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## UBVI CCD PHOTOMETRY OF THE OLD OPEN CLUSTER BERKELEY 17

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### ABSTRACT

Photometric *UBVI* CCD photometry is presented for NGC 188 and Berkeley 17. Color-magnitude diagrams (CMDs) are constructed and reach well past the main-sequence turnoff for both clusters. Cluster ages are determined by means of isochrone fitting to the cluster CMDs. These fits are constrained to agree with spectroscopic metallicity and reddening estimates. Cluster ages are determined to be  $7.0 \pm 0.5$  Gyr for NGC 188 and  $10.0 \pm 1.0$  Gyr for Berkeley 17, where the errors refer to uncertainties in the relative age determinations. These ages are compared to the ages of relatively metal-rich inner halo/thick-disk globular clusters and other old open clusters. Berkeley 17 and NGC 6791 are the oldest open clusters, with ages of 10 Gyr. They are 2 Gyr younger than the thick-disk globular clusters. These results confirm the status of Berkeley 17 as one of the oldest known open clusters in the Milky Way, and its age provides a lower limit to the age of the Galactic disk.

*Key words:* Galaxy: disk — Galaxy: formation — open clusters and associations: general — open clusters and associations: individual (NGC 188, Berkeley 17)

*Online material:* color figures; machine-readable tables

### 1. INTRODUCTION

Galaxy formation and evolution theory remains one of the great outstanding problems in contemporary astrophysics. Although considerable progress has been made in this field over the past few decades, there are many unanswered questions regarding the formation of galaxies like the Milky Way. Observations within the Milky Way can be used to probe galactic evolution. In particular, determining the relative ages of the different stellar populations in the Milky Way—the halo, thick disk, thin disk, and bulge—by dating open and globular stellar clusters provides significant insight into the chronology of Galaxy formation (Liu & Chaboyer 2000; Salaris et al. 2004).

Owing to the great importance of the old open cluster population in probing the chemical and dynamic evolution of the Galaxy, considerable effort has been devoted to determining the physical parameters of these clusters (e.g., Phelps et al. 1994; Janes & Phelps 1994; Scott et al. 1995). However, relatively few of the oldest open clusters have received commensurate attention in astrometric, photometric, and spectroscopic studies, despite the great promise they hold in determining the age of the Galactic disk (notable exceptions include NGC 188 and NGC 6791).

This paper presents accurate *UBVI* photometry for the old open clusters NGC 188 and Berkeley 17. A number of excellent studies have previously been performed for NGC 188 that have accurately determined its physical parameters (von Hippel & Sarajedini 1998; Sarajedini et al. 1999; Platais et al. 2003; Michaud et al. 2004; Stetson et al. 2004; VandenBerg & Stetson 2004). NGC 188 is used as a fiducial cluster, and a precise age is obtained for Berkeley 17 relative to NGC 188. In addition, by directly comparing it with previously published data, the NGC 188 photometry serves as an independent test of the accuracy of the photometric calibration from the instrumental to the standard system.

Since the first photometric study of NGC 188 by Sandage (1962) demonstrating that it belonged to the oldest open clusters in the Galactic disk, the cluster has been the subject of numerous studies. As the highest priority cluster in the WYIN Open Cluster Study, excellent, multicolor color-magnitude diagrams (CMDs)

and proper-motion data have been published for this cluster (von Hippel & Sarajedini 1998; Sarajedini et al. 1999; Platais et al. 2003). In their *UBVI* photometric study, Sarajedini et al. (1999) found that NGC 188 has an age of  $7.0 \pm 0.5$  Gyr, a reddening of  $E(B - V) = 0.09 \pm 0.02$ , and a distance modulus of  $(m - M)_V = 11.44 \pm 0.08$ . These values are in general agreement with other recent photometric studies of the cluster (Caputo et al. 1990; Twarog & Anthony-Twarog 1989). Stetson et al. (2004) obtained new data on NGC 188 and did a comprehensive review of existing data in the literature, resulting in a large homogeneous photometric database. These data were used by VandenBerg & Stetson (2004) to determine an age of  $6.8 \pm 0.7$  Gyr for NGC 188.

Berkeley 17 was discovered by Setteducati & Weaver (1962) and is located at a low Galactic latitude in the direction of the Galactic anticenter. As a consequence of the cluster's location, as well as its large distance, the field in the direction of Berkeley 17 is highly reddened and greatly contaminated by field stars. Since the extensive open cluster study by Phelps et al. (1994), a general agreement has prevailed that Berkeley 17 is indeed the oldest known open cluster in the Galaxy. Soon after the Phelps et al. study, Kaluzny (1994) performed the first *BVI* photometry of the cluster and established that Berkeley 17 is as old or somewhat older than the previously oldest known open cluster, NGC 6791, based on comparisons of the morphologies of the two clusters' CMDs. However, the Kaluzny study was hampered by poor weather, thereby preventing absolute determinations of Berkeley 17's physical parameters.

The first age determinations for Be 17 based on isochrone fitting were made by Phelps (1997), who found an age of 10–13 Gyr, a metallicity of  $-0.30 < [\text{Fe}/\text{H}] < 0.00$ , a reddening of  $0.52 < E(B - V) < 0.68$  and  $0.61 < E(V - I) < 0.71$ , and a distance modulus of  $(m - M)_V = 14.05 \pm 0.25$ . Although other attempts at establishing the age of Berkeley 17 have been carried out (Carraro et al. 1999b; Salaris et al. 2004), no further observational data have been published for the cluster.

Section 2 describes the observations and the data reduction process, and § 3 presents cluster CMDs. Section 4 describes our stellar models, isochrone fits, and the age determinations of the clusters. These ages are compared to the ages of other old open

clusters and relatively metal-rich globular clusters in § 5. Section 6 evaluates these results in the context of the formation of the Milky Way.

## 2. CCD PHOTOMETRY

### 2.1. Observations

Observations were made at the MDM Observatory 1.3 m McGraw-Hill telescope for 13 nights between 2004 September 7 and 19. The Templeton camera, a thinned, backside-illuminated SITE 1024 × 1024 pixel CCD, was used, producing an image scale of 0".50 pixel<sup>-1</sup> and a field of view of 8'.5 × 8'.5. The observations are summarized in Table 1.

Preliminary processing of the data was carried out within the IRAF<sup>1</sup> data reduction software and consisted of standard zero-level correction and flat-fielding. For the zero-level correction, between 15 and 20 bias frames were obtained throughout each night. Twilight and dawn flats were acquired every evening and used for flat-fielding.

Four standard star fields from Landolt (1992) (PG1633, PG2213, and two fields in L95) were observed throughout the potentially photometric nights. These fields consisted of a total of 22 stars with a color range of  $-0.22 \leq (B - V) \leq 2.00$  and were observed at air masses ranging from 1.1 to 1.8 to ensure accurate determination of the photometric extinction and color terms.

