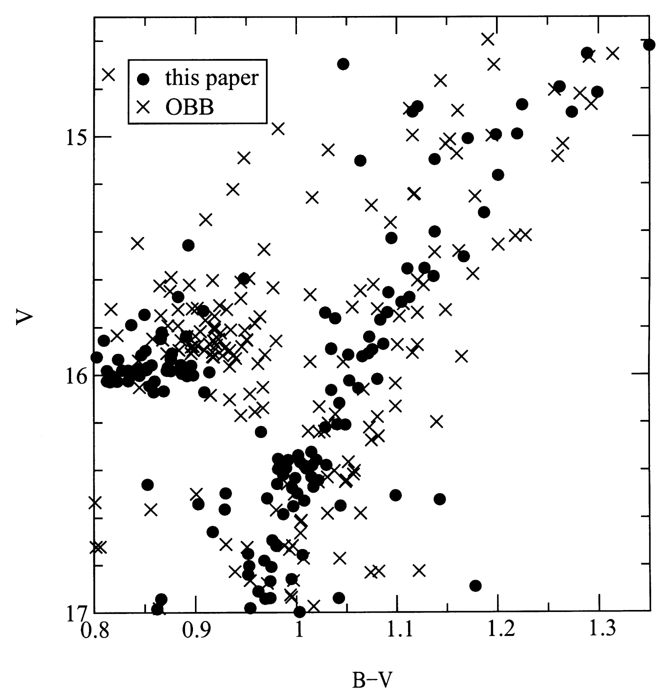

FIG. 6.—Comparison of the $(V, B-V)$ photometry measured from archival *HST* WFPC2 observations of NGC 6652 with that presented by OBB in the region of the HB.

observational transformation for globular cluster giant branches from $B-V$ to $V-I$ presented by Zinn & Barnes (1996). From the *HST* data, we find $(B-V)_g = 1.06$ and $(V-I)_g = 1.22$. The Zinn & Barnes transformation applied to the *HST* $B-V$ data implies $(V-I)_g = 1.24$, in good agreement with the measured value.

Finally, we note that OBB determined a brighter turnoff magnitude, $V_{\rm TO} \approx 19.2 \pm 0.15$, and found $\Delta V_{\rm HB}^{\rm TO} \approx 3.35 \pm 0.16$. These values differ by 2.5 σ and 2.1 σ, respectively, from the values obtained with our photometry. As the turnoff magnitude is a primary age indicator, the fainter turnoff found in our photometry implies an older age for NGC 6652.

5. THE AGE OF NGC 6652

5.1. *Isochrone Fitting*

A variety of methods may be used to determine the age of a globular cluster, each with its advantages and disadvantages. Perhaps the simplest method is to fit an isochrone to the data by adjusting the distance modulus and reddening (within their known uncertainties) such that the mean locus of observed points is matched to the theoretical isochrone. Because of uncertainties in surface boundary conditions, color–effective temperature transformations, and the treatment of convection, the colors of the isochrones may be in error. This is particularly true on the RGB, where a modest change in the choice of the mixing length can lead to a large change in the predicted RGB colors. For this reason, when fitting the isochrones to the data, only the main-sequence and turnoff regions were used in the fit. Such a fit is shown in Figure 7 for our [Fe/H] $= -0.85$, [α/Fe] $= +0.4$ isochrones. The best-fitting isochrone has an age of 13 Gyr. The best-fit distance modulus [$(m-M)_V = 15.15$] implies M_V(HB) $= 0.81 \pm 0.04$. This is in good agreement with the distance modulus derived using the preferred M_V(RR) relation given by Chaboyer (1999), which implies M_V(HB) $= 0.73 \pm 0.12$ at the metallicity of NGC 6652. The best-fit reddening of $E(V-I) = 0.15$ corresponds to $E(B-V) = 0.12$ and is in reasonable agreement with the value obtained by OBB [$E(B-V) = 0.10 \pm 0.02$]. The Schlegel, Finkbeiner, & Davis (1998) reddening maps based on *IRAS*/DIRBE dust emission yield $E(B-V) = 0.114$ for NGC 6652, also in good agreement.

