The Astrophysical Journal, 483:826–836, 1997 July 10

BERKELEY 17: THE OLDEST OPEN CLUSTER?

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Received 1996 September 19; accepted 1997 February 10

ABSTRACT

Faint magnitude *BVI* CCD photometry of the central region of the old open cluster Berkeley 17 (Be 17) has been undertaken to investigate the claim that it is the oldest open cluster yet discovered (Phelps, Janes, & Montgomery). This study reveals Be 17 to have a metallicity $-0.30 \leq [\mathrm{Fe/H}] \leq 0.00$; a reddening $0.52 \leq E(B-V) \leq 0.68$ or $0.61 \leq E(V-I) \leq 0.71$; a distance modulus, $(m-M)_0 = 12.15 \pm 0.10$, corresponding to a distance of 2.7 ± 0.1 kpc; a diameter of ~ 10 pc; a minimum mass of 400 $M_\odot$; and an age of 10–13 Gyr. With an adopted age of 12^{+1}_{-2} Gyr, these results suggest that Be 17 is indeed the oldest open cluster yet discovered. The inferred old age for Be 17 indicates that the cluster is an important one for studies of the differences between open and globular clusters, the transition from the halo/thick disk to the thin disk of the Galaxy, and even for establishing the minimum age of the universe.

Subject headings: Hertzsprung-Russell diagram — open clusters and associations: individual (Berkeley 17) — stars: abundances — stars: evolution

1. INTRODUCTION

In an extensive literature and CCD photometric survey of potential old open clusters, Phelps, Janes, & Montgomery (1994) identified 72 open clusters with ages as old as or older than the Hyades, with 19 of the clusters having ages as old as or older than the ~ 5 Gyr old M67. Using parameters based on the luminosity difference between the main-sequence turnoff and the horizontal branch and on the color difference between the turnoff and the giant branch, a "morphological age index" (MAI) was established for the clusters in the Phelps et al. (1994) list and for a sample of globular clusters (Janes & Phelps 1994).

The age distribution of the open clusters found by Janes & Phelps (1994) overlaps that of the globular clusters, which indicates that the Galactic disk began to develop toward the end of the period of star formation in the Galactic halo. This assertion by Janes & Phelps (1994) was based primarily on the MAI of the oldest open cluster in the sample, Berkeley 17 (Be 17), whose faintness made interpretation of the 0.9 m telescope photometry difficult.

Kaluzny (1994) subsequently performed a *BVI* study of Be 17 and estimated an apparent distance modulus, $(m-M)_v$, of greater than 15.0, or a heliocentric distance of 4.4 kpc, assuming $E(V-I) \geq 0.7$ [$E(B-V) \geq 0.5$]. He confirmed the Phelps et al. (1994) result that Be 17 is as old as, or older than, NGC 6791, which has an age of ≤ 10 Gyr (see Tripicco et al. 1995; Montgomery, Janes, & Phelps 1994 and references therein), and inferred that Be 17 has a composition more metal poor than NGC 6791, which has $+0.19 \leq [\mathrm{Fe/H}] \leq 0.44$ (Friel & Janes 1993; Tripicco et al. 1995). As discussed in Kaluzny (1994), however, poor weather hampered his observations, and in any event, direct information on reddening and metallicity was not available.

Be 17 was therefore reobserved with the Kitt Peak National Observatory (KPNO) 2.1 m telescope to improve the photometry for this important cluster. With this new photometry, and recently obtained spectroscopic data (Friel 1995), estimates have been obtained for the reddening and metallicity of this important cluster. With these new data, it is possible to investigate better the Phelps et al. (1994) and Janes & Phelps (1994) claim that Berkeley 17 is indeed the oldest open cluster yet discovered.

2. OBSERVATIONS AND DATA REDUCTION

Observations of Be 17 and an associated off-cluster control field were made at Kitt Peak National Observatory (KPNO) on 1994 January 16/17. The 2.1 m telescope with the TEK 1024 × 1024 CCD was used, giving a scale of 0".30 pixel^{-1} and a field of view of 5'.1. The standard KPNO *BVI* filters were used. The seeing was $\sim$1".5 during the Be 17 observations, and the sky was photometric.

Approximately 10 dithered twilight frames in each filter were obtained each night, in a direction relatively devoid of stars (Schoening 1988). Each set of ~ 10 images was median filtered using the sigma clipping algorithm in IRAF[2] to create a flat-field image for each filter. Standard bias and flat-fielding was subsequently performed within IRAF to complete the preliminary processing of the data.

Point-spread function (PSF) photometry of the images was undertaken using the stellar photometry software (SPS) package (Janes & Heasley 1992). Instrumental magnitudes derived from SPS were then transformed to the system defined by our observations of the equatorial standard stars observed by Landolt (1992) and by M67 stars observed by Montgomery, Marschall, & Janes (1993). Transformations from the instrumental to the standard system are given by

$$v = V + 2.0326 + 0.1996{*}X + 0.0257{*}(B-V) - 0.0189{*}(B-V){*}{*}2\ ,$$

$$b = V + 1.9969 + 0.6080{*}X + 0.9032{*}(B-V) - 0.03{*}X{*}(B-V) + 0.0034{*}(B-V){*}{*}2\ ,$$

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[2] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

and

$$i = V + 2.6308 + 0.2115*X - 1.0272*(V-I) + 0.0159*(V-I)**2 ,$$

where v, b, and i are the instrumental magnitudes, X is the air mass, and V, B, and I are the magnitudes to be determined. Typical residuals of the fits to the standard magnitudes were 0.02 mag. For further discussion of the transformation method, the reader is referred to Phelps & Janes (1994).

3. RESULTS

3.1. *Photometry Comparisons*

Previous studies of Be 17 include the *VI* study by Phelps et al. (1994), using the KPNO 0.9 m telescope, and the *BVI* study by Kaluzny (1994), using the KPNO 2.1 m telescope. With the addition of our 2.1 m photometry, there now exist several independent CCD photometric data sets for Be 17. Along with the deep 2.1 m data used for this study, *BVI* photometry from quick snapshots taken on the following night is also available for comparison. Table 1 presents the comparisons between these photometric data sets, where the Δ's are in the sense of the photometry from this current study minus the photometry from the other studies. Column (1) indicates the study to which the current photometry values are being compared, while the remaining columns indicate the differences in V (col. [2]), $(B-V)$ (col. [5]), and $(V-I)$ (col. [8]), the standard deviations of the mean for the comparisons in V (col. [3]), $(B-V)$ (col. [6]), and $(V-I)$ (col. [9]), the number of stars used in the comparisons for V (col. [4]), $(B-V)$ (col. [7]), and $(V-I)$ (col. [10]), along with the limiting V magnitude for the comparisons (col. [11]).

A sizable discrepancy between the current photometry and that of Phelps et al. (1994) is found. This is not surprising since the Phelps et al. (1994) photometry was often obtained in marginal conditions as time permitted during the course of other observing programs (as stated in their paper). Much closer agreement between the current photometry and that of Kaluzny (1994) and our quick snapshot photometry from the following night is found, although differences of several hundreths of a magnitude are typically found among all data sets. It is not obvious which of the data sets is most nearly on the standard system, so no corrections have been made to the current photometry since the night was deemed to be photometric and the Kaluzny (1994) photometry was hampered by poor weather. Neglecting the Phelps et al. (1994) photometry since the weather was considered the most marginal, the differences between photometry sets are at the ≤ 0.05 mag level, which does not seriously compromise the major conclusions of this paper.

3.2. *CMD Morphology*

Figure 1 presents the V, $B-V$ and V, $V-I$ color-magnitude diagrams (CMDs) for Be 17. Both diagrams reveal a populous cluster with a main-sequence turnoff near $V = 18$, along with a sparsely populated giant branch. The detection of blue straggler and binary stars is complicated by the presence of a substantial field star population in the diagrams. The V, $V-I$ CMD (Fig. 1 [*right*]), however, more clearly separates the main sequence from the field star distribution and reveals a distinct binary sequence of stars, located ~ 0.75 mag above the principal sequence. A group of four stars in the V, $V-I$ CMD at $V \sim 15.2$, $V-I \sim 1.72$ may represent the helium burning clump (see also §§ 3.3 and 3.4 below).