### 2.2. Standard Star Frame Reduction

Aperture photometry was completed on the standard star frames using the APPHOT package within IRAF. The transformation equations between the instrumental and standard systems were established using the PHOTCAL package; these equations contain a zero point, an extinction term, and a linear color term and are given by

$$u = U + u_1 + u_2X + u_3(U - B),$$

$$b = B + b_1 + b_2X + b_3(B - V),$$

$$v = V + v_1 + v_2X + v_3(B - V),$$

$$i = I + i_1 + i_2X + i_3(V - I),$$

where  $u$ ,  $b$ ,  $v$ , and  $i$  are the instrumental magnitudes,  $U$ ,  $B$ ,  $V$ , and  $I$  are the standard magnitudes, and  $X$  is the air mass. The color term coefficients represent a weighted mean average from the three photometric nights (September 10, 14, and 15) and were found to be  $u_3 = -0.025$ ,  $b_3 = -0.040$ ,  $v_3 = -0.014$ , and  $i_3 = 0.014$ . The zero-point and extinction terms, however, showed sufficient night-to-night variation to be determined separately for each night, assuming the average color terms. No trends were observed in the residuals to the fits with respect to time, air mass, or color. Typical rms deviations of the fits to the standard values were 0.10 mag for  $U$ , and 0.02 mag for  $B$ ,  $V$ , and  $I$ .

### 2.3. Cluster Frame Reduction

Point-spread function (PSF) photometry of the cluster frames was performed with the DAOPHOT II (Stetson 1992) photometry package. An average of 80 uncrowded stars from each frame were selected to construct a PSF. The PSF photometry was then carried out with the ALLSTAR package by fitting the final PSF

TABLE 1  
LOG OF OBSERVATIONS

Cluster	Exposure (s)	Filter	Air Mass	FWHM (arcsec)
2004 Sep 10				
Be 17.....	3 × 400	<i>U</i>	1.4	1.8
	3 × 90	<i>B</i>	1.3	1.7
	3 × 40	<i>V</i>	1.4	1.4
	3 × 40	<i>I</i>	1.4	1.4
Be 17 off-field.....	3 × 400	<i>U</i>	1.2	1.8
	3 × 90	<i>B</i>	1.1	1.8
	3 × 40	<i>V</i>	1.2	1.4
	3 × 40	<i>I</i>	1.2	1.4
2004 Sep 15				
NGC 188.....	3 × 120	<i>U</i>	1.7	2.5
	2 × 1200	<i>U</i>	1.7	2.5
	3 × 90	<i>B</i>	1.7	2.0
	2 × 900	<i>B</i>	1.7	2.0
	3 × 60	<i>V</i>	1.7	2.0
	2 × 600	<i>V</i>	1.7	2.0
	3 × 30	<i>I</i>	1.7	2.0
	2 × 300	<i>I</i>	1.7	2.0
Be 17.....	2 × 1200	<i>U</i>	1.2	1.8
	2 × 900	<i>B</i>	1.1	1.8
	2 × 600	<i>V</i>	1.3	1.6
	2 × 300	<i>I</i>	1.3	1.7
2004 Sep 16				
Be 17 off-field.....	2 × 1200	<i>U</i>	1.1	2.0
	2 × 900	<i>B</i>	1.1	1.7
	2 × 600	<i>V</i>	1.4	1.6
	2 × 300	<i>I</i>	1.2	1.5

to detected profiles on each frame. The subtracted frames were then examined to ensure that they contained only saturated stars, galaxies, and chip defects. Stars with magnitude errors larger than 0.1 were edited out of the final photometry file.

Aperture corrections were determined by performing aperture photometry on 100–150 bright, uncrowded stars in each frame. The difference between the magnitudes given by the PSF and aperture photometry constituted the aperture correction, which was then applied to the original PSF photometry. Typical values for the aperture correction ranged between 0.1 and 0.2, and the values showed no trends in variation across the chip.

## 3. COLOR-MAGNITUDE DIAGRAMS

CMDs for the clusters were constructed using the standard magnitudes given by the transformation equations (see § 2.2). Stars detected in at least two frames of a given filter and exposure time were averaged and were included in the final CMD if they also appeared in two other filters. The final Be 17 cluster CMDs are shown in Figures 1–2, and photometry files are given in Table 2 for NGC 188 and Table 3 for Be 17. Entries of 99.99 in these tables indicate that a star was not detected in that filter.

The NGC 188 photometry includes only stars within the central region of the cluster, as the cluster has an estimated angular size of approximately 1°. The photometry extends around 6 mag fainter than its main-sequence turnoff at  $V \approx 15$ . The CMD includes 536 stars and displays a well-defined main sequence, sub-giant branch, and red giant branch. A helium-burning clump cannot be accurately identified. A binary sequence located 0.75 mag

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

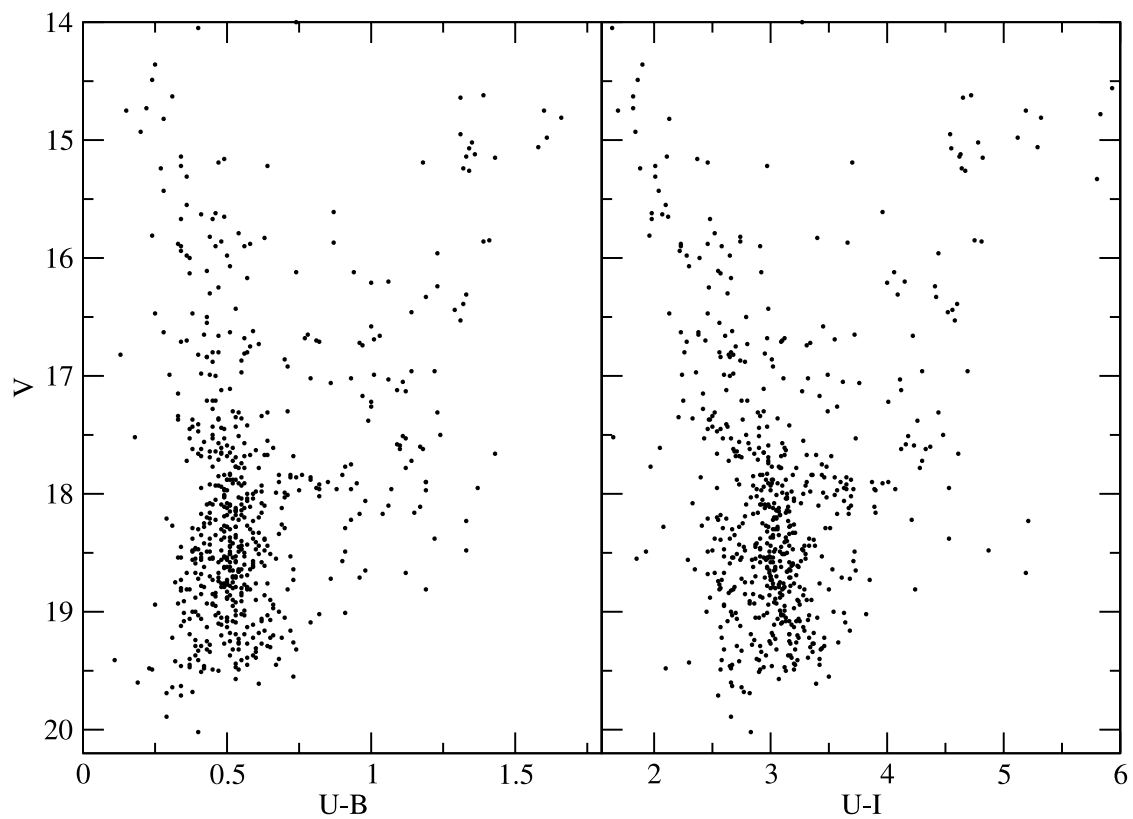


FIG. 1.—Be 17 ( $V$ ,  $U - B$ ) and ( $V$ ,  $U - I$ ) CMDs.