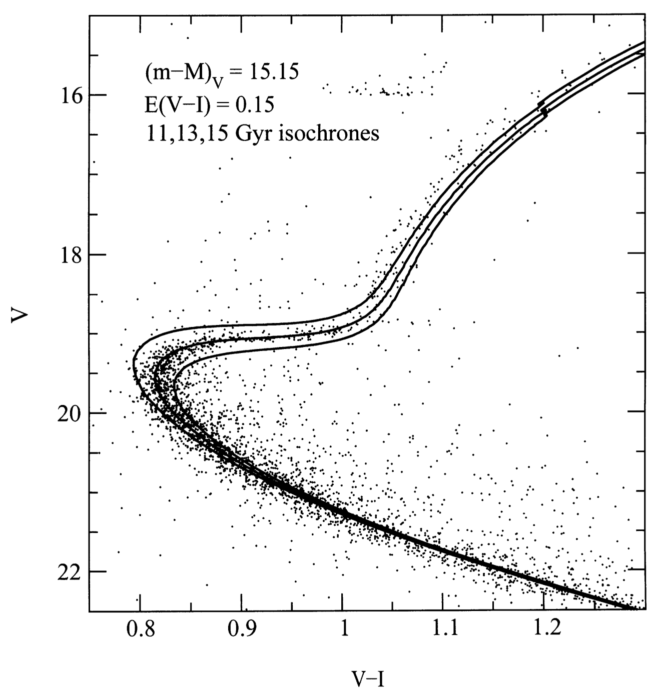

FIG. 7.—Fit of the [Fe/H] $= -0.85$, [α/Fe] $= +0.4$ isochrones to the data.

When performing main-sequence fitting, there is considerable degeneracy between the derived distance modulus and the reddening. For example, changing the reddening to $E(V-I) = 0.13$ leads to a derived distance modulus of $(m-M)_V = 15.05$ and an age of 15 Gyr. Assuming an uncertainty in the reddening of ± 0.02 mag leads to an uncertainty in the derived distance modulus of ± 0.10 mag and in the age of ± 2 Gyr. In fitting the isochrones to the data, the degeneracy between the distance modulus and reddening was broken by examining the region around the turnoff and the subgiant branch to obtain the best fit shown in Figure 7. This allows us to determine our preferred values for the age and distance modulus, but it is important to realize that the errors in these best-fit parameters are rather large.

The implicit assumption in this fitting procedure is that the location of the unevolved main sequence predicted by the theoretical isochrones is accurate. The validity of this assumption was discussed at the end of § 3, where we conclude that at the level of approximately ± 0.10 mag the isochrones correctly predict the location of the unevolved main sequence in relatively metal-poor stars ($-1.5 \leq$ [Fe/H] ≤ 0.6). Combining the uncertainty in the theoretical location of the unevolved main sequence with the uncertainty in our fitting procedure due to errors in the reddening leads us to conclude that the age and distance modulus we derive from isochrone fitting are accurate to $\pm 15\%$ and ± 0.15 mag, respectively.

Fits of the isochrones with the different compositions discussed in § 3 were also performed. In all cases, the fits in the turnoff, SGB, and RGB regions were considerably inferior to the fit shown in Figure 7, which uses our best estimate for the composition ([Fe/H] $= -0.85$, [α/Fe] $= +0.4$). The best-fitting parameters for the various isochrone fits are shown in Table 2. Given that the other compositions yielded inferior fits to the data, we prefer to take as our central values those found from the isochrones with the best estimate for the compositions. Taking into account the uncertainty in the reddening, along with the variation in derived parameters shown in Table 2, isochrone fitting implies the following parameters for NGC 6652: $(m-M)_V = 15.15 \pm 0.15$, $E(V-I) = 0.15 \pm 0.02$, and an age of 13 ± 2 Gyr. As a consequence of uncertainties in the theoretical models and the reddening of NGC 6652, the age we derive based upon isochrone fitting has a relatively large error. The isochrone-fitting procedure serves as a first-order test of our models (ensuring they are in reasonable agreement with the observations) and allows us to determine an age for the cluster that is independent of the HB.

5.2. $\Delta V_{\rm HB}^{\rm SGB}$ *Ages*

A more robust determination of the cluster's age may be found using the difference in magnitude of the point on the subgiant branch that is 0.05 mag redder than the turnoff and the HB ($\Delta V_{\rm HB}^{\rm SGB}$; Chaboyer et al. 1996). The magnitude of the SGB point as a function of age is determined from the