3.3. *Field Star Contamination*

The V, $V-I$ CMD of a nearby field region is shown in Figure 2, while a superposition of the stars in the field region (*open squares*) and cluster region (*stars*) is shown in Figure 3. The off-cluster field region data surveyed the same amount of area on the sky as that of the cluster region data. As can be seen in Figures 2 and 3, no obvious trace of a cluster is found in the field region CMD, particularly in the region of the CMD where one finds the giant branch and presumed clump stars in Figure 1 (*right*). This strengthens the argument that the stars at $V \sim 15.2$, $(V-I) \sim 1.72$ in Figure 1 (*right*) are indeed helium-burning clump stars. This also suggests that the majority of stars in Figure 1 (*right*) that are in the red giant region are in fact cluster members.

Figure 4 presents a "cleaned" CMD for Be 17, obtained by statistically removing field stars shown in Figure 2 from the cluster CMD of Figure 1 (*right*). Each star in the field region CMD (Fig. 2) was used to find the nearest star in the cluster CMD (Fig. 1 [*right*]). If the difference in magnitude and color between the paired stars from each CMD were within a specified "radius," the corresponding star in Figure 1 (*right*) was assumed to represent a field star, and it was removed from the cluster CMD. After several trials, a rather liberal "radius" of 1 mag in V (0.2 mag in color) was chosen to represent a match. Since the area on the sky was the same for both the cluster frame and the field region frame, only one removal from the cluster CMD was permitted for each star in the field region CMD.

The "cleaned" CMD of Figure 4 no longer necessarily contains true cluster members, although the lack of field stars in the giant region of the CMD of Figure 2 indicates that nearly all of the giants in Figure 4 are true cluster members. The plume of stars blueward of the well-defined lower edge of the main sequence also indicates that the field star subtraction was not perfect, which suggests that the detailed distribution of stars in the field region used for Be 17 is not is not identical to that of the field star distribution in the cluster region (although the overall distribution of field stars in both the cluster CMD and the field region

TABLE 1

PHOTOMETRY COMPARISONS

Study (1)	ΔV (2)	σV (3)	N_V (4)	$\Delta(B-V)$ (5)	$\sigma(B-V)$ (6)	$N_{(B-V)}$ (7)	$\Delta(V-I)$ (8)	$\sigma(V-I)$ (9)	$N_{(V-I)}$ (10)	$V_{\rm lim}$ (11)
2.1 m (short)......	0.041	0.031	51	0.027	0.081	51	0.030	0.040	46	19
PJM94	−0.137	0.056	45	...	...	...	−0.087	0.031	39	17
Kal94	0.058	0.034	279	0.057	0.039	273	−0.003	−0.040	270	20

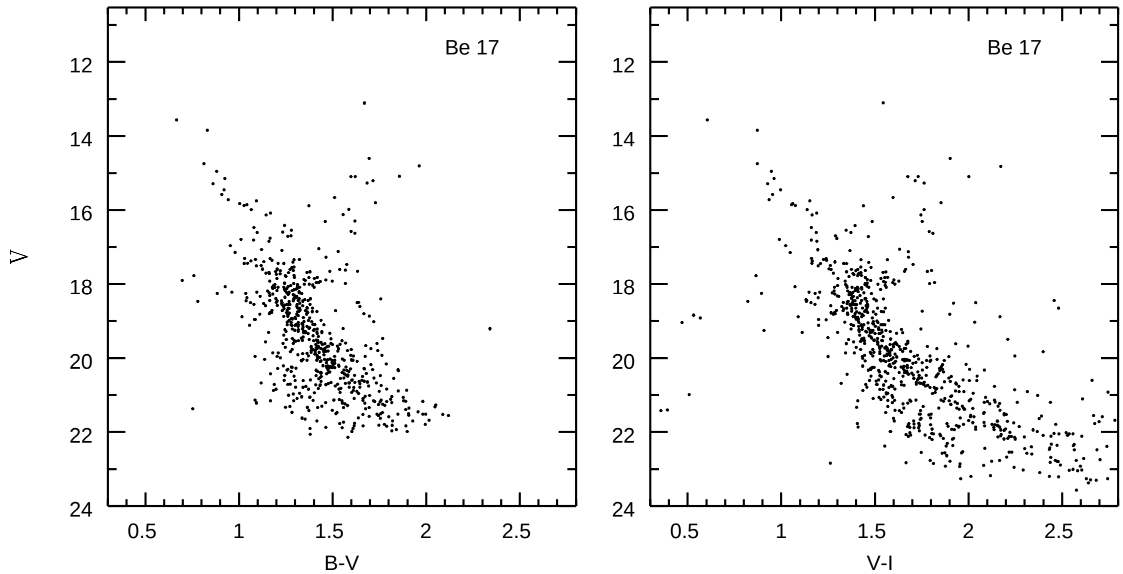

FIG. 1.—*Left*: V, $B-V$ and *right*: V, $V-I$ color-magnitude diagrams for Be 17

CMD is generally similar—see Fig. 3). Nevertheless, the "cleaned" CMD of Figure 4 is useful for confirmation of several features of the CMD detected in the full set of photometry (Fig. 1).

Several features in the "cleaned" CMD immediately are apparent. The sparse giant branch remains quite obvious in this diagram as does the apparent helium-burning clump. A well-defined, unevolved main sequence is seen extending from $V \sim 20$, $(V-I) \sim 1.5$ to $V \sim 23$, $(V-I) \sim 2.5$, and a conspicuous binary sequence, located $\sim$0.75 mag brighter than the unevolved main sequence is also seen. A pronounced clump of stars just above the main-sequence turnoff ($V \sim 17.7$, $V-I \sim 1.4$) is also detected and possibly represents the extension of the binary sequence above the main-sequence turnoff. A number of stars are detected in the region where one might expect to find blue stragglers, but the imperfect field star subtraction makes identification of a blue straggler population speculative.

3.4. $\delta V/MAI$

Phelps et al. (1994) introduced two age parameters to rank relative cluster ages based on the morphology of the CMD. These parameters are δV, the difference between the magnitude of the clump and that of the main-sequence turnoff, and $\delta 1$, the difference in color between the main sequence turnoff and the color of the giant branch located 1 mag brighter than the magnitude of the main-sequence turnoff. Similar age parameters were introduced by Anthony-Twarog & Twarog (1985) and have been shown to be independent of reddening and nearly independent of metallicity (see, e.g., Buonanno, Corsi, & Fusi Pecci 1989). As discussed in Phelps et al. (1994), not all old open clusters

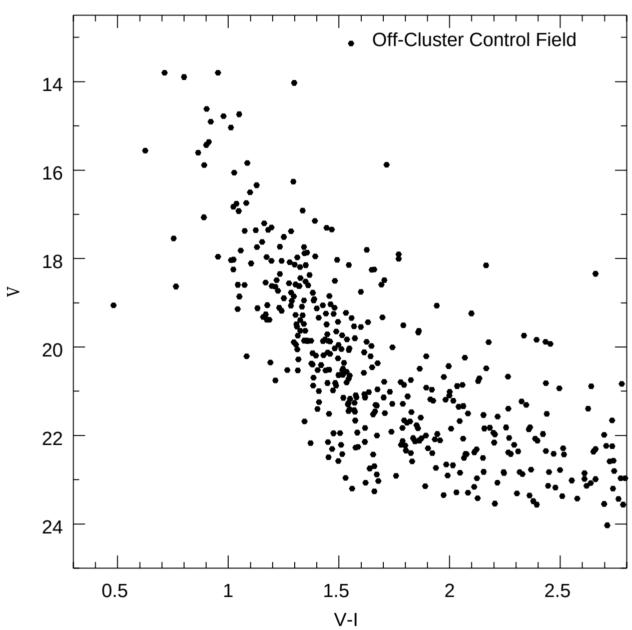

FIG. 2.—V, $V-I$ color-magnitude diagram for the Be 17 off-cluster control field.