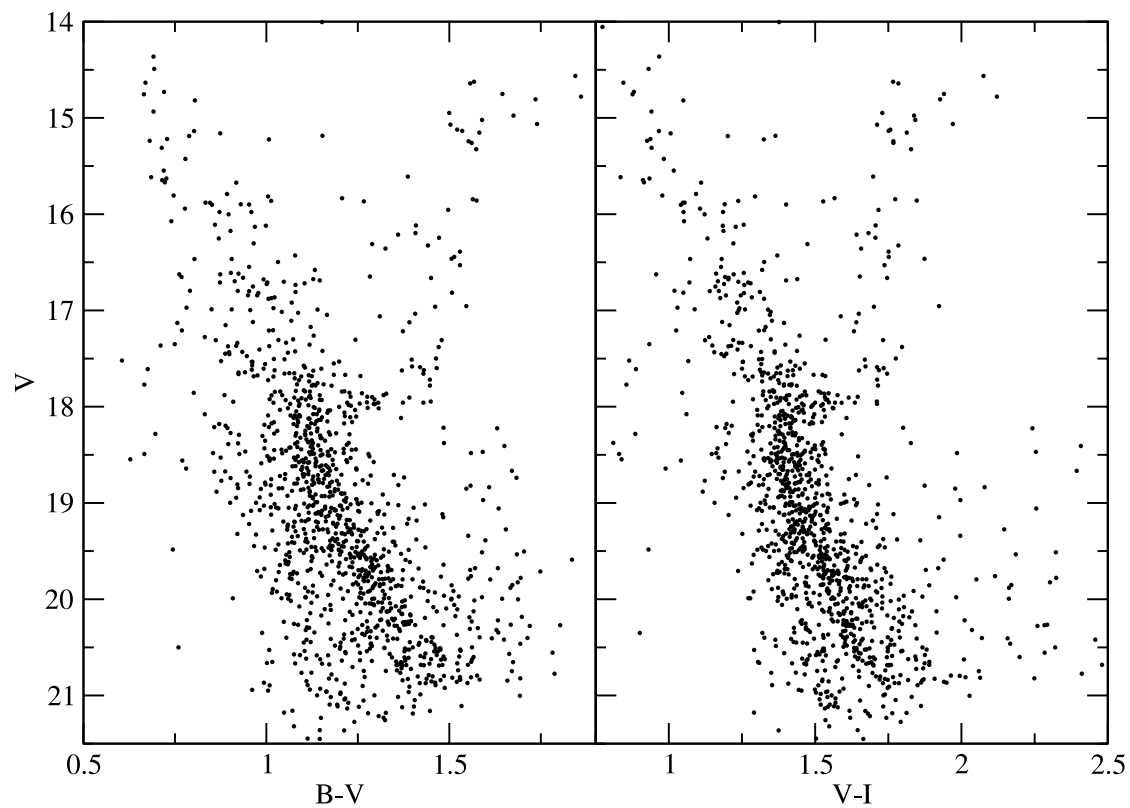


FIG. 2.—Be 17 ( $V$ ,  $B - V$ ) and ( $V$ ,  $V - I$ ) CMDs.

TABLE 2  
NGC 188 PHOTOMETRY FILE SAMPLE

Number	$x$ (pixels)	$y$ (pixels)	$U$ (mag)	$B$ (mag)	$V$ (mag)	$I$ (mag)
1.....	921.222	1.588	99.99	19.92	18.74	17.31
2.....	265.934	4.543	99.99	21.26	19.83	18.05
3.....	62.563	5.192	17.45	17.18	16.39	15.57
4.....	12.556	9.095	99.99	20.52	19.17	17.60
5.....	63.443	9.635	19.66	18.52	17.28	15.94
6.....	405.515	9.803	17.64	17.53	16.83	16.00
7.....	350.567	11.787	15.38	15.39	14.78	14.03
8.....	314.874	15.181	19.74	18.79	17.72	16.44
9.....	634.737	17.929	16.65	16.47	15.81	15.04

NOTE.—Table 2 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

above the main sequence is detected, most notably in the ( $V$ ,  $V - I$ ) CMD. Our photometry covers a much smaller area and is not quite as deep as the photometry presented by Sarajedini et al. (1999) and Stetson et al. (2004). Our photometry of NGC 188 was obtained so that a precise, relative comparison could be made between the well-studied cluster NGC 188 and Be 17. In addition, the NGC 188 data can be used to assess the absolute calibration of our photometry via a comparison to other data sets.

This paper's NGC 188 photometry was compared to that of Stetson et al. (2004) on a star-by-star basis. We were able to compare photometry of 533 stars in  $B$ , 531 stars in  $V$ , 525 stars in  $I$ , and 304 stars in  $U$ . Zero-point offsets of +0.026 mag in  $U$ , +0.013 mag in  $B$ , +0.031 mag in  $V$ , and +0.044 mag in  $I$  were found, in the sense that our photometry was fainter in all filters. The residuals between our photometry and that of Stetson et al. (2004) had no systematic trends with magnitude or color. A sample comparison is shown in Figure 3, in which the differences between our  $V$  photometry and Stetson et al. (2004) are plotted as a function of magnitude and color. A similar comparison with the NGC 188 photometry of Sarajedini et al. (1999) determined somewhat smaller zero-point offsets of +0.025 mag in  $U$ , -0.028 mag in  $B$ , -0.002 mag in  $V$ , and +0.016 mag in  $I$ , in the sense that our photometry was fainter in  $U$  and  $I$  and brighter in  $B$  and  $V$ . Again, the comparison revealed no systematic trends with magnitude or color. It is not clear whose data are best calibrated onto the standard system. Based on these comparisons it

TABLE 3  
BERKELEY 17 PHOTOMETRY FILE SAMPLE

Number	$x$ (pixels)	$y$ (pixels)	$U$ (mag)	$B$ (mag)	$V$ (mag)	$I$ (mag)	Member?
1.....	479.796	1.618	99.99	21.98	20.40	17.79	1
2.....	445.481	2.832	99.99	20.69	19.06	16.80	1
3.....	677.789	3.111	99.99	21.37	19.97	18.11	1
4.....	41.351	5.832	99.99	21.27	20.14	18.57	1
5.....	391.842	5.954	20.00	19.13	17.79	99.99	1
6.....	692.070	5.973	99.99	20.86	19.59	18.04	1
7.....	608.705	6.829	99.99	21.66	20.43	18.79	1
8.....	689.438	7.807	20.17	19.92	18.94	17.57	1
9.....	56.520	9.221	21.39	20.78	19.61	18.00	1