TABLE 2

Isochrone Fit Parameters

[Fe/H]	[α/Fe]	Y	$(m-M)_V$	$E(V-I)$	Age (Gyr)	Note
−0.85......	0.40	0.2420	15.15	0.15	13	Best fit
	0.40	0.2420	15.05	0.13	15	Good fit
	0.00	0.2379	15.09	0.17	14	Poor fit to RGB
−1.00......	0.40	0.2395	15.13	0.16	14	Poor fit to SGB
−0.70......	0.40	0.2453	15.12	0.12	13	Poor fit to RGB
	0.40	0.2630	15.12	0.12	13	Poor fit to RGB

isochrones. The theoretical value of M_V(HB) was calculated using M_V(RR) = 0.23([Fe/H] + 1.6) + 0.56 (Chaboyer 1999) and corrected for the fact that the HB was only apparent redward of the RR Lyrae instability strip in NGC 6652. This correction was determined using the theoretical HB models of Demarque et al. (2000). From this procedure, we obtain an age of 11.7 ± 1.6 Gyr, where the error includes a ±0.1 dex uncertainty in [Fe/H], the observational error in determining $\Delta V_{\rm HB}^{\rm SGB}$, and the error in our adopted M_V(RR) calibration. This may be compared with the age of 13 ± 2 Gyr that was found from isochrone fitting. This age difference of 1.3 ± 2.6 Gyr is well within our errors. From the theoretical point of view, $\Delta V_{\rm HB}^{\rm SGB}$ is a more robust age indicator than isochrone fitting, as it does not depend critically on the (uncertain) colors of the theoretical models (Chaboyer et al. 1996). Thus, we prefer the use of the $\Delta V_{\rm HB}^{\rm SGB}$ age indicator. Ignoring the error in the zero-point calibration of our M_V(RR) relation yields a precise *relative* age for NGC 6652 of 11.7 ± 1.0 Gyr.

The above relative age may be compared to other clusters with a similar metallicity. For example, there exists excellent $V-I$ photometry of the thick disk globular cluster 47 Tuc from Kaluzny et al. (1998). This cluster has a well-established metallicity of [Fe/H] = −0.71 on both the Zinn & West (1984) and Carretta & Gratton (1997) scales, which is 0.14 dex more metal-rich than our preferred [Fe/H] for NGC 6652. This difference in metallicity precludes the use of the δ-color technique to determine an age difference for the two clusters.

The electronic data of Kaluzny et al. (1998) were used to determine

$$(V-I)_{\rm TO} = 0.714 \pm 0.004 \ , \quad V_{\rm SGB} = 17.25 \pm 0.03 \ ,$$

$$\langle V_{\rm HB} \rangle = 14.07 \pm 0.04 \ , \quad \Delta V_{\rm HB}^{\rm SGB} = 3.18 \pm 0.05 \ .$$

These values were determined in exactly the same manner as for NGC 6652. The value of $\Delta V_{\rm HB}^{\rm SGB}$ for 47 Tuc is very similar to that of NGC 6652. Formally, $\Delta V_{\rm HB}^{\rm SGB}$(NGC 6652 − 47 Tuc) = −0.05 ± 0.07. Assuming that 47 Tuc has [α/Fe] = +0.40 and a helium abundance that is given by equation (1), then a precise relative age of 12.2 ± 0.7 Gyr is obtained for 47 Tuc using the $\Delta V_{\rm HB}^{\rm SGB}$ method. This is virtually identical to the age derived for NGC 6652. To the precision of the data, the two clusters have the same age to within ±1.2 Gyr.

Brown & Wallerstein (1992) found an enhancement in α-capture elements of [α/Fe] = 0.22 in 47 Tuc. Using this value of [α/Fe] and using the same assumptions as this paper, Liu & Chaboyer (2000) found a $\Delta V_{\rm HB}^{\rm SGB}$ age of 12.9 ± 0.7 Gyr for 47 Tuc, implying that 47 Tuc is 1.2 ± 1.2 Gyr older than NGC 6652. If 47 Tuc has a solar helium abundance, the absolute magnitude of the HB would be different from what has been assumed, implying that the derived age would be altered. Salaris & Weiss (1998) found that increasing the helium abundance by 0.019 to (their) solar value decreased the estimated age of 47 Tuc by 1.1 Gyr. This difference in helium abundance between our solar value and that implied by equation (1) is 0.0177, and so if 47 Tuc has a solar helium abundance, the $\Delta V_{\rm HB}^{\rm SGB}$ age we determined should be decreased by 1.0 Gyr. This would imply that NGC 6652 is 0.9 ± 1.2 Gyr older than 47 Tuc. Thus, allowing for differences in the [α/Fe] or in the helium abundance between the two clusters does not change our conclusion that, to the precision of the data, NGC 6652 and 47 Tuc are the same age. This lack of age difference between 47 Tuc and NGC 6652 implies that the formation of the thick disk overlapped with the formation of the inner halo.