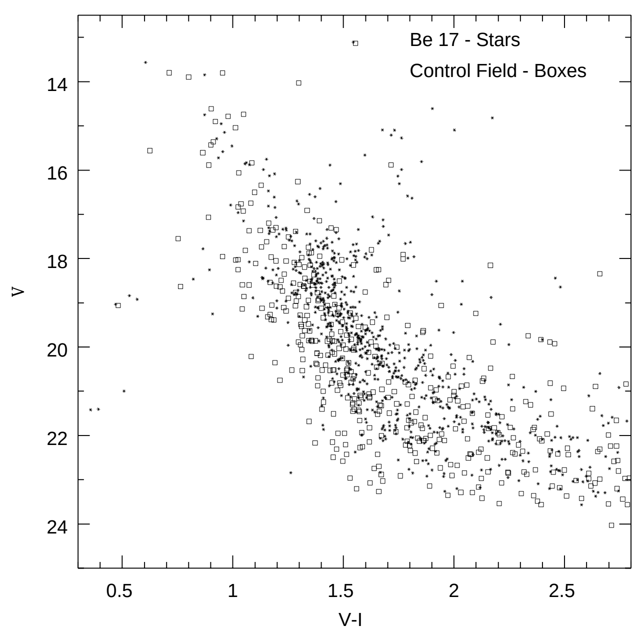

FIG. 3.—V, $V-I$ color-magnitude diagram for Be 17 (*stars*) and an off-cluster control field (*open squares*).

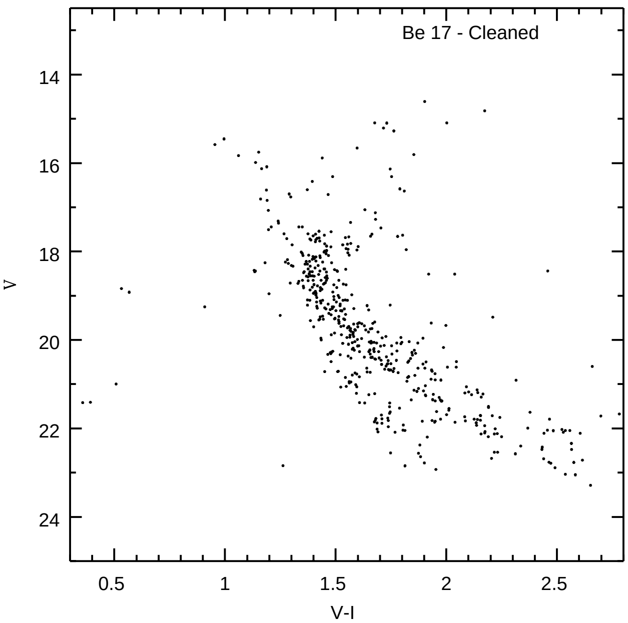

FIG. 4.—"Cleaned" color-magnitude diagram for Be 17, resulting from a statistical subtraction of field stars from the color-magnitude diagram. Points do not necessarily represent true cluster members.

have populous helium-burning clumps, thereby making a direct determination of the parameter δV difficult. In these cases, the parameter $\delta 1$ becomes especially useful. For Be 17, the values of $\delta 1$ are 0.31 and 0.32 for the $(B-V)$ and $(V-I)$ colors, respectively. The measured $\delta 1$ values result in derived values of $\delta V = 2.6$ and 2.7 for $(B-V)$ and $(V-I)$ after applying the relations between $\delta 1$ and δV in Phelps et al. (1994). Using the observed turnoff magnitudes, and subtracting the δV computed from $\delta 1$, a predicted value of $V \sim 15.3$–15.4 results for the magnitude of the helium-burning clump. Within the errors resulting from the determination of $\delta 1$ (estimated to be about 0.03 in color), this is the same magnitude as the stars previously identified as helium-burning clump stars, thereby strengthening the assertion that these stars represent the clump for Be 17. A direct measure for these stars gives $\delta V = 2.8$, which when averaged with the value derived from the $\delta 1$ determination, gives a final estimate of $\delta V = 2.7$ for Be 17. This value is slightly lower than that found by Phelps et al. (1994), who found $\delta V = 2.8$ for Be 17 based on their 0.9 m telescope photometry.

Janes & Phelps (1994) introduced a morphological age index (MAI) to rank cluster ages based on the δV parameter. They found that the parameter δV is highly correlated with the logarithm of cluster age, as determined by fitting to theoretical isochrones. With the derived value of $\delta V = 2.7$ and using the relation in Janes & Phelps (1994) between δV and the MAI, an MAI of 10.9 Gyr is found.

Assuming the mean absolute magnitude ($M_v = 0.90 \pm 0.40$) of clump stars for clusters with $\delta V \geq 1$ (Janes & Phelps 1994), and mean intrinsic clump colors of $(B-V) = 0.95 \pm 0.10$ (Janes & Phelps 1994), and $(V-I) = 1.0$ as is found for M67 (Montgomery et al. 1993), we derive values of $E(B-V) = 0.70$ and $E(V-I) = 0.72$. Values of $(m-M)_v = 14.30$, or $(m-M)_0 = 12.13$, using $E(B-V) = 0.70$ and assuming a value of $R_v = 3.1$ for the ratio of total to selective absorption are also found. These values indicate that Be 17 is at a distance of 2.7 kpc from the Sun.

Note that values of $E(B-V) = 0.70$ and $E(V-I) = 0.72$ are not consistent with the Dean, Warren, & Cousins (1978) relation, $E(V-I) = 1.25 * E(B-V)$, which, given $E(B-V) = 0.70$, would predict a value of $E(V-I) = 0.88$. Given the large uncertainties in the assumed intrinsic colors, however, this discrepancy is not unexpected.

3.5. *Morphological Ratio*

Anthony-Twarog & Twarog (1985) derived morphological parameters from cluster CMDs and used them to construct a "morphological age ratio" (MAR) to make maximum use of the effect of age on the parameters—a luminosity difference (analogous to δV) increases with age, while a color difference (analogous to $\delta 1$) decreases with age. In addition, this ratio has been shown to be relatively insensitive to metallicity since metallicity effects on both indices affect the age in the same way (Anthony-Twarog & Twarog 1985). The quantity $\delta V/\delta 1$, defined to be the "morphological ratio," or "MR," should therefore provide a greater separation in age than either of the two quantities taken in isolation. The term "morphological ratio" is used rather than the term "morphological age ratio," since the morphological parameters that define it (δV and $\delta 1$) are not identical to those used by Anthony-Twarog & Twarog (1985).

As discussed by Phelps et al. (1994), both δV and $\delta 1$ cannot always be measured for all old clusters, thereby making comparison of the entire system of old open clusters impossible based on the MR. However, an MR can be computed for the clusters listed by Phelps et al. (1994) as being among the five oldest, and these values are summarized in Table 2. The parameters for Be 17 are taken from this study, while the parameters for the remaining clusters are taken from Phelps et al. (1994). As can be seen from Table 2, the MR values for these clusters reinforce the assertion that Be 17 is the oldest open cluster yet discovered.