NOTES.—A 0 in this column indicates that the star has a low reddening and is not a member of the cluster. A 1 indicates that the star has a reddening consistent with being a member of the cluster. Table 3 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

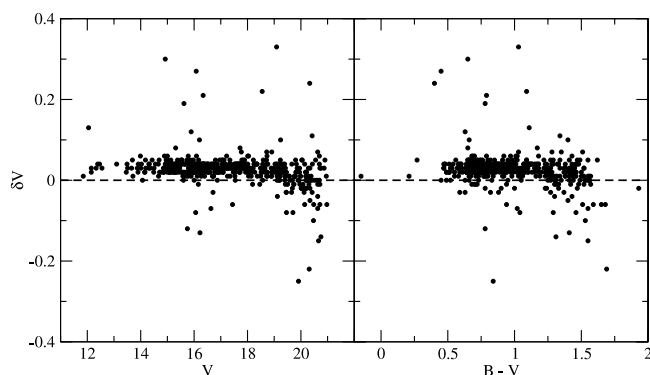


FIG. 3.—Comparison between the  $V$ -band photometry from Stetson et al. (2004) and that from this paper.

appears that our photometry is on the Landolt (1992) photometric system to an accuracy of  $\pm 0.03$  mag.

As a result of Berkeley 17's large distance and low Galactic latitude, its CMD is highly contaminated by field stars. The CMD consists of a total of 1239 stars and extends approximately 4 mag fainter than the main-sequence turnoff, located at  $V \approx 18$ . A highly contaminated main sequence can be discerned, along with a well-populated subgiant branch and a scarcely populated giant branch. Neither a helium-burning clump nor a binary sequence can be discerned. The ( $U - B$ ,  $V - I$ ) color-color diagram can be used to estimate reddening, and thereby remove many foreground stars (which typically have a lower reddening) from the CMD of Be 17. The color-color diagram of NGC 188 (which has a low reddening and few foreground stars) was compared with the Be 17 color-color diagram to partially eliminate field star contamination (Fig. 4). The cleaned Berkeley 17 CMD contains 1083 stars and is shown in Figure 5. Stars that are deemed to be nonmembers of Be 17 are denoted by a zero in the final column of Table 3.

A comparison between this paper's ( $V$ ,  $B - V$ ) photometry (before field star removal) and that of Phelps (1997) is shown in Figure 6. While the Phelps photometry (which surveyed a somewhat smaller region) reaches approximately a magnitude deeper, this paper's photometry displays both a tighter main sequence and a more well-defined main-sequence turnoff. The Phelps photometry is redder than our photometry, with  $\delta(B - V) \sim 0.1$  mag. Given the good agreement of our NGC 188 photometry

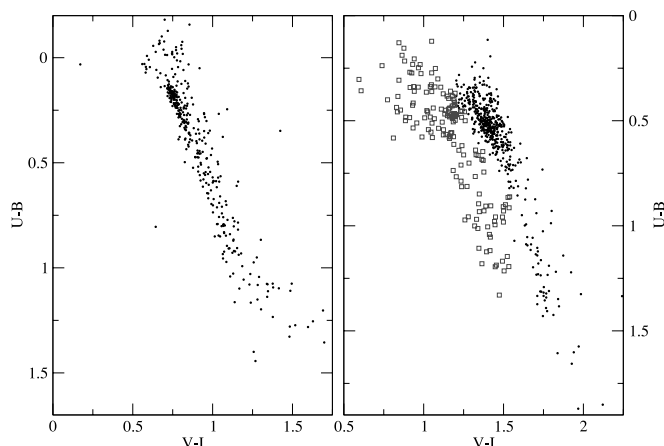


FIG. 4.—NGC 188 (left) and Be 17 (right) ( $U - B$ ,  $V - I$ ) color-color diagrams. Eliminated stars in the Be 17 color-color diagram are marked with open squares. [See the electronic edition of the *Journal* for a color version of this figure.]

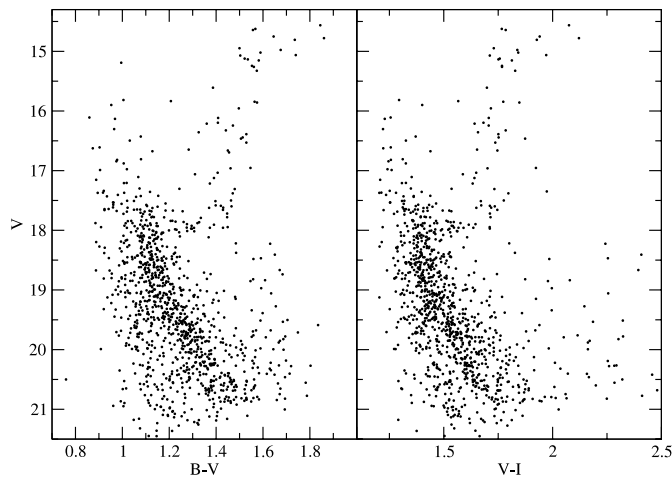


FIG. 5.—Cleaned Be 17 ( $V$ ,  $B - V$ ) and ( $V$ ,  $V - I$ ) CMDs.

with the photometry from Sarajedini et al. (1999) and Stetson et al. (2004), we believe that our photometry in the standard Landolt (1992) system is within  $\pm 0.03$  mag.

#### 4. ISOCHRONE FITTING AND AGE DETERMINATIONS

##### 4.1. Stellar Models and Isochrones

Stellar evolution tracks were constructed using our stellar evolution code (Chaboyer et al. 1999, 2001) for masses in the range of  $0.5$ – $2.0 M_{\odot}$  in increments of  $0.05 M_{\odot}$ . The models were evolved in 2000 time steps from the zero-age main sequence through the red giant branch. The models include the diffusion of helium and heavy elements. A solar-calibrated model was calculated, yielding  $Z = 0.02 Z_{\odot}$  and  $Y = 0.275 Y_{\odot}$  (initial abundances). For other metallicities,  $dY/dZ = 1.5$  was assumed (corresponding to a primordial helium abundance of  $Y_{\text{BBN}} = 0.245$ ). The solar-calibrated mixing length was used for all the models. The isochrones were created for metallicities of  $[\text{Fe}/\text{H}] = +0.20, +0.10, +0.00, -0.12, -0.30, -0.40, -0.60, -0.70, -0.82$ , and  $-1.00$ .

The transformation from the theoretical  $\log L - \log T_{\text{eff}}$  plane to observed colors and magnitudes for the constructed isochrones was completed using two separate color transformations, as this represents one of the greatest uncertainties of the theoretical isochrones. The first transformation utilized the Kurucz (1993) model atmospheres as described in Chaboyer et al. (1999), and the second, the Vandenberg & Clem (2003) color tables. The isochrones were constructed in the age range of 100 Myr to 15 Gyr for each of the aforementioned metallicities and color transformations, thereby allowing for considerable flexibility in performing the isochrone fits to the cluster CMDs.

