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DEVELOPMENT OF THE GALACTIC DISK: A SEARCH FOR THE OLDEST OPEN CLUSTERS

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ABSTRACT

In an extensive CCD photometric survey of potential old open clusters, we have identified a number of systems that are indeed old; some of them are among the oldest of the open clusters. Using our versions of two well-known morphological age indices, one based on the luminosity difference between the main sequence turnoff and the horizontal branch and the other on the color difference between the turnoff and the giant branch, we have ranked the open clusters in approximate order of age. Our data together with previously published photometry of other old open clusters, yields a catalogue of 72 clusters of the age of Hyades or older with 19 of the clusters as old or older than M67 (about 5 Gyr). Among the oldest open clusters are Be 17, Cr 261, NGC 6791, Be 54, and AM 2. Be 17 and another old cluster, Lyngå 7, are possibly as old as the youngest globulars. The data also suggest that the formation rate of open clusters may have been higher early in the history of the disk than at intermediate times since numerous clusters have survived from that time.

1. INTRODUCTION

At the present time we do not know the ages of the oldest disk stars. Winget *et al.* (1987) concluded that the oldest white dwarfs are about 9 Gyr in age, and at least one old open cluster, NGC 6791, is thought to be approximately the same age (Garnovich *et al.* 1993; Meynet *et al.* 1993). If these ages do represent the age of the Galactic disk, there may have been little or no delay in time between the formation of the halo and the beginning of the development of the disk, since the youngest halo globulars are thought to be only slightly older than this (Chaboyer *et al.* 1992). That would suggest some continuity between the formation of the halo and the growth of the disk. Yet, recent observations such as those by Carney *et al.* (1990), leave one with the distinct impression that the disk and the halo are rather disconnected from one another (see especially, Fig. 3 of Carney *et al.*).

The problem is to find ways to date the oldest disk stars. Since the only old objects in the Galaxy whose ages we can reliably date are the star clusters, they constitute a powerful tool for probing Galactic structure and the formation and development of the Galactic disk. In addition to the known 135 or so globular clusters, which define the halo, over 1200 open clusters are known to exist. However, only about one-third of the open clusters have sufficiently well-determined photometry to permit the estimation of their ages and other parameters, and the vast majority of them are much younger than the Galaxy. Unfortunately for the present problem, most open clusters are destroyed by interactions with molecular clouds on time scales of a few hundred mil yr or less (Spitzer 1958). Janes *et al.* (1988) found that the median age of clusters whose ages have been estimated is about 100 mil yr.

However, some open clusters survive for billions of years, and a few may be as old as the disk. Until recently only a handful of such clusters were known, with most of them located in the outer disk of the Galaxy and far from the Galactic plane, compared to most open clusters. Because the old clusters are of such importance for an understanding of Galactic evolution, several searches for additional clusters have been made. King (1964) published a list of clusters that appeared to be old on the basis of their appearance on the Palomar Observatory Sky Survey (POSS) prints. He recognized that a young cluster will appear to contain only a few bright stars, while in an old cluster there will be a substantial number of stars of about the same magnitude. "Old" in this context means a cluster with a significant population of giant stars which typically means clusters as old or older than the Hyades.

Most of the clusters in King's list have now been observed and were found to be old systems. Janes & Adler (1982) presented a somewhat expanded list of unstudied, rich open clusters using the King prescription and Janes & Phelps (1990) derived a more extensive list based on a systematic examination of clusters in the Lund Catalog of Open Clusters (Lyngå 1987). Janes and Phelps limited the

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TABLE 1. Summary of observations.