4. ISOCHRONE AGE

Figures 5 and 6 show matches between the *BV* and *VI* photometry of Be 17 and the 12.5 Gyr and 10.0 Gyr VandenBerg (1985) isochrones, respectively, using metallicities [Fe/H] = 0.00 ($Z = 0.0169$), -0.23 ($Z = 0.0100$), and -0.46 ($Z = 0.0060$). Since no independent measure of the reddening or distance to Be 17 is available, isochrone age determinations must be made by shifting various isochrones in color and magnitude until the best match of the isochrone to the shape of the observed CMD is found. The VandenBerg (1985) isochrones, however, are not perfectly normalized to the Sun, either in terms of the helium abundance (which affects the luminosity scale) or in terms of the

TABLE 2

MORPHOLOGICAL RATIOS OF THE FIVE OLDEST OPEN CLUSTERS

	BV			*VI*		
CLUSTER	δV	$\delta 1$	MR	δV	$\delta 1$	MR
Be 17	2.8	0.31	9.03	2.8	0.32	8.75
NGC 6791......	2.8	0.34	8.24	2.8	0.33	8.48
Cr 261	...	...	...	2.5	0.34	7.35
AM 2	2.4	0.33	7.27	...	...	...
Be 39	2.6	0.37	7.03	2.5	0.37	6.76

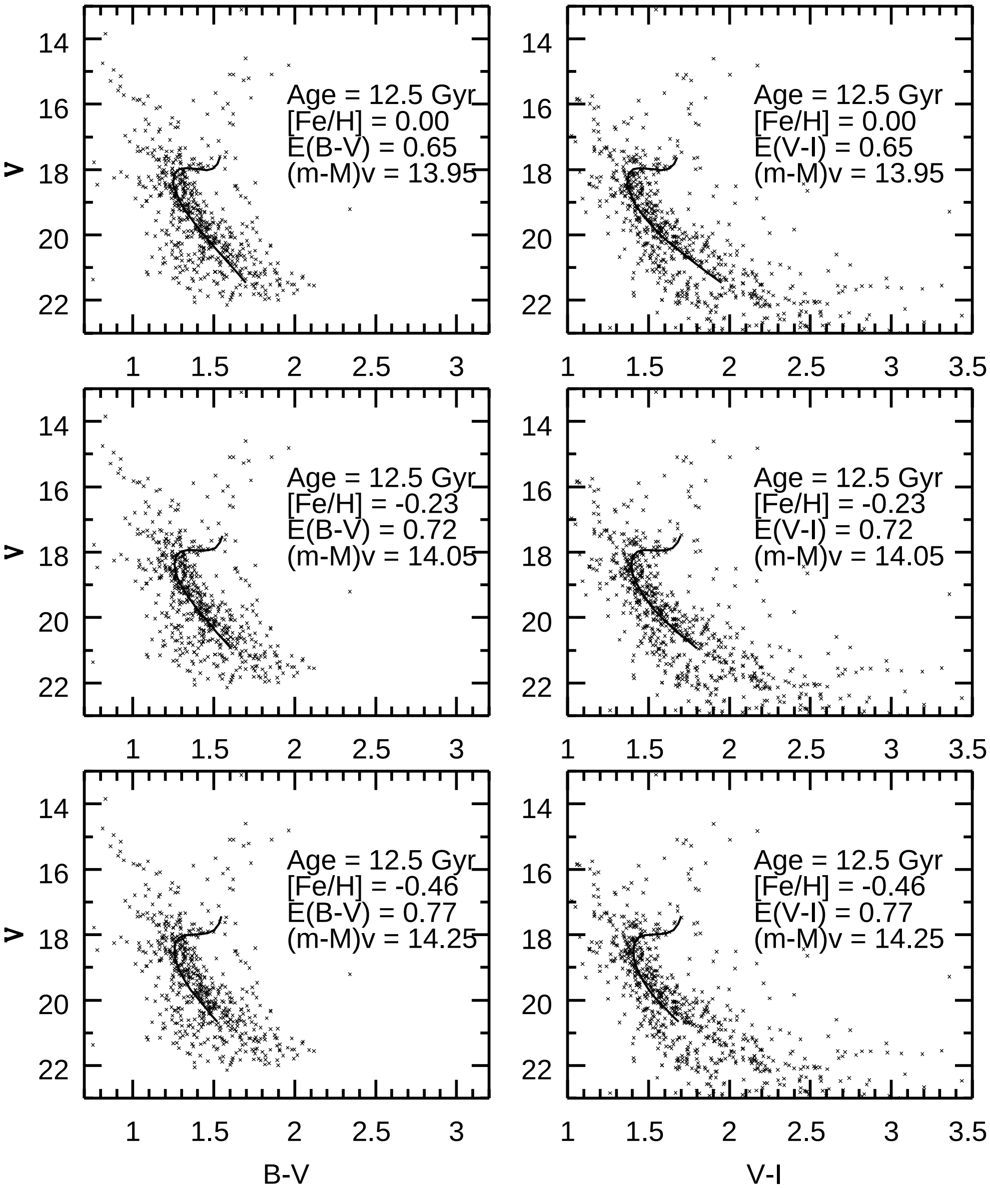

FIG. 5.—12.5 Gyr VandenBerg (1985) isochrone matches to the V, $B-V$ and V, $V-I$ color-magnitude diagrams of Be 17 for metallicities, [Fe/H], 0.00, -0.23, and -0.46.

mixing-length parameter (which affects the effective temperature scale). A mismatch for the Sun was accepted to allow model atmospheres to be used for boundary conditions (VandenBerg & Poll 1989). This mismatch affects the color and the luminosity of the isochrones but does not affect the overall shape of the isochrone. Age estimates, based on a match of the isochrone to the morphology of the observed CMD, will not be affected, although the actual color excess and distance modulus will be affected by the mismatch of the isochrones to the Sun.

Figure 5 shows matches between the *BV* and *VI* CMDs for Be 17 and the 12.5 Gyr VandenBerg (1985) isochrones. The length and slope of the subgiant branch suggests that 12.5 Gyr is a good estimate of the age for Be 17. The best match is found for the [Fe/H] = 0.00 isochrones since not only is the length and slope of the subgiant branch found to be in good agreement with that observed in the CMD, but good matches are also found for the shape of the main-sequence turnoff region and the slope of the unevolved portion of the main sequence in both the *BV* and *VI* CMDs. The [Fe/H] = -0.23 isochrones also provide reasonable matches to the CMDs, although the match to the main-sequence turnoff region is less satisfactory than that found for the [Fe/H] = 0.00 isochrones. The [Fe/H] = -0.46 isochrones do not match the shape of the main-sequence turnoff region, nor do they match the shape of the unevolved main-sequence observed in the CMD. The steepness of the [Fe/H] = -0.46 isochrones compared to the observed CMD suggests that the metallicity of Be 17 is likely to be considerably higher than [Fe/H] = -0.46.

Figure 6 shows matches between the *BV* and *VI* CMDs for Be 17 and the 10.0 Gyr VandenBerg (1985) isochrones (again for metallicities [Fe/H] = 0.00, -0.23, and -0.46). In all cases, no consistent match between the isochrones and the observed CMD can be found. In all cases, no simultaneous match to the unevolved main sequence and the observed magnitude of the subgiant branch can be found since a match to the subgiant branch would force the iso-