##### 4.2. Isochrone Fitting

One of the most important isochrone input parameters is metallicity, and therefore, accurate cluster metallicities are crucial to obtaining reliable age estimates. We are interested in obtaining precise relative ages for NGC 188 and Be 17. For this reason we elected to use the metallicity estimates from Friel et al. (2002), who conducted an extensive, homogeneous spectroscopic survey of a large number of old open clusters, seeking to accurately determine both cluster metallicities and reddenings. This paper's clusters, NGC 188 and Be 17, were both included in their investigation. As the Friel et al. (2002) metallicities for these two clusters were done in a homogeneous manner, it is likely that the metallicity difference between the two clusters was robustly measured.

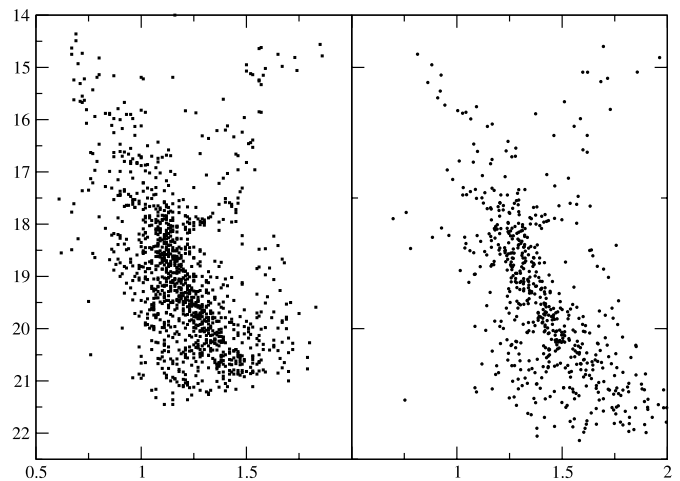


FIG. 6.—Comparison between this paper's Be 17 ( $V$ ,  $B - V$ ) photometry (left) and that of Phelps (1997) (right).

For relative age determinations, using precise relative metallicity determinations is more important than the zero-point of the metallicity scale. In this regard, high-resolution spectroscopy of M67 (Hobbs & Thorburn 1991; Tautvaišienė et al. 2000) found  $[\text{Fe}/\text{H}]$  values that are about 0.1 dex higher than those from Friel et al. (2002). Thus, the Friel et al. (2002) study may be underestimating the metallicity of the clusters. This implies that our absolute age determinations could be systematically in error but does not effect our relative age determinations. A 0.1 dex increase in  $[\text{Fe}/\text{H}]$  would systematically decrease our age estimates by approximately 8%.

Friel et al. (2002) used Fe I and Fe-peak blends to measure metallicities, and the  $H\beta$  strengths of main-sequence stars spanning the distance to the cluster were used to determine reddening values. Friel et al. (2002) determined  $[\text{Fe}/\text{H}] = -0.10 \pm 0.09$  and  $E(B - V) = 0.04 \pm 0.04$  for NGC 188. However, Friel et al. (2002) note that their  $H\beta$  reddening value is lower than published estimates and adopt  $E(B - V) = 0.08$ . For Be 17, Friel et al. (2002) found  $[\text{Fe}/\text{H}] = -0.33 \pm 0.12$  and  $E(B - V) = 0.58 \pm 0.09$ .

In fitting the isochrones to the CMDs of the two clusters, fits are made to the upper main sequence, main-sequence turnoff, and subgiant regions. The color of the red giant branch was not used in the fitting process, as its location in the theoretical models depends sensitively on superadiabatic convection, which is not well understood. Similarly, the color of the lower main sequence was not used in the fit, as there are difficulties with the conversion between theoretical temperatures and colors for cool main-sequence stars. The range of acceptable isochrone fits is constrained by the requirement of simultaneous fits in the ( $V$ ,  $B - V$ ) and ( $V$ ,  $V - I$ ) CMDs. The metallicity, reddening, and distance modulus are required to be identical in both CMDs, assuming  $E(V - I) = 1.25[E(B - V)]$  (Dean et al. 1978). Metallicities and reddenings are required to be consistent with those obtained by Friel et al. (2002). Isochrone fit parameters are summarized in Table 4.

#### 4.3. Discussion

##### 4.3.1. NGC 188

As a result of the high quality of the photometry and its distinct CMD morphology, NGC 188 is determined to be  $7.0 \pm 0.5$  Gyr old. The results obtained using the two individual sets of color transformations are consistent, and an excellent agreement

TABLE 4  
ISOCHRONE FIT PARAMETERS

Cluster	[Fe/H]	$E(B - V)$	$(m - M)_V$	Age (Gyr)	Color Transformation
NGC 188.....	+0.00	0.06	11.40	6.5	VandenBerg & Clem 2003
	-0.12	0.07	11.35	7.0	VandenBerg & Clem 2003
	-0.12	0.07	11.35	7.0	Kurucz 1993
	-0.12	0.08	11.45	6.5	Kurucz 1993
	-0.12	0.08	11.45	6.5	Kurucz 1993
Be 17.....	-0.30	0.59	14.20	9	VandenBerg & Clem 2003
	-0.30	0.57	14.10	10	VandenBerg & Clem 2003
	-0.40	0.61	14.20	9	VandenBerg & Clem 2003
	-0.40	0.60	14.10	10	VandenBerg & Clem 2003
	-0.40	0.58	14.10	10	Kurucz 1993
	-0.40	0.56	14.00	11	Kurucz 1993
	-0.40	0.56	14.00	11	Kurucz 1993

with the spectroscopic values from Friel et al. (2002) is also evident. A sample isochrone fit is shown in Figure 7. An age of  $7.0 \pm 0.5$  Gyr agrees well with the previous age determination of  $7.0 \pm 0.5$  Gyr by Sarajedini et al. (1999),  $6.8 \pm 0.7$  Gyr by VandenBerg & Stetson (2004), and 6.4 Gyr by Michaud et al. (2004). These studies used different photometry and stellar evolution models. The agreement between the different studies suggests that the age of NGC 188 has been robustly determined.

#### 4.3.2. Berkeley 17

The age of Be 17 is found to be  $10.0 \pm 1.0$  Gyr. As a result of the larger reddening uncertainty, greater field star contamination, and the less distinct cluster CMD morphology, the established age for Be 17 has a greater uncertainty than does that for NGC 188. However, by using the constraints on reddening and metallicity from spectroscopy and requiring simultaneous fitting in  $(V, B - V)$  and  $(V, V - I)$ , reliable results are obtained. Similar ages are obtained using the two separate color transformations. A sample isochrone fit is shown in Figure 8.