Cluster	Date	Observatory	Telescope	Detector	Scale ("/pix)	Field (arcmin)	Filters	Calibrated
NGC 188	1992 Sept. 1/2	KPNO	0.9m	T2KA	0.68	23x23	BV	Y
King 2	1992 Dec. 16/17	KPNO	2.1m	T1KA	0.30	5.1x5.1	BVI	N
NGC 1193	1989 Sept. 28/29	KPNO	0.9m	Tek1	0.77	6.6x6.6	BV	N
NGC 1220	1992 Aug. 30/31	KPNO	0.9m	T2KA	0.68	23x23	BVI	N
King 5	1991 Nov. 29/30	KPNO	0.9m	T2KB	0.68	23x23	VI	Y
King 7	1992 Aug. 29/30	KPNO	0.9m	T2KA	0.68	23x23	BVI	N
NGC 1798	1989 Sept. 25/26	KPNO	0.9m	Tek1	0.77	6.6x6.6	BV	N
Be 17	1991 Nov. 29/30	KPNO	0.9m	T2KB	0.68	23x23	VI	Y
Be 20	1992 Dec. 16/17	KPNO	2.1m	T1KA	0.30	5.1x5.1	VI	N
Be 21	1988 Nov. 4/5	KPNO	0.9m	Tek1	0.77	6.6x6.6	BVI	Y
Be 22	1992 Mar. 5/6	CTIO	0.9m	T2K1[1]	0.80	14x14	VI	Y
NGC 2192	1990 Feb. 18/19	KPNO	0.9m	T5HA	0.77	6.6x6.6	BV	N
NGC 2266	1990 Feb. 18/19	KPNO	0.9m	T5HA	0.77	6.6x6.6	BV	N
Be 28	1992 Mar. 4/5	CTIO	0.9m	T1K2	0.40	6.6x6.6	VI	Y
Be 29	1992 Dec. 17/18	KPNO	2.1m	T1KA	0.30	5.1x5.1	BVI	N
Be 31	1991 Nov. 29/30	KPNO	0.9m	T2KB	0.68	23x23	VI	Y
Be 30	1991 Nov. 29/30	KPNO	0.9m	T2KB	0.68	23x23	VI	Y
Be 32	1991 Feb. 23/24	CTIO	0.9m	Tek1024	0.40	6.8x6.8	BVI	N
To 2	1990 Mar. 1/2	CTIO	0.9m	Tek4	0.45	3.8x3.8	BVI	Y
NGC 2355	1990 Feb. 18/19	KPNO	0.9m	T5HA	0.77	6.6x6.6	BV	N
Be 39	1988 Nov. 6/7	KPNO	0.9m	Tek1	0.77	6.6x6.6	BV	N
Pi 2	1992 Mar. 5/6	CTIO	0.9m	T2K1[1]	0.80	14x14	VI	Y
	1991 Feb. 24/25	CTIO	0.9m	Tek1024	0.40	6.8x6.8	BVI	N
NGC 2627	1992 Mar. 4/5	CTIO	0.9m	T1K2	0.40	6.6x6.6	VI	Y
NGC 2671	1991 Feb. 20/21	CTIO	0.9m	Tek1024	0.40	6.8x6.8	BV	N
NGC 2849	1990 Mar. 2/3	CTIO	0.9m	Tek4	0.45	3.8x3.8	VI	N
092-SC18	1992 Mar. 4/5	CTIO	0.9m	T1K2	0.40	6.6x6.6	BV	Y
Cr 261	1992 Mar. 4/5	CTIO	0.9m	T1K2	0.40	6.6x6.6	VI	Y
NGC 4815	1992 Mar. 5/6	CTIO	0.9m	T2K1[1]	0.80	14x14	VI	Y
096-SC04	1990 Mar. 1/2	CTIO	0.9m	Tek4	0.45	3.8x3.8	BV	Y
	1992 Mar. 5/6	CTIO	0.9m	T2K1[1]	0.80	14x14	VI	Y
Pi 19	1992 Mar. 5/6	CTIO	0.9m	T2K1[1]	0.80	14x14	VI	Y
	1990 Feb. 27/28	CTIO	0.9m	Tek4	0.45	3.8x3.8	BVI	N
NGC 6827	1989 Sept. 22/23	KPNO	0.9m	Tek1	0.77	6.6x6.6	BVI	N
Be 54	1989 Sept. 23/24	KPNO	0.9m	Tek1	0.77	6.6x6.6	BV	Y
Be 56	1991 Nov. 29/30	KPNO	0.9m	T2KB	0.68	23x23	VI	N
King 9	1989 Sept. 27/28	KPNO	0.9m	Tek1	0.77	6.6x6.6	VI	Y
King 10	1989 Sept. 24/25	KPNO	0.9m	Tek1	0.77	6.6x6.6	VI	Y
NGC 7419	1992 Sept. 1/2	KPNO	0.9m	T2KA	0.68	23x23	BV	N
King 11	1988 Nov. 6/7	KPNO	0.9m	Tek1	0.77	6.6x6.6	BVI	Y

[1] CCD binned 2x2

examination of clusters to those with estimated angular diameters less than 10 arcmin that are of Trumpler (1930) richness class "*r*" or "*m*," on the premise that larger clusters have either already been observed, or there are practical reasons why they are unobservable. For example, some clusters are located toward nebulous regions and others are poorly separated from rich star fields. We selected as candidate old clusters, those containing a large number of stars which are clearly separated from the field and in which a number of the brightest stars are about the same magnitude. The technique for identifying candidate old clusters is not sensitive to the actual age of the cluster, however, since clusters old enough to contain giants appear similar on sky survey prints regardless of whether they are very old or closer to the Hyades in age.

2. THE SEARCH PROGRAM

Many of the clusters in the Janes and Phelps and Janes and Adler lists have now been observed; we report here on a program in which we observed all but a few of the rest, along with a number of other old clusters. Although many of the clusters are faint, or located in crowded star fields, broadband (*B*, *V*, and *I*) photometry with a CCD on a 1 m class telescope reaches to at least the giants and main sequences of all of the candidate old clusters, permitting reasonable age estimates to be made in all but a few cases. We conducted the survey with the KPNO and CTIO 0.9 m telescopes and the KPNO 2.1 m telescope using available CCD detectors over the past 6 yr. Several observing runs were dedicated to this project, but many of the images were obtained when gaps or marginal weather occurred during other observing programs. Keeping in mind that the purpose for the survey was to identify which clusters are actually old, and to get preliminary estimates of the relative ages of the clusters, this was an effective use of poor observing conditions.

The images were processed following standard procedures described in the IRAF[3] CCDPROC documentation. The CCD zero level (bias) was determined from the me-

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

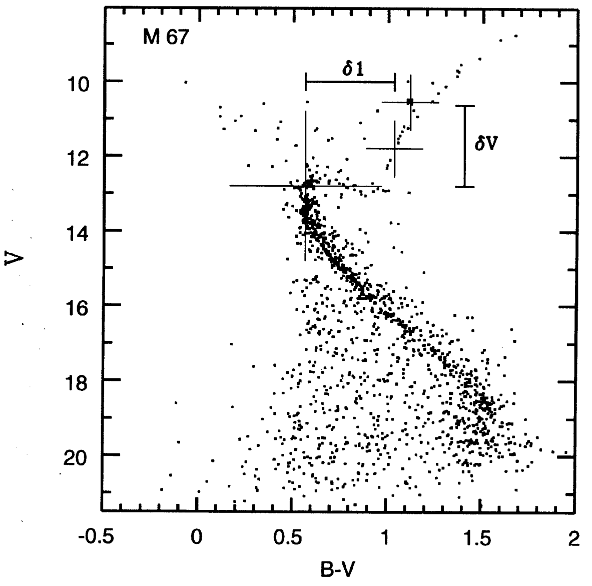

FIG. 1. Illustration of the determination of δV and $\delta 1$ using the photometry of M67 from Montgomery *et al.* (1993). The large cross indicates the color and magnitude of the main-sequence turnoff while the smaller crosses indicate the positions of the clump, used for the measurement of δV, and the point on the giant branch 1 mag brighter than the main-sequence turnoff, used to measure $\delta 1$.