At the suggestions of the referee, we have tested the results of our $\Delta V_{\rm HB}^{\rm SGB}$ analysis by overlaying the CMD of 47 Tuc with that of NGC 6652. The 47 Tuc data were shifted so that the turnoff colors and the luminosities of the observed ZAHBs were made coincident. The results of this comparison are shown in Figure 8. A careful inspection of this figure reveals that when the ZAHBs of the two clusters are made coincident, the 47 Tuc subgiant branch is slightly fainter (by 0.06 ± 0.03 mag) than the subgiant branch of NGC 6652. Thus, $\Delta V_{\rm HB}^{\rm SGB}$ for 47 Tuc is slightly larger than $\Delta V_{\rm HB}^{\rm SGB}$ in NGC 6652. This is exactly what was determined by the $\Delta V_{\rm HB}^{\rm SGB}$ analysis presented in the previous paragraph.

The age of NGC 6652 may also be compared with that of NGC 6171 (M107). M107 is also considered a member of the halo (Zinn 1985). From their Ca II triplet analysis, Rutledge, Hesser, & Stetson (1997) found [Fe/H] = −1.09 on the Zinn & West (1984) scale and [Fe/H] = −0.95 on the Carretta & Gratton (1997) scale. This implies that M107 is ≃0.1 dex more metal-poor than NGC 6652. A $(V, B-V)$ CMD for M107 has been presented by Ferraro et al. (1991). As no $(V, V-I)$ data are publicly available for this cluster, we cannot perform a differential age comparison using the δ-color technique, and we instead analyze the age difference using $\Delta V_{\rm HB}^{\rm SGB}$. The electronic data of Ferraro et al. (1991) were carefully inspected, and the following points measured:

$$(B-V)_{\rm TO} = 0.870 \pm 0.01 \ , \quad V_{\rm SGB} = 18.86 \pm 0.04 \ ,$$

$$\langle V_{\rm HB} \rangle = 15.59 \pm 0.03 \ , \quad \Delta V_{\rm HB}^{\rm SGB} = 3.27 \pm 0.05 \ .$$

This value of $\Delta V_{\rm HB}^{\rm SGB}$ is 0.14 ± 0.07 mag larger than that found for NGC 6652 ($\Delta V_{\rm HB}^{\rm SGB}$ = 3.13 ± 0.05). Using our isochrones, a $\Delta V_{\rm HB}^{\rm SGB}$ age for M107 of 14.0 ± 1.1 Gyr is found, which is 2.7 ± 1.5 Gyr older than the $\Delta V_{\rm HB}^{\rm SGB}$ age of NGC 6652. This suggests that M107 may be older than NGC

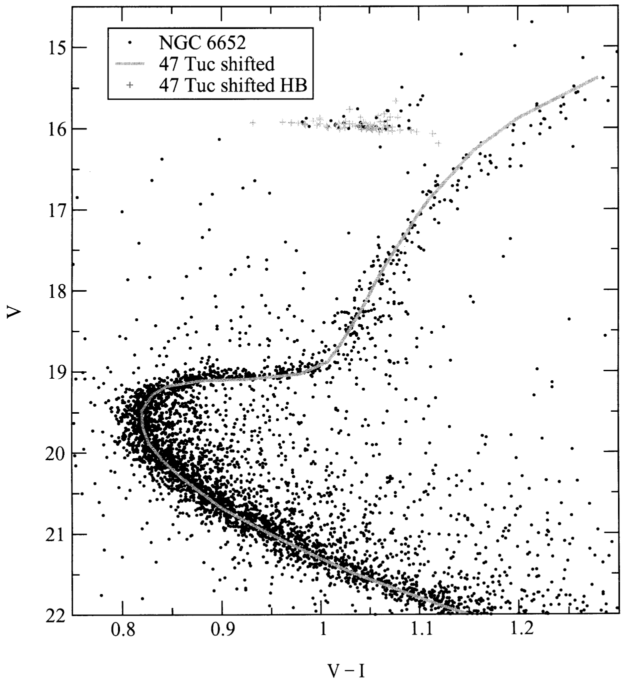

FIG. 8.—Comparison between our data for NGC 6652 and the Kaluzny et al. (1998) data for 47 Tuc. To facilitate the comparison, a fiducial for the 47 Tuc main sequence and RGB was determined and is shown in the figure. The 47 Tuc data were shifted by $\Delta V = +1.88$ and $\Delta(V-I) = +0.105$. These values were determined by requiring that the turnoff colors and the luminosities of the observed ZAHBs be coincident between the two clusters.

6652. However, this result is only significant at the 1.8 σ level. A more definitive study (using $V-I$ photometry for M107) is needed to determine whether NGC 6652 is younger than M107.