Our age for Be 17 is on the low side of the estimates made by Phelps (1997), who determined an age of 12.5 Gyr based on the VandenBerg (1985) isochrones and 10.0–13.0 Gyr based on the Bertelli et al. (1994) isochrones. However, as no accurate spectroscopic study had been performed for Be 17 at the time, Phelps (1997) allowed for a large range of metallicities and reddenings. Also, simultaneous fitting in the  $(V, B - V)$  and  $(V, V - I)$  CMDs was not an important factor in Phelps' iso-

chrone fitting process, mainly because the isochrones were not normalized to the Sun in terms of either helium abundance or in terms of the mixing-length parameter.

On the other hand, Carraro et al. (1999a) found a lower estimate of  $9.0 \pm 1.0$  Gyr using the Girardi et al. (2000) isochrones on both the Kaluzny (1994) and Phelps (1997) photometry. Carraro et al. (1999b), using the same methodology as Carraro et al. (1999a), made age determinations of the previously well-studied clusters NGC 188 and NGC 6791, for which age estimates of  $6.5 \pm 0.5$  Gyr (NGC 188) and  $8.5 \pm 0.5$  Gyr (NGC 6791) were determined. The Carraro et al. (1999b) results imply an age difference between NGC 188 and Be 17 of approximately 2.5 Gyr, consistent with the results obtained in this paper. The fact that our age estimates for Be 17 agree with Phelps (1997) and Carraro et al. (1999a) is surprising, given that our photometry has a significant offset from the Phelps (1997) photometry (see Fig. 6).

#### 5. COMPARISON TO OTHER CLUSTERS

In order to study the early formation history of the Milky Way, it is useful to compare the derived ages of NGC 188 and Be 17 to other old open clusters and globular clusters. As accurate estimates of the metallicity of a cluster are critical for age determinations, open clusters were selected from the Friel et al. (2002) metallicity study, which included [Fe/H] measurements for 39 clusters. From this list, clusters were selected that had good quality photometry and a morphological age index (Janes & Phelps 1994) greater than 2.0 (corresponding to an age of

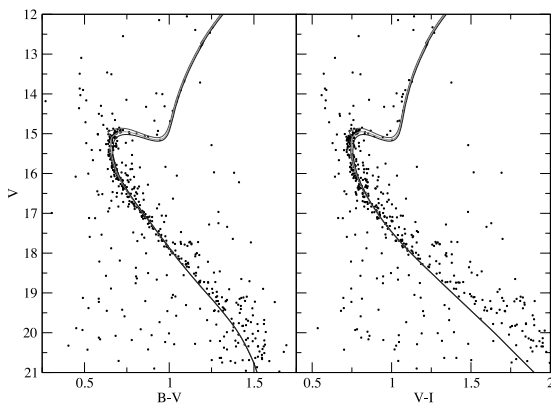


FIG. 7.—Best simultaneous isochrone fits for NGC 188. Isochrones constructed with the VandenBerg & Clem (2003) color transformation with [Fe/H] = -0.12 for 6.5, 7.0, and 7.5 Gyr are plotted assuming  $E(B - V) = 0.07$  and  $(m - M)_V = 11.35$ . [See the electronic edition of the *Journal* for a color version of this figure.]

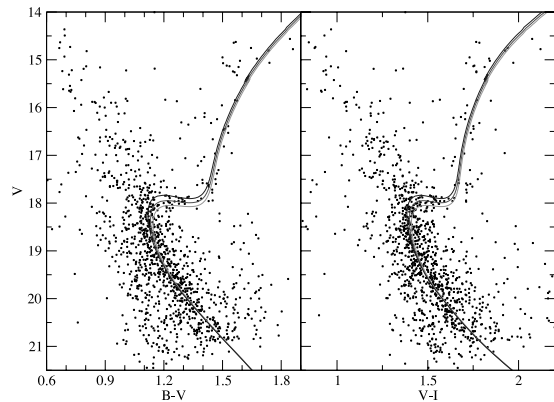


FIG. 8.—Best simultaneous isochrone fits for Be 17. Isochrones constructed with the VandenBerg & Clem (2003) color transformation with [Fe/H] = -0.30 for 9, 10, and 11 Gyr are plotted assuming  $E(B - V) = 0.57$  and  $(m - M)_V = 14.10$ . [See the electronic edition of the *Journal* for a color version of this figure.]

approximately 1 Gyr). The final sample of open clusters contains 18 clusters.

Globular clusters were selected from the extensive homogeneous *Hubble Space Telescope* (*HST*) photometric study of globular clusters carried out by Piotto et al. (2002). We elected to restrict our sample to relatively metal-rich ( $[\text{Fe}/\text{H}] > -1.2$ ) clusters located in the inner part of the Galaxy ( $R_{\text{GC}} \leq 8$  kpc). Requiring the globular clusters to be relatively metal-rich makes the age comparisons to the more metal-rich open clusters more direct. The restriction on galactocentric distance was made in an attempt to only include clusters that were formed as part of the initial Galactic collapse, and not as part of a latter accretion event. Salaris & Weiss (2002) found that globular clusters within a galactocentric radius of 8 kpc are nearly coeval, implying that the inner halo globular clusters formed in the initial Galactic collapse, whereas the outer halo—where clusters were found to have a larger range in age—was likely formed through the accretion of extragalactic fragments. Finally, the globular classification provided in the recent study by Mackey & van den Bergh (2005) was used to exclude clusters belonging to the young halo (YH), as these are believed to have been formed in external satellites eventually accreted by the Milky Way. Our globular cluster sample contains 13 clusters with *B* and *V* photometry from Piotto et al. (2002). For three of these clusters (47 Tuc, NGC 5927, and NGC 6652) *HST VI* photometry was also available.

Given the sensitivity of isochrone fitting to the assumed metallicity, it is important that a consistent metallicity scale be used for the open and globular clusters. While numerous studies have attempted to determine uniform globular cluster (Carretta & Gratton 1997; Rutledge et al. 1997; Kraft & Ivans 2003) and open cluster (Piatti et al. 1995; Twarog et al. 1997; Friel et al. 2002) metallicities, these studies have generally not overlapped between the two cluster populations.

Rutledge et al. (1997) used equivalent width observations to establish a linear relationship between Ca II triplet equivalent widths and the globular cluster abundance scale of Carretta & Gratton (1997). This led to a relative metallicity abundance ranking for a total of 71 globular clusters. Cole et al. (2004) sought to extend the Ca II triplet abundance scale to the younger ages and higher metallicities of open clusters. New spectra were obtained for a sample of five globular clusters and six old open clusters, and using globular cluster abundances on the Carretta & Gratton (1997) scale and open cluster abundances on the Friel et al. (2002) scale, a linear relationship between  $[\text{Fe}/\text{H}]$  and Ca II line strength was found. A crucial point in their study was to establish the compatibility of the two metallicity scales, given that the calibration of two scales differs in two respects: the atmosphere models used, and the effective temperature derivations. Cole et al. (2004) concluded that the systematic offsets between the two scales are comparable to or smaller than their respective internal uncertainties. They believe that the offset resulting from the choice of model atmospheres is of similar magnitude but opposite sign to that of the choice of effective temperature scale. Cole et al. (2004) concluded that the offset between the two metallicity scales is no more than 0.1 dex. Globular and open cluster metallicities were thus taken from Rutledge et al. (1997) and Friel et al. (2002).