dian of approximately 20 frames of zero exposure time. Flatfield frames were generally constructed using sky images taken during twilight, in regions relatively devoid of stars. Approximately 10 exposures, each a few thousand ADU above bias, were obtained with the telescope position randomly moved several tens of arcsec between exposures. The sky frames were subsequently merged using the sigma clipping algorithm in IRAF to remove stellar images and the resulting frame was used for the flatfield correction. When sky frames were not obtained (due to overcast skies at twilight, for example), dome flats were used. Bias subtraction and flatfielding were performed by standard techniques with the NOAO IRAF package.

The Stellar Photometry Software (SPS) point-spread function photometry package (Janes & Heasley 1993) was used to obtain instrumental magnitudes from the CCD frames. Whenever possible, the instrumental magnitudes were tied to the Landolt standard star observations (Landolt 1973, 1983), or the Graham (1982) *E*-region standards, by a variation on the method of Harris *et al.* (1981) (see Phelps & Janes 1994). On many of the KPNO nights, stars in M67 were also observed and treated as standards, using the values from Montgomery *et al.* (1993).

Because some of the observing was done under marginal conditions, not all of the cluster photometry could be transformed to the standard *BVI* colors and magnitudes. Nevertheless, the photometry is still useful for the present purposes. For if the CCD detector is a truly linear device, the observed instrumental color–magnitude diagram (CMD) of a cluster will differ from a proper CMD that is strictly on the photometric system by a unknown zero point error in (V) magnitude plus a small color term and by an unknown zero point and scale factor in color index ($B-V$ or $V-I$). But even the proper, transformed CMD will itself differ from a "true" CMD by a zero point error in M_V due to the generally unknown distance modulus and a zero point error in color index due to the interstellar reddening which is also generally unknown. Finally, if this hypothetical true CMD were to be compared to theoretical CMDs for the purpose of estimating ages, the comparison would also suffer from uncertainties in magnitude zero points and color zero points and scale terms in the theoretical diagrams.

As has been noted by Bolte (1992), to find the *morphology* of a cluster CMD, which at the present time provides the best determinant of a cluster's age, it is sufficient to account reasonably well for color transformations, but magnitude and color zero points are unnecessary. The color terms are functions of airmass (atmospheric extinction) and the instrumental spectral response characteristics of the filters, telescope, and detectors. With modern instrumentation, the latter are extremely consistent from night to night, and even from year to year. The extinction color terms will generally not change dramatically at a given observatory over short periods of time, although large changes from one year to another may occur (e.g., as a result of events such as the 1989 Mount Pinatubo eruption). For that reason, even though many of the nights on which the present observations were made may not have been photometric, we have accumulated enough photometric extinction and transformation information from the observing runs in question to correct all the photometry except for the zero points in color index and magnitude.

Table 1 summarizes the observing program and lists the clusters for which we have used our observations in the analysis. We have chosen not to present tables of the photometry of individual stars, partly because of the huge amount of data involved, and partly to avoid possible future misunderstandings relating to those clusters for which the magnitudes are on the instrumental photometric system.

3. MORPHOLOGICAL AGES OF CLUSTERS

The difficulties inherent in fitting theoretical isochrones to observed star cluster CMDs have prompted a number of attempts to parametrize the morphology of either the theoretical diagrams (Janes & Demarque 1983) or the observational diagrams (Anthony-Twarog & Twarog 1985). The concept of the "morphological age" of a cluster was introduced by Anthony-Twarog and Twarog, who computed the ratio of the difference between the luminosity of the main-sequence turnoff and that of the horizontal branch to the color difference between the turnoff and the giant branch. Similar strategies were used by VandenBerg *et al.* (1990), Sarajedini & Demarque (1990), and Buonanno *et al.* (1989). All of their morphological indices are attempts to quantify the visible differences in the CMDs of stellar systems of different ages in a way that bypasses the many observational and theoretical calibration problems.

Table 2. Morphological age parameters of old open clusters.