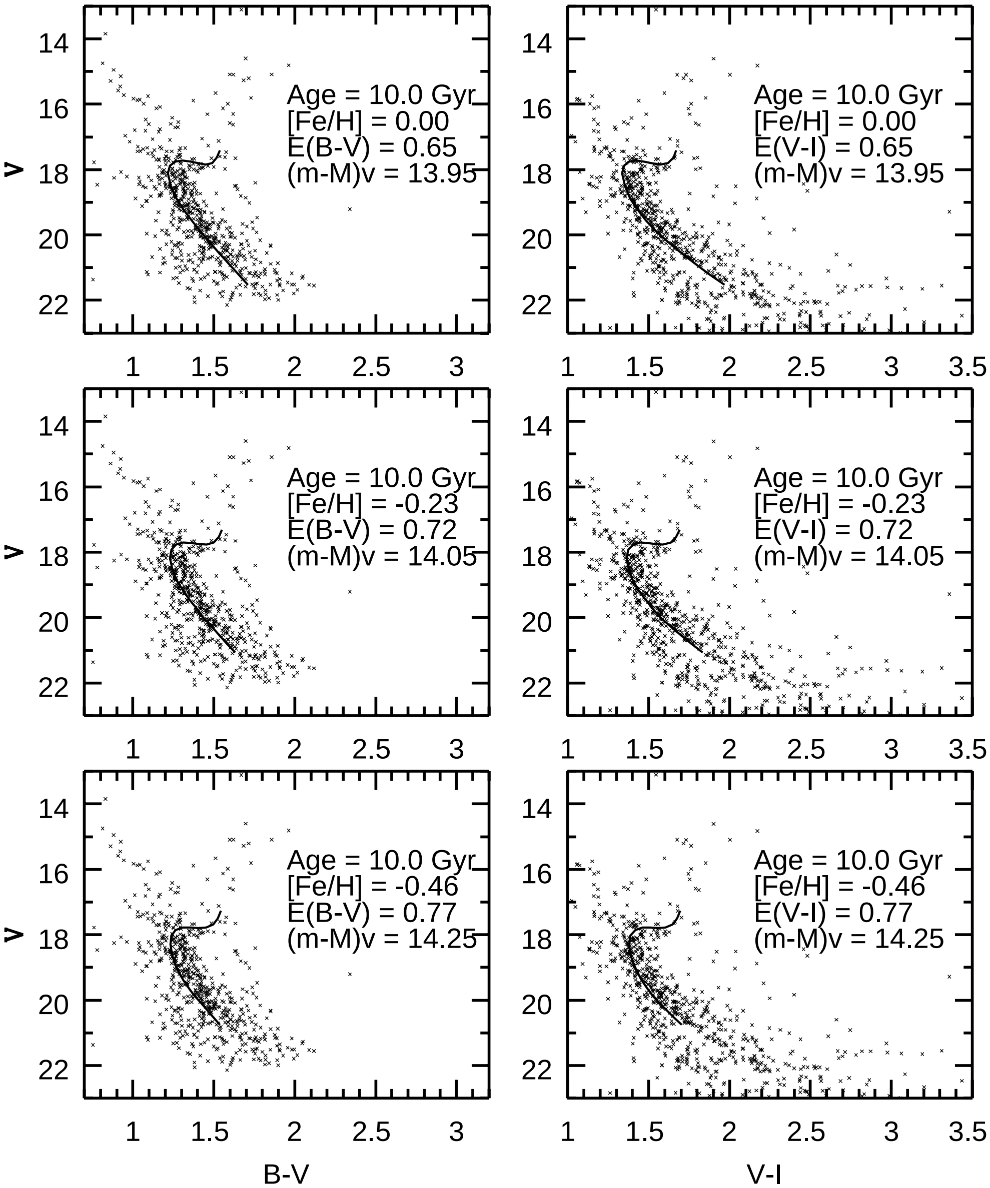

FIG. 6.—10.0 Gyr VandenBerg (1985) isochrone matches to the V, $B-V$ and V, $V-I$ color-magnitude diagrams of Be 17 for metallicities, [Fe/H], 0.00, -0.23, and -0.46.

chrone main sequence fainter than that observed for the cluster. In any event, neither the length nor the shape of the subgiant branch observed in the cluster CMD matches the 10.0 Gyr isochrones. As was the case for the 12.5 Gyr isochrones, the 10.0 Gyr isochrones with [Fe/H] = -0.46 are too steep to match the observed CMD, although the higher metallicity isochrones do reproduce the slope of the unevolved main sequence, as is to be expected based on the matches found using the 12.5 Gyr isochrones. The poor matches found in Figure 6 therefore suggest that Be 17 is *older* than 10.0 Gyr.

Note that in all cases, for a given metallicity, the color excess used is the same for both the BV and VI CMDs. This result is inconsistent with expectations that the ratio $E(V-I)/E(B-V)$ should be 1.25 (Dean et al. 1978) and is likely a result of the color mismatch in the VandenBerg (1985) isochrones.

To confirm the old age derived for Be 17, the Bertelli et al. (1994) isochrones have also been used to estimate cluster parameters. The Bertelli et al. isochrones are calculated for initial chemical compositions [$Z = 0.0004$, $Y = 0.23$], [$Z = 0.004$, $Y = 0.24$], [$Z = 0.008$, $Y = 0.25$], [$Z = 0.02$, $Y = 0.28$], and [$Z = 0.05$, $Y = 0.352$] and ages between 4 Myr and 16 Gyr. Radiative opacities (OPAL) by Iglesias, Rogers, & Wilson (1992) were used. The Bertelli et al. isochrones include evolution along the red giant branch, which has the advantage that it allows for isochrone matches to the brighter portions of the red giant branch in the CMD, where metallicity effects become more pronounced. Based upon the above results using the VandenBerg (1985) isochrones, only the $Z = 0.008$, $Z = 0.02$, and $Z = 0.05$ isochrone matches were investigated. Figures 7, 8, and 9 show the matches to the Be 17 CMD for the 10.0 Gyr, 12.0 Gyr, and 13.2 Gyr Bertelli et al. isochrones, respectively, for $Z = 0.008$, $Z = 0.02$, and $Z = 0.05$. As was the case for the VandenBerg (1985) isochrones, distance moduli were selected to provide a match of the magnitude of the subgiant branch, and reddenings were selected to provide matches of