To investigate this issue further, we have also determined the age of NGC 1851, a somewhat more metal-poor cluster. Rutledge et al. (1997) found [Fe/H] $= -1.23$ on the Zinn & West (1984) scale and [Fe/H] $= -1.03$ on the Carretta & Gratton (1997) scale, implying that NGC 1851 is $\simeq$0.2 dex more metal-poor than NGC 6652. Walker (1998) obtained *BVI* CCD data for this cluster. Using the (V, $V-I$) data, we determined

$$(V-I)_{\rm TO} = 0.581 \pm 0.01 , \quad V_{\rm SGB} = 19.11 \pm 0.04 ,$$

$$\langle V_{\rm HB} \rangle = 16.12 \pm 0.04 , \quad \Delta V_{\rm HB}^{\rm SGB} = 2.99 \pm 0.06 .$$

This implies an age of 10.4 ± 1.0 Gyr, adopting [Fe/H] $= -1.10$. Thus, NGC 1851 is 0.9 ± 1.4 Gyr *younger* than NGC 6652, and 3.6 ± 1.5 Gyr younger than M107. Salaris & Weiss (1998) and Rosenberg et al. (1999) have also concluded that NGC 1851 is somewhat younger than M107 (2.1 ± 1.4 and 2.9 ± 1.3 Gyr, respectively, using different age diagnostics). In summary, there is a suggestion that NGC 6652 is somewhat younger (2.7 ± 1.5 Gyr) than the halo cluster M107, while it appears to be slightly older (0.9 ± 1.4 Gyr) than NGC 1851.

6. SUMMARY

HST (V, I) photometry has been obtained for the inner halo globular cluster NGC 6652. This photometry includes a well-populated horizontal branch and extends well below the main-sequence turnoff. From these data, we determined

$$V_{\rm ZAHB} = 16.00 \pm 0.03 , \quad \langle V_{\rm HB} \rangle = 15.96 \pm 0.04 ,$$

$$(V-I)_{\rm TO} = 0.818 \pm 0.004 ,$$

$$V_{\rm TO} = 19.55 \pm 0.07 , \quad V_{\rm SGB} = 19.09 \pm 0.03 ,$$

$$\Delta V_{\rm HB}^{\rm TO} = 3.59 \pm 0.08 , \quad \Delta V_{\rm HB}^{\rm SGB} = 3.13 \pm 0.05 .$$

This turnoff magnitude is 0.35 ± 0.17 mag fainter than that found in the previous study of NGC 6652 by OBB. As a consequence, the age derived from our photometry is substantially older than age determinations based upon the OBB photometry. The OBB photometry shows considerable scatter around the turnoff, while the data presented here clearly delineate the main sequence turnoff region.

New stellar evolution models and isochrones were calculated for [Fe/H] $= -1.20$, -1.00, -0.85, and -0.70 in order to determine the age of NGC 6652 and other globular clusters with similar metallicities. Estimates for the metallicity of NGC 6652 vary from [Fe/H] $= -0.96$ on the Zinn & West (1984) scale to [Fe/H] $= -0.85$ on the Carretta & Gratton (1997) scale. Our best-fitting isochrones have [Fe/H] $= -0.85$ and imply $(m-M)_V = 15.15 \pm 0.10$ and $E(V-I) = 0.15 \pm 0.02$. With $R_{\rm GC} \simeq 2.0$ kpc, NGC 6652 is the globular cluster closest to the Galactic center for which a precise relative age comparison can be made to other globular clusters that are relatively metal-poor. From the *HST* data, NGC 6652 has an age of 11.7 ± 1.6 Gyr (using $\Delta V_{\rm HB}^{\rm SGB}$ as the age indicator). Using data from the literature, $\Delta V_{\rm HB}^{\rm SGB}$ ages of 12.2 ± 0.7 Gyr for 47 Tuc (thick disk cluster with [Fe/H] $= -0.71$), 14.0 ± 1.1 Gyr for M107 (halo cluster with [Fe/H] $= -0.95$), and 10.4 ± 1.0 Gyr for NGC 1851 (halo cluster with [Fe/H] $\simeq -1.1$) were determined. These precise relative ages demonstrate that the halo clusters NGC 6652 and NGC 1851 are the same age as the thick disk cluster 47 Tuc. There is some evidence that M107 is somewhat older, but the difference in age between M107 and NGC 6652 is only significant at the 1.5 σ level. A more definitive study (using $V-I$ photometry for M107) is needed to determine whether NGC 6652 is younger than M107.

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