Cluster	δV	δ_1	δV	δ_1	Source	Cluster	δV	δ_1	δV	δ_1	Source
	V,(B-V)		V,(V-I)				V,(B-V)		V,(V-I)		
NGC 188	-	0.39	-	—	10	NGC 2423	0.1	—	-	—	BDA
	-	0.35	-	—	Table 1	Mel 71	0.5	—	-	—	20
King 2	2.2	—	-	—	9	NGC 2420	1.6	0.58	-	—	BDA
	2.2	—	2.2	—	Table 1	AM 2	2.4	0.33	-	—	5
IC 166	1.0	—	-	—	BDA	Be 39	2.7	0.43	-	—	15
NGC 752	0.9	—	-	—	BDA		2.6	0.41	2.6	0.37	16
NGC 1193	-	0.44	-	—	8		2.6	0.37	2.5	0.37	Table 1
	-	0.45	-	—	Table 1	NGC 2477	0.5	—	-	—	BDA
King 5	-	—	0.4	—	Table 1	NGC 2506	1.4	0.59:	-	—	BDA
NGC 1245	0.7	—	-	—	BDA	Pi 2	-	—	1.0	—	Table 1
Hyades	0.4	—	-	—	BDA		1.1	—	1.1	—	Table 1
NGC 1798	0.8	0.70	-	—	Table 1	NGC 2627	-	—	1.6	—	Table 1
NGC 1817	0.8	—	-	—	BDA	Praesape	0.3	—	-	—	BDA
Be 17	-	—	2.8	0.31	Table 1	NGC 2660	0.4	—	-	—	BDA
Be 18	2.1	0.37	-	—	11	M 67	2.3	0.46	2.3	0.35	19
Be 20	-	—	-	0.41	Table 1	NGC 2849	-	—	0.5	—	Table 1
King 8	0.2	—	-	—	BDA	092-SC18	-	—	2.2:	0.40:	Table 1
Be 21	1.5	0.56	1.6	0.51	Table 1	NGC 3680	1.0	—	-	—	BDA
Be 22	-	—	2.0	0.41	Table 1	NGC 3960	0.2	—	-	—	6
NGC 2141	1.9	0.65:	-	—	BDA	Cr 261	-	—	2.5	0.34	Table 1
NGC 2158	1.2	0.59:	-	—	BDA	NGC 4815	-	—	1.1:	—	Table 1
NGC 2194	0.5	—	-	—	BDA	096-SC04	0.2:	—	-	—	Table 1
NGC 2192	0.6	—	-	—	Table 1	NGC 5822	0.8	—	-	—	21
NGC 2204	1.5	0.66:	-	—	BDA	IC 4651	1.2	—	-	—	3
NGC 2236	0.4	—	-	—	BDA	IC 4756	0.4	—	-	—	BDA
NGC 2243	2.1	0.43	-	—	BDA	Be 42	0.4	—	-	—	BDA
Tr 5	2.2	0.38	-	—	7	NGC 6791	2.8	0.34	2.8	0.33	17
NGC 2266	0.5	—	-	—	Table 1	NGC 6802	0.4	—	-	—	BDA
	0.4	—	-	—	13	NGC 6819	1.7	0.55	-	—	BDA
Be 29	2.1	0.43	2.0	0.42	Table 1	NGC 6827	0.5	—	0.6:	—	Table 1
Be 31	-	0.47	-	0.38	4	IC 1311	0.2	—	-	—	1
	-	—	-	0.34	Table 1	NGC 6939	1.4	0.66:	-	—	BDA
Be 30	-	—	0.3	—	Table 1	NGC 6940	0.2	—	-	—	BDA
Be 32	2.5	0.39	2.5	0.36	Table 1	Be 54	2.4	0.35	-	—	Table 1
	2.4	0.41	-	—	12	NGC 7044	0.7	—	-	—	9
To 2	1.4	0.55	1.4	0.54	Table 1	Be 56	—	—	2.3	0.39	Table 1
	1.5	0.57	1.5:	0.58	18	NGC 7142	2.1	0.53	-	—	BDA
NGC 2324	0.3	—	-	—	BDA	King 9	—	—	1.8:	0.41	Table 1
NGC 2354	0.8	—	-	—	BDA	King 11	2.3	0.42	-	—	2
NGC 2355	0.6	—	-	—	Table 1		2.6:	0.46:	-	—	9
	0.2	—	-	—	14		2.2	0.41	-	—	Table 1
NGC 2360	0.5	—	-	—	BDA	NGC 7789	1.0	0.70	-	—	BDA
Mel 66	2.1	0.36	-	—	BDA						

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BDA – Mermilliod 1992

The horizontal branch is a distinctive feature of globular cluster CMDs but the analogous structure in an open cluster CMD generally has the appearance of a "clump" just on the blue side of the red giant branch. We have adopted as our primary age parameter, an index δV, defined as the magnitude difference between the main-sequence turnoff and the clump. Observationally, the luminosity of the main-sequence turnoff, when defined as the magnitude at the bluest point on the CMD, is intrinsically a poorly defined quantity, as the cluster sequence lies along a line of nearly constant color for almost a magnitude in luminosity. The problem is compounded in the open clusters, first because they contain far fewer stars than the globulars, and second because many open clusters have a substantial binary star sequence. A better measure of the main-sequence turnoff luminosity can be found at the inflection point on the CMD between the turnoff and the base of the giant branch. This parameter is well defined even when the photometry is of marginal quality and even in the presence of a binary sequence or substantial numbers of field stars. In the following discussion, we will call the magnitude at this inflection point the "turnoff magnitude." We have chosen the notation δV to avoid confusion with the slightly different index, ΔV, that has been used by others.

We have also defined another CMD age parameter, independent of δV, from color differences. Our color index parameter, $\delta 1$, is the difference in color index between the bluest point on the main sequence at the luminosity of the turnoff and the color of the giant branch 1 mag brighter than the turnoff luminosity. This parameter is especially

TABLE 3. Clusters found to be "young."

Name	$\alpha(1950)$ (^{h}:^{m})	$\delta(1950)$ (°:')	l (°)	b (°)
NGC 1220	03:08.0	+53:09	143.05	−3.97
King 7	03:55.2	+51:39	149.76	−1.04
Be 28	06:49.6	+03:00	210.39	+1.52
NGC 2671	08:44.4	−41:42	262.15	+0.79
NGC 2818	09:14.0	−36:25	261.99	+8.58
Pismis 19	14:26.9	−60:46	314.68	−0.38
NGC 6451	17:47.5	−30:12	359.48	−1.61
NGC 6520	18:00.2	−27:54	2.88	−2.86
NGC 6811	19:36.7	+46:27	79.44	+11.95
King 10	22:52.9	+58:54	108.49	−0.40

useful since it can be measured in clusters with no noticeable clump. Since the giant branch of many of the younger clusters does not extend more than 1 mag above the turnoff, the $\delta 1$ parameter cannot be measured from the CMDs of clusters younger than about 1.5–2.0 Gyr.