Individual ages for all of the clusters were determined using main-sequence fitting, in the same manner that was done for NGC 188 and Pal 11. In making these fits, the metallicity of the isochrone was required to be consistent to within 0.1 dex of the cluster metallicity. The isochrones were constructed using scaled solar compositions, while globular clusters are typically enhanced in their  $\alpha$ -element (O, Mg, Si, S, and Ca) abundances.

To take this into account, the relationship between the heavy element mass fraction ( $Z$ ) in the isochrones and  $[\text{Fe}/\text{H}]$  followed the relationship given by Chieffi et al. (1991) and Chaboyer et al. (1992). In making this correction, globular cluster  $[\alpha/\text{Fe}]$  abundances were assumed to follow the relationship between  $[\alpha/\text{Fe}]$  and  $[\text{Fe}/\text{H}]$  found in Edvardsson et al. (1993). The  $\alpha$ -abundances of 47 Tuc were found to correspond well with this relationship (Carretta et al. 2004). The derived ages are listed in Table 5.

The globular clusters in the sample can be divided up into three categories based on their location in the Galaxy and their metallicity: thick disk, bulge, and inner halo. The three thick-disk globular clusters, 47 Tuc, NGC 5927, and NGC 6838, are found to have a mean age of  $12.3 \pm 0.4$  Gyr. The three bulge clusters, NGC 6304, NGC 6624, and NGC 6637, have a mean age of  $12.7 \pm 0.2$  Gyr. The seven clusters in the inner halo have an age range of 11.8–14.0 Gyr, with a mean age of  $13.0 \pm 0.9$  Gyr.<sup>2</sup> Collectively, the 13 high-metallicity globular clusters in the sample are found to be effectively coeval, with an average age of  $12.8 \pm 0.7$  Gyr and with all ages falling within  $2\sigma$  of the mean. We note that, in general, our globular cluster ages are somewhat larger ( $\sim 10\%$ ) than those from other studies that attempt to get good absolute ages for globular clusters (Salaris & Weiss 2002; Krauss & Chaboyer 2003; Lewis et al. 2006).

The oldest open clusters are found to be NGC 6791, Be 17, and Collinder 261, with ages of  $10.0 \pm 1.0$ ,  $10.0 \pm 1.0$ , and  $8.0 \pm 1.0$  Gyr, respectively. As a result of its extreme physical parameters—it is one of the oldest, most metal-rich, and most populous open clusters—NGC 6791 has been investigated in countless photometric and spectroscopic studies. The age obtained for NGC 6791 in this study,  $10.0 \pm 1.0$  Gyr, is in excellent agreement with the result found by Salaris et al. (2004), who determined an age of  $10.2 \pm 1.2$  Gyr.

Salaris et al. (2004) used a combination of main-sequence fitting and a new calibration of the morphological age indicator to determine the age of 71 old open clusters. The age of NGC 188 from isochrone fitting was found to be  $6.3 \pm 0.8$  Gyr, while the derived age for Be 17 was  $10.1 \pm 2.8$  Gyr. Our new photometry has allowed us to put a much tighter constraint on the age of Be 17. A comparison between the 17 open cluster ages in common between this study and Salaris et al. (2004) is found in Figure 9. In general, our open cluster ages are found to be consistent, within the error bars, with the ages obtained in Salaris et al. (2004). On average, the error bars in our age determinations are  $\sim 50\%$  smaller than the error bars in the Salaris et al. (2004) age determinations.

The only cluster for which our age disagrees with the age obtained by Salaris et al. (2004) is Berkeley 20. Be 20 is one of the most distant known open clusters, with a galactocentric distance of 16.4 kpc. The *BVI* photometry of Durgapal et al. (2001) for this cluster contains significant field star contamination. The main-sequence turnoff, the most important region in the CMD in performing the isochrone fitting, was poorly defined. However, it is evident from the cluster CMD that no so-called hook exists in the main-sequence turnoff region, a characteristic CMD feature of clusters with ages below around 5.0 Gyr. Therefore, it is unlikely that the cluster has an age below 5.0 Gyr, as suggested by the Salaris et al. (2004) study. Furthermore, simultaneous

<sup>2</sup> The errors in the mean ages of the three globular cluster populations represent the standard deviation of the ages with respect to the mean and do not include errors due to isochrone fitting. The errors in the ages of individual clusters given in Table 5 represent relative, rather than absolute, errors, and therefore no conflict with cosmological constraints on the age of the universe exists.



TABLE 5  
CLUSTER PARAMETERS

Name	$E(B - V)$	$D$ (kpc)	$R_{GC}$ (kpc)	Class <sup>a</sup>	[Fe/H]	Age (Gyr)	Reference
47 Tuc.....	0.04	4.5	7.4	TD	-0.78	$12.8 \pm 1.0$	1
NGC 5904.....	0.03	7.5	6.2	IH	-1.12	$12.0 \pm 1.0$	2
NGC 5927.....	0.45	7.6	4.5	TD	-0.64	$12.0 \pm 1.0$	2, 3
NGC 6171.....	0.33	6.4	3.3	IH	-0.95	$13.5 \pm 1.5$	2
NGC 6218.....	0.19	4.9	4.5	IH	-1.14	$14.0 \pm 1.0$	2
NGC 6304.....	0.53	6.0	2.2	B	-0.66	$13.0 \pm 1.0$	2
NGC 6362.....	0.09	7.6	5.1	IH	-0.99	$14.0 \pm 1.0$	2
NGC 6624.....	0.28	7.9	1.2	B	-0.70	$12.5 \pm 0.5$	2
NGC 6637.....	0.16	9.1	1.9	B	-0.78	$12.5 \pm 0.5$	2
NGC 6652.....	0.09	10.1	2.8	IH	-0.85	$11.8 \pm 1.0$	2, 4
NGC 6712.....	0.45	6.9	3.5	IH	-0.94	$12.5 \pm 0.5$	2
NGC 6723.....	0.05	8.7	2.6	IH	-0.96	$13.5 \pm 1.5$	2
NGC 6838.....	0.25	4.0	6.7	TD	-0.73	$12.0 \pm 1.0$	2
NGC 188.....	0.08	1.5	9.3	OC	-0.10	$7.0 \pm 0.5$	5
NGC 1193.....	0.12	4.0	12.0	OC	-0.51	$4.0 \pm 0.5$	6
NGC 2141.....	0.33	4.1	12.4	OC	-0.33	$3.0 \pm 0.5$	7
NGC 2204.....	0.08	4.0	11.5	OC	-0.32	$2.0 \pm 0.5$	8
NGC 2243.....	0.06	3.7	10.8	OC	-0.49	$3.8 \pm 0.8$	9
NGC 2420.....	0.05	2.3	10.6	OC	-0.38	$2.0 \pm 0.5$	10
NGC 2506.....	0.07	3.3	10.9	OC	-0.44	$2.0 \pm 0.5$	11
NGC 2682.....	0.05	0.8	9.05	OC	-0.15	$5.0 \pm 0.5$	12
NGC 6791.....	0.15	4.2	8.12	OC	+0.11	$10.0 \pm 1.0$	13
NGC 6819.....	0.16	2.3	8.18	OC	-0.11	$2.5 \pm 0.5$	14
NGC 6939.....	0.50	1.2	8.70	OC	-0.19	$1.6 \pm 0.4$	15
Be 17.....	0.58	2.7	11.2	OC	-0.33	$10.0 \pm 1.0$	5
Be 20.....	0.14	8.4	16.4	OC	-0.61	$6.0 \pm 1.0$	16
Be 21.....	0.76	5.0	13.5	OC	-0.62	$2.0 \pm 0.5$	17
Be 31.....	0.20	3.8	12.0	OC	-0.40	$3.5 \pm 0.5$	18
Be 32.....	0.15	3.1	11.4	OC	-0.50	$5.0 \pm 1.0$	19
Be 39.....	0.12	3.8	11.5	OC	-0.26	$6.5 \pm 1.5$	8
Cr 261.....	0.33	2.4	7.5	OC	-0.16	$8.0 \pm 1.0$	20