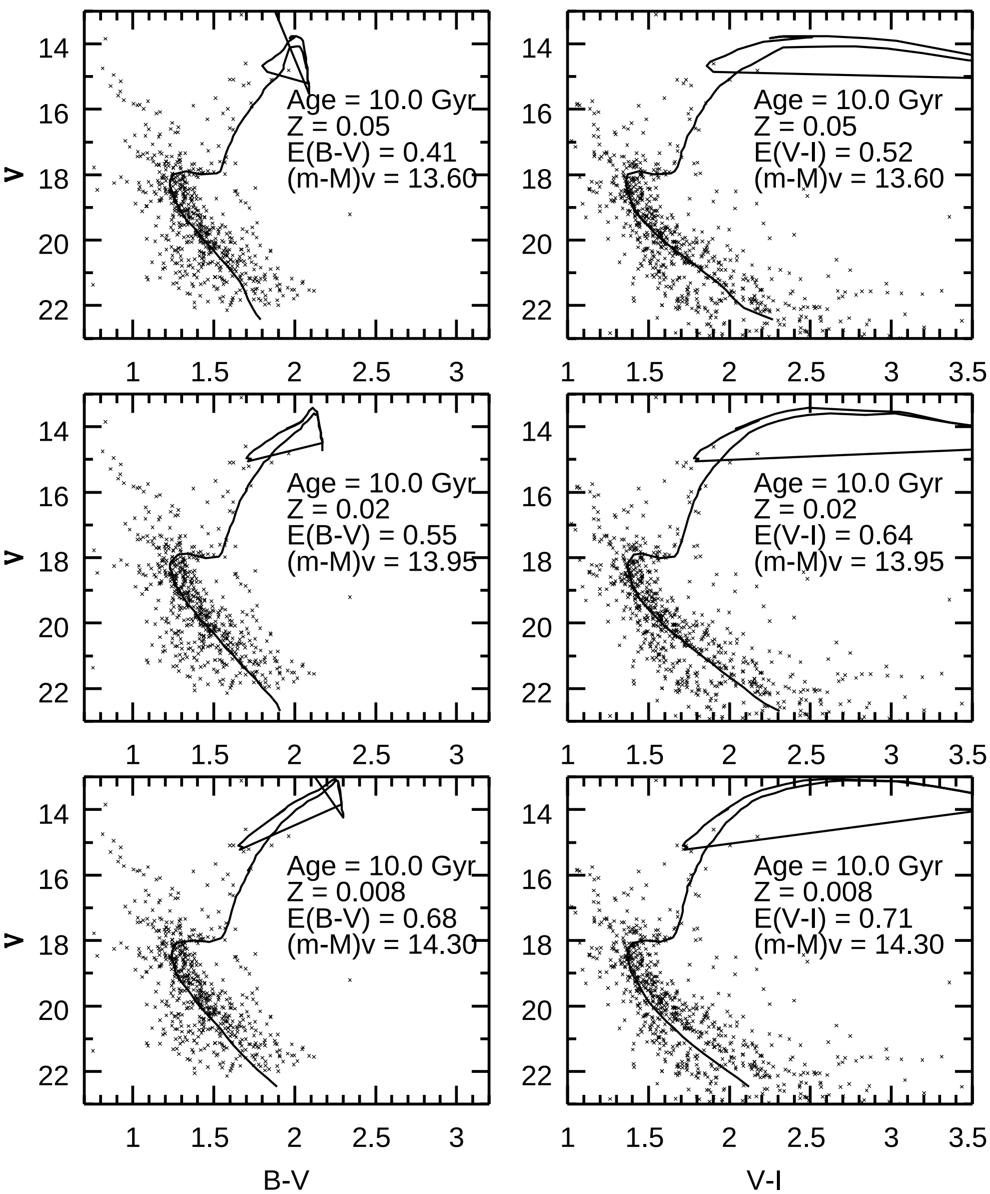

FIG. 7.—10.0 Gyr Bertelli et al. (1994) isochrone matches to the V, $B-V$ and V, $V-I$ color-magnitude diagrams of Be 17 for metallicities, Z, 0.05, 0.02, and 0.008.

the isochrones with the blue edge of the cluster main sequence and turnoff region.

In all cases, the $Z = 0.05$ isochrones provide a good match to the main sequence and to the slope of the upper portion of the red giant branch in both the BV and VI CMDs. None of the $Z = 0.05$ isochrones, however, are able to match the stars that are likely to represent the core helium-burning clump at $V \sim 15.2$, $(V-I) \sim 1.72$ $(B-V = 1.65)$. The inferred reddenings using the $Z = 0.05$ isochrones are also quite low, a result that contrasts with the minimum reddening of $E(B-V) = 0.58 \pm 0.09$ derived by Friel et al. (1997) using a spectroscopic technique, and by Kaluzny (1994) who found $E(V-I) \geq 0.7$ and $E(B-V) \geq 0.5$. The derived ratio of $E(V-I)/E(B-V)$ for the $Z = 0.05$ isochrones, however, is close to the value of 1.25 found by Dean et al. (1978).

The $Z = 0.02$ isochrones generally provide a much better match to all features in the cluster CMD than do the $Z = 0.05$ isochrones. For all ages, the match of the $Z = 0.02$ isochrones to the main sequence is quite good. The match of the isochrones to the slope of the upper red giant branch is less satisfactory than that found for the $Z = 0.05$ isochrones but is nevertheless reasonable for most of the stars in the cluster CMD. All of the $Z = 0.02$ isochrones provide a reasonable, but by no means perfect, match to the clump stars. The derived ratios of $E(V-I)/E(B-V)$ are in reasonable agreement with the value found by Dean et al. (1978).

The $Z = 0.008$ isochrones generally provide good matches to the BV CMD, but with the exception of the 13.2 Gyr isochrone, they fail to match the shape of the VI cluster main sequence. The $Z = 0.008$ isochrones also fail to match the shape of the upper red giant branch. These results suggest that the metallicity of Be 17 is higher than $Z = 0.008$. However, the poor agreement of VI isochrones to the well-studied open cluster M67 (Montgomery et al. 1993) may suggest that the VI isochrones themselves may have problems, so the poor match of the VI isochrones may not automatically preclude a metallicity as low as

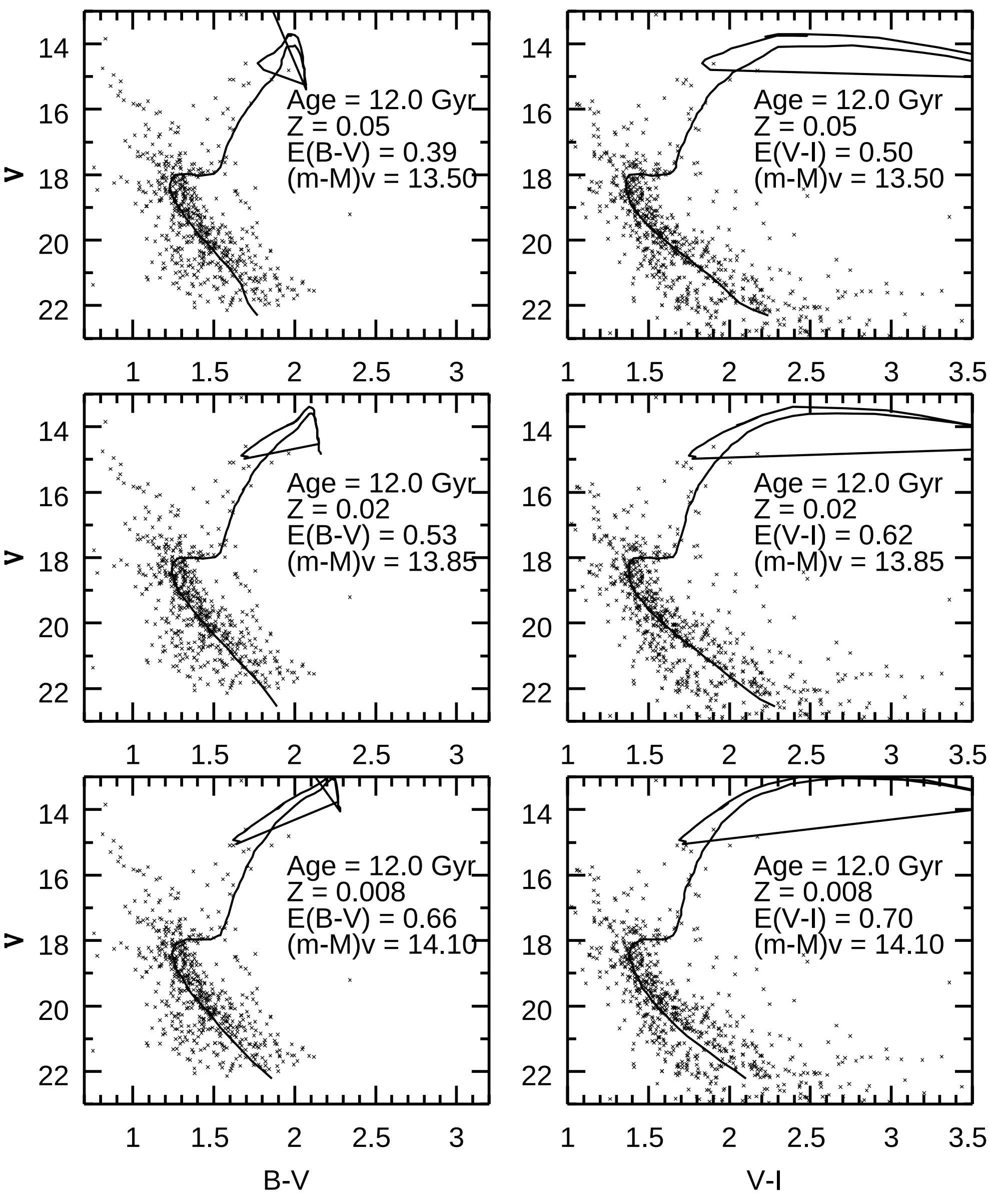

FIG. 8.—12.0 Gyr Bertelli et al. (1994) isochrone matches to the V, $B-V$ and V, $V-I$ color-magnitude diagrams of Be 17 for metallicities, Z, 0.05, 0.02, and 0.008.

$Z = 0.008$. The $Z = 0.008$ isochrones do provide a much better match to the clump stars than do the higher metallicity isochrones. However, the derived values of $E(V-I)/E(B-V)$ are significantly lower than those found by Dean et al. (1978).