Figure 1 illustrates the determination of δV and $\delta 1$ for the well-known old open cluster M67 (NGC 2682), using data from Montgomery *et al.* (1993). For the example of M67, the parameters refer to those from BV photometry, but similar indices can be measured using VI, or other photometric indices.

We have estimated, wherever possible, both age parameters for all clusters that appear to be old, based on the available data. In addition to using the clusters for which we obtained new photometry in this program (Table 1), we searched the literature for published photometry of other clusters which appear to be old, based on the appearance of their CMDs. The actual color and magnitude estimates for the morphological parameters were made from CMDs displayed on a workstation, the graphics cursor being used to delineate the fiducial points in the cluster sequences. For the clusters listed in Table 1, we measured the parameters from our photometry; for most of the clusters with published photometry, we made use of the "BDA" (see Mermilliod 1992), a database of open cluster

TABLE 4. Omitted clusters.

Name	$\alpha(1950)$ (^{h}:^{m})	$\delta(1950)$ (°:')	l (°)	b (°)
Be 66	03:00.4	+58:34	139.42	+0.23
IC 361	04:14.8	+58:11	147.49	+5.71
Be 19	05:20.9	+29:33	176.90	−3.59
NGC 2112	05:51.3	+00:22	205.90	−12.61
Tombaugh 1	06:58.2	−20:24	232.22	−7.32
Hafner 6	07:17.8	−13:02	227.85	+0.25
Ru 46	07:59.9	−19:20	238.37	+5.89
Lyngå 7	16:07.0	−55:10	328.78	-2.77
NGC 6208	16:45.5	−53:44	333.69	−5.82
NGC 6603	18:15.5	−18:26	12.86	−1.32
NGC 6882/5	20:09.9	+26:20	65.53	−4.07
NGC 7419	22:52.3	+60:34	109.13	+1.14
NGC 7762	23:47.4	+67:45	117.20	+5.84

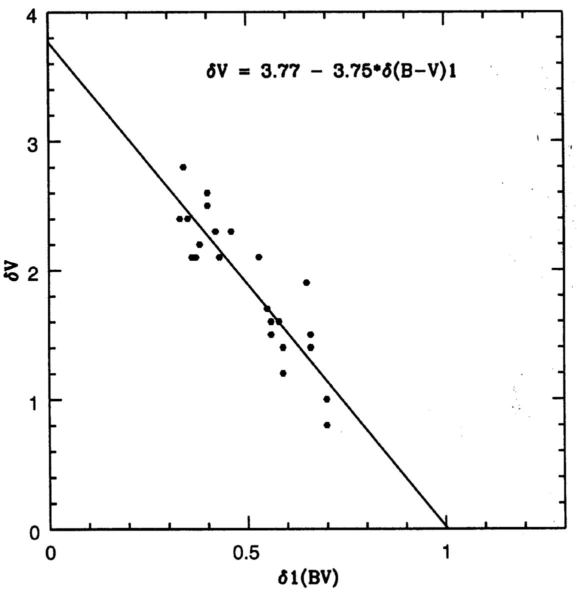

FIG. 2. Relationship between δV and $\delta 1(BV)$ for clusters where both parameters can be measured. The straight line results from a least-squares fit to the data, with coefficients given in the included equation. The rms deviation of the points about the line is 0.2 mag.

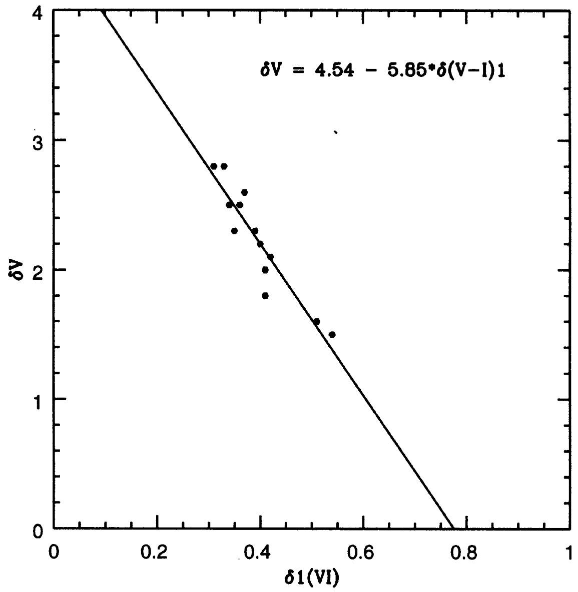

FIG. 3. Relationship between δV and $\delta 1(VI)$ for clusters where both parameters can be measured. The straight line results from a least-squares fit to the data, with coefficients given in the included equation. The rms deviation of the points about the line is 0.1 mag.

TABLE 5. Old open clusters.