<sup>a</sup> Classification: (B) bulge globular cluster; (TD) thick disk globular cluster; (IH) inner halo globular cluster; (OC) open cluster.

REFERENCES.—Galactic coordinates, reddenings, and distances for globular clusters are from Harris (1996); Galactic coordinates, reddenings, and distances for open clusters are from Friel et al. (2002). Sources for photometry: (1) Kaluzny et al. 1998; (2) Piotto et al. 2002; (3) Feltzing & Gilmore 2000; (4) Chaboyer et al. 2000; (5) this paper; (6) Kaluzny 1988; (7) Carraro et al. 2001; (8) Kassis et al. 1997; (9) Bergbusch et al. 1991; (10) Anthony-Twarog et al. 1990; (11) Kim et al. 2001; (12) Sandquist 2004; (13) Stetson et al. 2003; (14) Kalirai et al. 2001; (15) Andreuzzi et al. 2004; (16) Durgapal et al. 2001; (17) Tosi et al. 1998; (18) Guetter 1993; (19) Kaluzny & Mazur 1991; (20) Gozzoli et al. 1996. All OC photometry was obtained from WEBDA, maintained by J.-C. Mermilliod (<http://obswww.unige.ch/webda/navigation.html>).

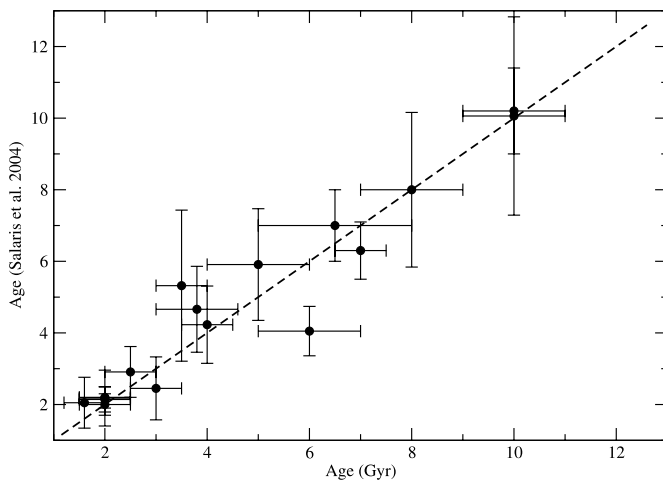


FIG. 9.—Age determinations for the 17 clusters in common between this study (horizontal axis) and the ages derived by Salaris et al. (2004). The dashed line has unit slope and illustrates perfect agreement; it is not a fit to the data. The only cluster whose age, within the error bars, does not agree is Be 20 (with an age of 6.0 Gyr in our study).

fitting in the  $(V, B - V)$  and  $(V, V - I)$  CMDs was only possible with isochrones of around 6 Gyr, for which the reddening value was also consistent with the value given in the literature [ $E(B - V) = 0.14$ ]. Be 20 is thus determined to be  $6.0 \pm 1.0$  Gyr old, which is consistent with the age of 5.0 Gyr obtained from isochrone fitting by Durgapal et al. (2001).

## 6. SUMMARY

This paper confirms the well-established age of old open cluster NGC 188 at  $7.0 \pm 0.5$  Gyr. Be 17 is found to be  $10.0 \pm 1.0$  Gyr old. As a result of the internal consistency of the ages obtained for the two clusters, the age difference of Be 17 relative to NGC 188 is highly robust: Be 17 is  $3.0 \pm 1.1$  Gyr older than NGC 188. These ages were determined using the metallicity scale of Friel et al. (2002). There are some indications that the Friel et al. (2002) [Fe/H] measurements are too low by about 0.1 dex, as high-resolution spectroscopic studies of M67 (Hobbs & Thorburn 1991; Tautvaišienė et al. 2000) find [Fe/H] values 0.1 dex higher than those of Friel et al. (2002). If the Friel et al. (2002) metallicities are 0.1 dex too low, then our ages need to be revised downward by about 8%.

Using the same age-determination technique, the Friel et al. (2002) metallicity measurements, and photometry from the literature, ages of 16 other old open clusters were determined. Be 17 was found to be the oldest open cluster, with the same age as the well-studied cluster NGC 6791. The ages of 13 relatively metal-rich globular clusters were determined using the same methodology as for the open cluster ages. Table 5 summarizes the age determinations. These ages were determined using isochrone fitting in a self-consistent manner. This leads to precise relative ages, but the absolute ages have considerably larger uncertainties. We note that the globular cluster ages we derive are  $\sim 8\%$  larger than the accurate absolute ages found by Krauss & Chaboyer (2003). This is the same age reduction estimated for the open clusters, based on the suggestion that the Friel et al. (2002) metallicity values are too low by 0.1 dex.

The globular clusters have ages in the range 11.8–14.0 Gyr, but given the error in the age determinations, there is no evidence for an intrinsic age spread among the globular clusters. The thick-disk globular clusters (the most metal-rich clusters in our sample) were found to have an average age of  $12.3 \pm 0.4$  Gyr,

while the two oldest open clusters in our sample have an age of  $10.0 \pm 0.7$  Gyr. Thus, the oldest open clusters in the thin disk are found to be  $2.3 \pm 0.8$  Gyr younger than the thick-disk globular clusters.

In contrast, Salaris et al. (2004) found no significant age difference between the thin and thick disks in the Galaxy. However, their age determinations generally had larger error bars than our determinations, and Salaris et al. (2004) determined the age of two thick-disk globular clusters, while we determine the age of three thick-disk globular clusters. Combined, these two effects made it difficult for Salaris et al. (2004) to determine if age differences less than 3 Gyr existed. In summary, we find that the oldest open clusters imply that the thin disk started forming  $2.3 \pm 0.8$  Gyr after the formation of the thick disk.

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