5. ADOPTED CLUSTER PROPERTIES

5.1. *Metallicity*

The metallicity range used for the isochrone matches covers the range $-0.40 \leq [\mathrm{Fe/H}] \leq 0.40$. The higher metallicity Bertelli et al. (1994) isochrones tend to match the shape of the main sequence and giant branch better than do the lower metallicity isochrones, which in turn tend to match the location of the clump stars better than do the higher metallicity isochrones. The best match of the VandenBerg (1985) isochrones to the cluster CMD occurs for the 12.5 Gyr, $[\mathrm{Fe/H}] = -0.23$ isochrone, which matches both the shape of the main sequence and the turnoff region. Friel (1995) lists the spectroscopically determined metallicity of Be 17 as $[\mathrm{Fe/H}] = -0.29$ with an uncertainty estimated to be about 0.1 dex. The most probable range of the metallicity, [Fe/H], is therefore taken to be $-0.3 \leq [\mathrm{Fe/H}] \leq 0.0$, with little hope of improving upon this estimate with only the current data.

5.2. *Reddening*

Kaluzny (1994) inferred a reddening of $E(V-I) \geq 0.7$ and $E(B-V) \geq 0.5$, based on a comparison of the CMD to that of the (presumed) more metal rich open cluster NGC 6791. Using the mean colors of clump stars found in the sample of old open clusters as given in Janes & Phelps (1994) (see § 3.4), values of $E(V-I) = 0.72$ and $E(B-V) = 0.70$ are found. Using the Bertelli et al. (1994) isochrones, reddenings of $0.39 \leq E(B-V) \leq 0.68$ and $0.49 \leq E(V-I) \leq 0.71$ are inferred. Since the colors of the VandenBerg (1985) isochrones are known to be less reliable, only the Bertelli et al. (1994) isochrones are used to constrain the reddening.

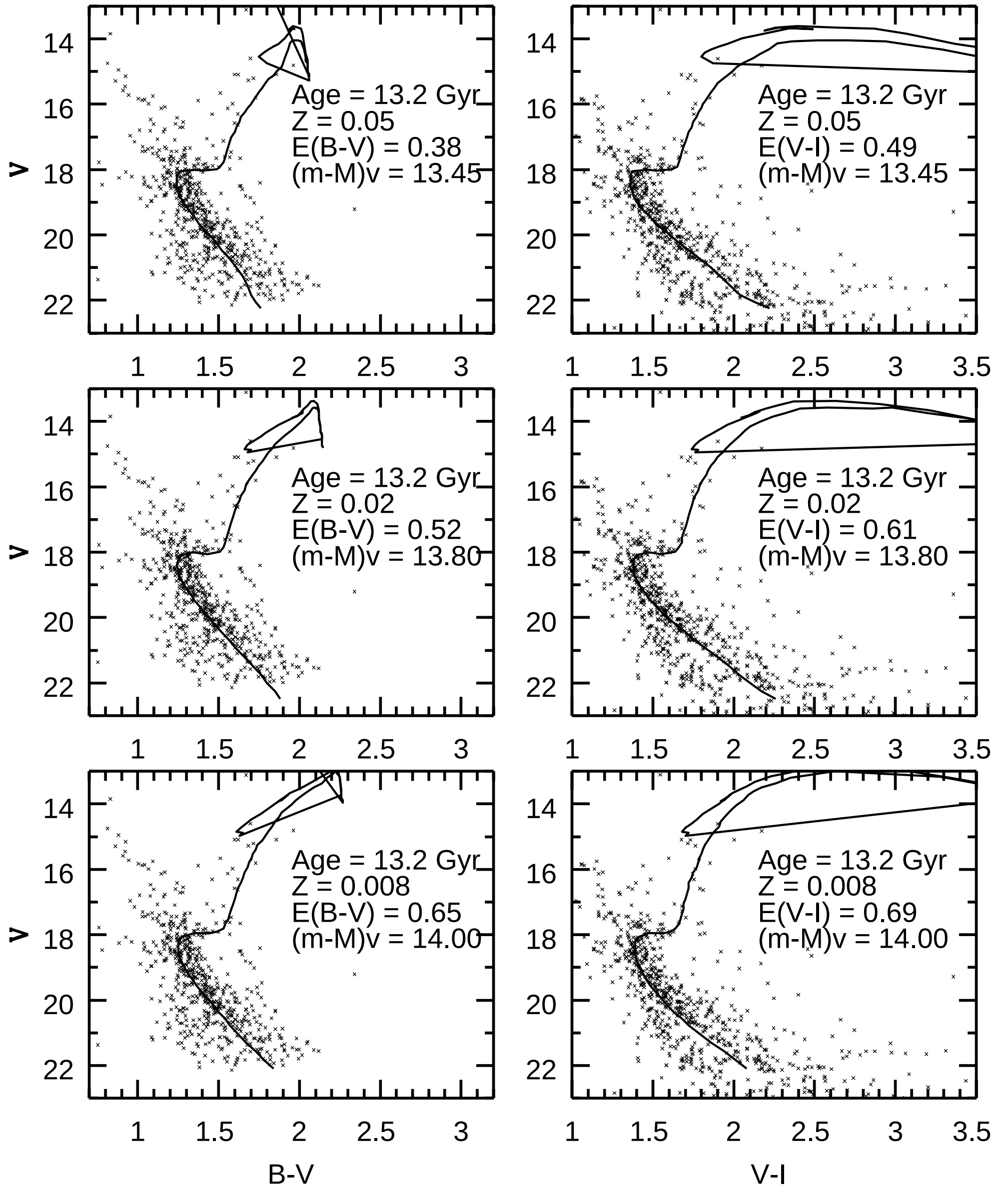

FIG. 9.—13.2 Gyr Bertelli et al. (1994) isochrone matches to the V, $B-V$ and V, $V-I$ color-magnitude diagrams of Be 17 for metallicities, Z, 0.05, 0.02, and 0.008.

Using the metallicity of $-0.3 \leq [\mathrm{Fe/H}] \leq 0.0$ as above, the reddening as determined from the isochrones is constrained to be $0.52 \leq E(B-V) \leq 0.68$ and $0.61 \leq E(V-I) \leq 0.71$, generally consistent with the values derived by Kaluzny (1994).

5.3. *Distance*

Kaluzny (1994), based on a comparison of Be 17 to NGC 6791, determined $(m-M)_v \geq 15.0$, or a distance of 4.4 kpc assuming a value $E(V-I) = 0.7$. Using the morphology of the CMD, values of $(m-M)_v = 14.30$, $(m-M)_0 = 12.13$, and a distance of 2.7 kpc from the Sun are found (§ 3.4). Again using only the Bertelli et al. (1994) isochrones, and using only the isochrone matches in the range $-0.3 \leq [\mathrm{Fe/H}] \leq 0.0$ (§ 5.1), limits of $13.80 \leq (m-M)_v \leq 14.30$ are obtained, corresponding to limits in the true distance modulus of $(m-M)_0 = 12.15 \pm 0.10$ and in the distance of 2.7 ± 0.1 kpc. The error in the distance was obtained using equation (14) in Phelps & Janes (1994). The distance inferred from both the isochrone matches and that from the use of the red giant clump are considerably lower than that found by Kaluzny (1994).

5.4. *Size*

The small field of view obtained with 2.1 m/CCD combination (5′.1) relative to the large cluster size (diameter 7′: Lynga 1987) precluded an estimate of the cluster size using our data. Kaluzny (1994), however, obtained wide field images (23′ × 23′) of the cluster using the KPNO 0.9 m telescope, which allowed him to estimate the cluster diameter to be about 13′, based on star counts as a function of distance from the cluster center. With our adopted distance of 2.7 kpc, an angular diameter of 13′ corresponds to a linear diameter of ~ 10 pc, a size that places Be 17 at the high end of the old open cluster size distribution (see Fig. 6 in Janes & Phelps 1994).