Name	α(1950) (^{h}:^{m})	δ(1950) (°:')	l (°)	b (°)	δV	q	Name	α(1950) (^{h}:^{m})	δ(1950) (°:')	l (°)	b (°)	δV	q
NGC 188	00:39.4	+85:04	122.78	+22.46	2.4	b	Melotte 71	07:35.2	−11:57	228.95	+4.51	0.5	b
King 2	00:48.1	+57:55	122.88	−4.67	2.2	b	NGC 2420	07:35.5	+21:41	198.11	+19.65	1.6	a
IC 166	01:49.0	+61:35	130.08	−0.19	1.0	c	AM 2	07:37.3	−33:44	246.89	−5.09	2.5	b
NGC 752	01:54.8	+37:26	137.17	−23.36	0.9	a	Berkeley 39	07:44.2	−04:29	223.47	+10.09	2.4	a
NGC 1193	03:02.5	+44:11	146.81	−12.18	2.1	b	NGC 2477	07:50.5	−38:25	253.58	−5.83	0.5	b
King 5	03:11.0	+52:32	143.75	−4.27	0.4	b	NGC 2506	07:57.8	−10:39	230.57	+9.91	1.5	a
NGC 1245	03:11.2	+47:04	146.64	−8.93	0.7	b	Pismis 2	08:16.3	−41:28	258.83	−3.29	1.1	c
Hyades	04:24.0	+15:45	180.05	−22.40	0.4	a	NGC 2627	08:35.2	−29:46	251.58	+6.65	1.6	b
NGC 1798	05:08.1	+47:34	160.76	+4.85	1.0	b	Praesepe	08:37.2	+20:10	205.54	+32.52	0.3	a
NGC 1817	05:09.2	+16.38	186.13	−13.13	0.8	a	NGC 2660	08:40.6	−46:58	265.86	−3.03	0.4	b
Berkeley 17	05:17.4	+30:33	175.65	−3.65	2.8	b	M 67	08:47.7	+12:00	215.58	+31.72	2.3	a
Berkeley 18	05:18.5	+45:21	163.63	+5.01	2.3	b	NGC 2849	09:17.4	−40:20	265.27	+6.33	0.5	c
Berkeley 20	05:30.4	+00:11	203.50	−17.28	2.1	a	092-SC18	10:13.4	−64:22	287.1	−6.7	2.2	c
King 8	05:46.1	+33:37	176.40	+3.12	0.2	c	NGC 3680	11:23.3	−42:58	286.77	+16.93	1.0	b
Berkeley 21	05:48.7	+21:46	186.83	−2.50	1.6	c	NGC 3960	11:48.4	−55:25	294.41	+6.18	0.2	c
Berkeley 22	05:55.7	+07:50	199.80	−8.05	2.1	c	Cr 261	12:34.9	−68:12	301.69	−5.64	2.6	b
NGC 2141	06:00.3	+10:26	198.07	−5.79	1.6	c	NGC 4815	12:54.9	−64:41	303.63	−2.09	1.1	c
NGC 2158	06:04.4	+24:06	186.64	+1.76	1.4	b	096-SC04	13:11.8	−65:40	305.35	−3.17	0.2	c
NGC 2194	06:11.0	+12:49	197.26	−2.33	0.5	c	NGC 5822	15:01.5	−54:09	321.71	+3.58	0.8	c
NGC 2192	06:11.7	+39.52	173.41	+10.64	0.6	b	IC 4651	17:20.8	−49:54	340.07	−7.88	1.2	b
NGC 2204	06:13.5	−18:38	226.01	−16.07	1.4	b	IC 4756	18:36.5	+05:24	36.37	+5.26	0.4	b
NGC 2236	06:27.0	+06:52	204.37	−1.69	0.4	c	Berkeley 42	19:02.6	+01:48	36.17	−2.19	0.4	c
NGC 2243	06:27.9	−31:15	239.50	−17.97	2.2	b	NGC 6791	19:19.0	+37:45	70.01	+10.96	2.6	a
Tr 5	06:34.0	+09:29	202.86	+1.05	2.3	c	NGC 6802	19:28.4	+20:10	55.34	+0.93	0.4	c
NGC 2266	06:40.1	+27:01	187.78	+10.28	0.5	c	NGC 6819	19:39.6	+40:04	73.98	+8.47	1.7	b
Berkeley 29	06:50.4	+16:59	197.98	+8.03	2.1	a	NGC 6827	19:46.7	+21:04	58.24	−2.35	0.5	c
Berkeley 31	06:54.9	+08:20	206.26	+5.12	2.3	c	IC 1311	20:08.6	+41:04	77.70	+4.25	0.2	c
Berkeley 30	06:55.1	+03:17	210.80	+2.89	0.3	b	NGC 6939	20:30.4	+60:28	95.88	+12.30	1.4	c
Berkeley 32	06:55.4	+06:30	207.95	+4.40	2.4	b	NGC 6940	20:32.5	+28:08	69.90	−7.16	0.2	b
Tombaugh 2	07:01.2	−20:47	232.90	−6.84	1.5	a	Berkeley 54	21:01.3	+40:16	83.13	−4.14	2.5	c
NGC 2324	07:01.6	+01:08	213.45	+3.31	0.3	c	NGC 7044	21:11.1	+42:17	85.87	−4.13	0.7	b
NGC 2354	07:12.2	−25:39	238.42	−6.80	0.8	c	Berkeley 56	21:15.8	+41:41	86.04	−5.18	2.3	c
NGC 2355	07:14.1	+13:52	203.36	+11.80	0.4	b	NGC 7142	21:44.7	+65:34	105.42	+9.45	2.0	b
NGC 2360	07:15.5	−15:32	229.80	−1.42	0.5	a	King 9	22:13.6	+54:09	101.45	−1.84	2.0	c
Melotte 66	07:24.9	−47:38	259.61	−14.29	2.3	b	King 11	23:45.4	+68:21	117.16	+6.47	2.3	b
NGC 2423	07:34.8	−13:45	230.47	+3.55	0.1	c	NGC 7789	23:54.5	+56:27	115.49	−5.36	1.1	a

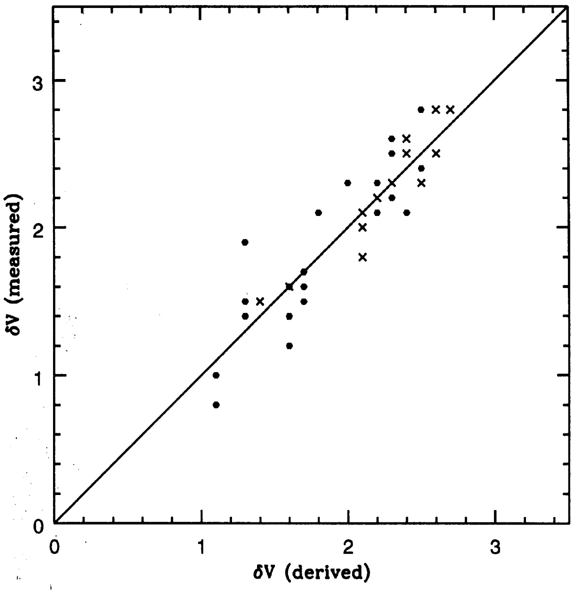

FIG. 4. Comparison of the measured δV and the δV derived from δ1(*BV*), indicated by dots, and δ1(*VI*), indicated by crosses, using the relations given in Figs. 2 and 3. The straight line is not a fit to the data, but represents a one to one correlation of the data. The rms deviation of the points about the line is 0.2 mag.

information. The individual references to the photometry are available in the BDA. In addition, for a few recent references we measured the CMD parameters directly from the published figures.

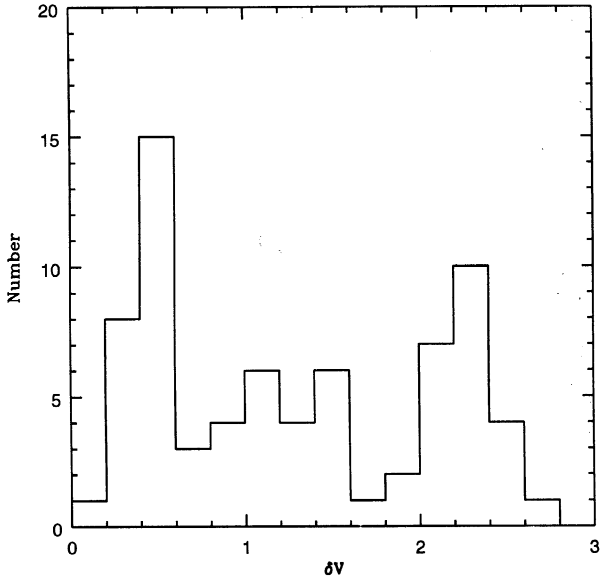

FIG. 5. Histogram of adopted δV's.

TABLE 6. The oldest open clusters.

Name	δV	Name	δV
Berkeley 17	2.8	Melotte 66	2.3
Cr 261	2.6	M 67	2.3
NGC 6791	2.6	Tr 5	2.3
AM 2	2.5	King 2	2.2
Berkeley 54	2.5	NGC 2243	2.2
Berkeley 32	2.4	092-SC18	2.2
Berkeley 39	2.4	Berkeley 20	2.1
NGC 188	2.4	Berkeley 22	2.1
Berkeley 18	2.3	Berkeley 29	2.1
Berkeley 31	2.3	NGC 1193	2.1
Berkeley 56	2.3	King 9	2.0
King 11	2.3	NGC 7142	2.0

For the clusters with new photometry (Table 1), R.L.P. and K.A.J. independently judged the fiducial points on the cluster sequences. We then compared our answers; in a few cases where our results disagreed by more than 0.02 in color or 0.2 in magnitude, we jointly reexamined the cluster data and agreed on a compromise value. Most of the disagreements stemmed from the difficulty in discerning the existence of a significant red giant clump in the more sparse cases; for several of these we simply rejected the δV values altogether. No systematic differences between our two measurements of any of the parameters were found, so the final values are straight averages of the two.

The photometric age parameters for all the clusters evaluated and found to be old are presented in Table 2. Several candidate old clusters have no obvious giant or horizontal branch and we classified them as being young.

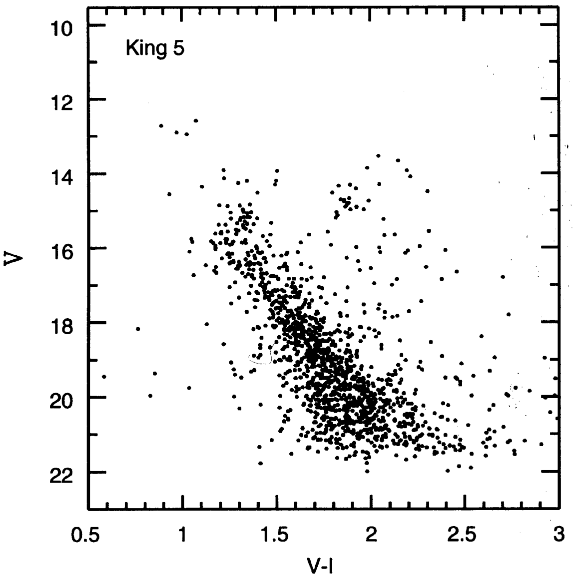

FIG. 7. *VI* CMD for King 5.

These clusters are listed in Table 3. For a few other possibly old clusters, the photometry was too limited or the field too crowded for a reliable determination of the cluster's evolutionary status; they are listed in Table 4. The clusters Be 66 and NGC 6603 are included in Table 4 because they are the two clusters from the Janes & Adler (1982) list that remain unstudied. Lyngå 7 was added to Table 4 because it is certainly very old, but its classification as an open cluster has been called into question by Ortolani *et al.* (1993). Since it is likely that several of the clusters in Table 4 are old, additional observations of them would be of interest.