TABLE 3

Be 17: Adopted Values

Parameter	Value
$\alpha(1950)$	05:17:24
$\delta(1950)$	+30:33
Longitude	175.65
Latitude	−3.65
Age	12.0^{+1}_{-2} Gyr
$E(B-V)$	0.52–0.68
$E(V-I)$	0.61–0.71
[Fe/H]	0.00 to −0.30
R.V.[a]	-84 ± 10 km s^{-1}
$(m-M)_0$	12.15 ± 0.10
Distance	2.7 ± 0.1 kpc
R_g[b]	11.2 ± 0.2 kpc
Z	-160 ± 20 pc
Diameter	10 pc

[a] From Scott et al. 1995.
[b] Assuming $R_0 = 8.5$ kpc.

5.5. *Mass*

Our data, covering only a portion of the cluster, do not permit an estimate of the cluster mass to be made. Using wider field 0.9 m data, however, Kaluzny (1994) determined that a minimum of 400 cluster members with magnitudes in the range $17.8 \le V \le 20.0$ are present in the cluster. Using our derived range of $(m-M)_v$ (§ 5.3) and the mass-luminosity relation of Scalo (1986), this corresponds to 400 cluster members with absolute magnitudes in the range $3.5\text{–}4.0 \le M_v \le 5.7\text{–}6.2$, or masses in the range $1.2\text{–}1.3 \ge M/M_\odot \ge 0.8\text{–}0.9$. Assuming an average stellar mass of 1 $M_\odot$, this corresponds to a cluster mass of $\sim 400\ M_\odot$. Given the incompleteness of the photometry at faint magnitudes and the likelihood that the mass function is rising for still lower masses, the estimated mass of Be 17 is likely to be considerably greater than 400 $M_\odot$ but still well within the range of masses observed for other old open clusters (e.g., $\ge 700\ M_\odot$ for M67: Montgomery et al. 1993; $\ge 4000\ M_\odot$ for 092-sc18: Kassis, Friel, & Phelps 1996) and considerably less massive than the globular clusters (see, e.g., Pryor & Meylan 1993).

5.6. *Age*

The uncertainty in the reddening and metallicity make a definitive determination of the cluster age difficult. Nevertheless, the matches to the VandenBerg (1985) isochrones strongly suggest an age near 12.5 Gyr, while the Bertelli et al. (1994) isochrone matches suggest a range in age between 10 and 13 Gyr. An age of 12^{+1}_{-2} is therefore adopted for Be 17.

5.7. *Kinematics*

The only information currently available concerning the kinematics of Be 17 is from the radial velocity study of Scott, Friel, & Janes (1995). The Scott et al. study reveals Be 17 to have a heliocentric radial velocity of -84 km s^{-1}, which, given the Galactic longitude of the cluster (175.75), reflects a high velocity toward the Galactic center. At 88 km s^{-1}, Be 17 also has the largest deviation from the Galactic rotation curve of any of the clusters they studied.

The adopted parameters for Be 17 are given in Table 3.

6. DISCUSSION

6.1. *Be 17: The Transition from Globular Clusters and Open Clusters*

With a metallicity of $-0.3 \le [\mathrm{Fe/H}] \le 0.0$, a location near the Galactic plane, and a mass of $\ge 400\ M_\odot$, Be 17 has many characteristics of an open cluster. However, its age of ~ 12 Gyr is considerably higher than the next known old open cluster, NGC 6791, which has an age of ≤ 10 Gyr. Also, the ~ 10 pc diameter of Be 17 places it at the high end of the open cluster size distribution (Janes & Phelps 1994). The youngest known globular cluster is Terzan 7, with an age of ~ 9 Gyr and a metallicity of $[\mathrm{Fe/H}] \sim -0.4$ (Chaboyer, Demarque, & Sarajedini 1996). Several other globulars, including Pal 12, Arp 2, Ru 106, and IC 4499, are also thought to be young, although their metallicities are considerably lower than Terzan 7 (Chaboyer et al. 1996). It is apparent, based on age and metallicity considerations, that Terzan 7 and Be 17 may represent "transition" clusters, those with properties intermediate between open and globular clusters. Clearly, Be 17 will play an important role in understanding not only the transition from the halo to the disk of the Milky Way but also for understanding the transition from globular to open clusters.

6.2. *Be 17 and the Age of the Galactic Disk: Is the Disk Older than the Universe?*

Although Be 17 has characteristics of a "transition" object, including a high radial velocity, its location in the outer Galaxy and proximity to the Galactic plane, as well as the fact that it has properties in common with open clusters, suggests that the cluster is a thin disk object. Proper motion data, leading to an orbit determination, are clearly required in order to ascertain whether this designation as a thin disk object is correct.

If Be 17 is a thin disk object, however, its adopted age of 12 Gyr places an important constraint on the timescale for the formation of the disk and also provides an important constraint for a minimum age of the universe itself. Recent determinations of the Hubble constant, H_0, from the *HST* Extragalactic Distance Scale Key Project suggest the value of H_0 is ~ 70 km s^{-1} Mpc^{-1} (see, e.g., Freedman et al. 1997; Madore et al. 1997), which gives an expansion age for the universe of ~ 9.5 Gyr based on the Einstein–de Sitter cosmology ($\Lambda = 0, \Omega = 1$) or ~ 13.5 Gyr for $\Lambda = 0$ and $\Omega = 0$. Although it is widely recognized that the current isochrone age estimates for globular clusters (see, e.g., Chaboyer et al. 1996) are in conflict with these low ages, it has not been widely appreciated that recent age estimates of the age of the Galactic disk are also providing problems for the cosmologically determined low ages of the universe. Unlike the case for the halo, which is dated by isochrone age estimates of globular clusters, the age of the disk can be independently dated with white dwarf cooling theory and the observed white dwarf luminosity function. An age of 12 Gyr for Be 17 is consistent with recent determinations of the age of the disk from new white dwarf cooling curve models, which give an age of the disk between 10 and 13 Gyr, with the most likely value being ~ 12 Gyr (Hernanz et al. 1994). An age of 12 Gyr for the Galactic disk, based on two independent methods, provides an important constraint on the minimum age of the universe since it is universally recognized that the halo globular cluster system must be older than the Galactic disk.

7. SUMMARY

Faint magnitude *BVI* CCD photometry of the central region of the old open cluster Berkeley 17 (Be 17) confirms the Phelps et al. (1994) claim that it is the oldest open cluster yet discovered. The adopted parameters for the cluster are a metallicity $-0.30 \leq [Fe/H] \leq 0.00$; a reddening $0.52 \leq E(B-V) \leq 0.68$ or $0.61 \leq E(V-I) \leq 0.71$; a distance modulus, $(m-M)_0 = 12.15 \pm 0.10$, corresponding to a distance of 2.7 ± 0.1 kpc; a diameter of ~ 10 pc; a minimum mass of 400 $M_\odot$; and an age of 10–13 Gyr, with ~ 12 Gyr being the most likely age. The old age and relatively high metallicity indicate that Be 17 is an important object for understanding the differences between open and globular clusters, and for understanding the transition from the halo/thick disk to the thin disk of the Galaxy. If Be 17 is confirmed to be a thin disk object, its age of 12 Gyr, coupled with independent, similar estimates of the age of the disk from white dwarf cooling curve theory, indicate that the Galactic disk is ~ 12 Gyr old. Since the Galactic halo is known to be older than the disk, an age of 12 Gyr for the disk places important constraints on the minimum age of the universe itself.

The photometry file for Be 17 is available by request from the author and it will also be available through the AAS CD-ROM Series, Vol. 9.

The author would like to thank Kenneth A. Janes and Eileen D. Friel for many hours of insightful discussions on the Galactic system of old open star clusters. Appreciation is also extended to Wendy L. Freedman for the opportunity to pursue my independent research while working on the *HST* Extragalactic Distance Scale Key Project. Finally, the author wishes to extend his thanks to the referee for comments and suggestions that have improved the quality of the work.

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