The uncertainties in the morphological parameters can be estimated from the differences in the independent deter-

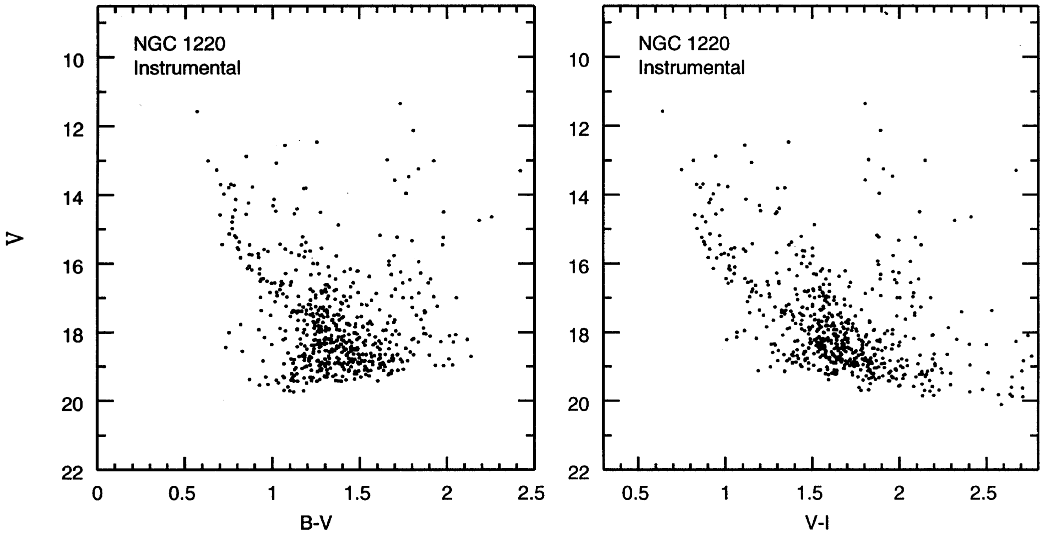

FIG. 6. Instrumental *BV* and *VI* CMDs for NGC 1220.

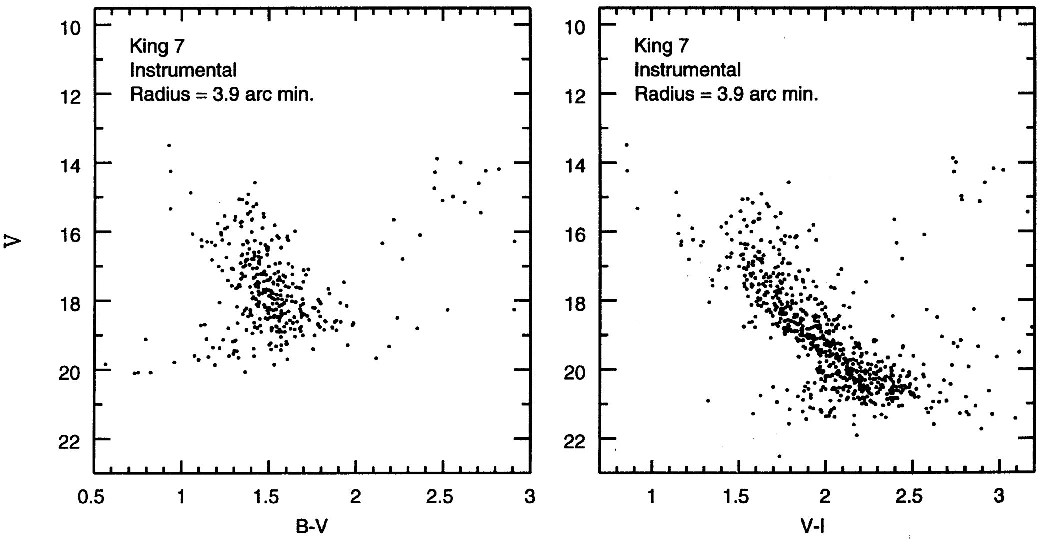

FIG. 8. Instrumental *BV* and *VI* CMDs for King 7 for stars within 3.9 arcmin of the apparent cluster center.

minations by R.L.P. and K.A.J. For these 39 clusters, the rms differences between the two estimates of the parameters are 0.1 and 0.02 for δV $\delta 1$, respectively. We consider these values to be indicative of the uncertainties in the morphological parameters. Clusters with sparse photometry, poorly populated sequences, and those located in very crowded regions of the sky are more uncertain and their parameters are followed by a colon in the tables.

For the reasons discussed above, we were able to measure δV in most clusters, $\delta 1$ in many clusters, and both parameters in some clusters. Further, some of the clusters were observed with B and V filters and others with V and I filters. Since all these variants are presumed to be measures of the single parameter, age, there is a need to combine them into one index. We first averaged multiple determinations of δV and $\delta 1$ made in a single color (*BV* or *VI*), weighting the uncertain values (indicated by a colon in Table 2) one-half the other measures. Next, since the δV measures from *BV* photometry and those from *VI* photometry agree, on average, to within 0.1 mag (see Table 2) a straight average was taken when both were available for a cluster. Finally, while we have chosen δV to be our primary age indicator, some clusters do not have a visible red giant clump making it impossible to measure δV. There are, however, enough clusters for which both δV and $\delta 1$ can be measured so that correlations between the indices can be established (Figs. 2 and 3), allowing a conversion between $\delta 1$ and δV to be made in such cases.

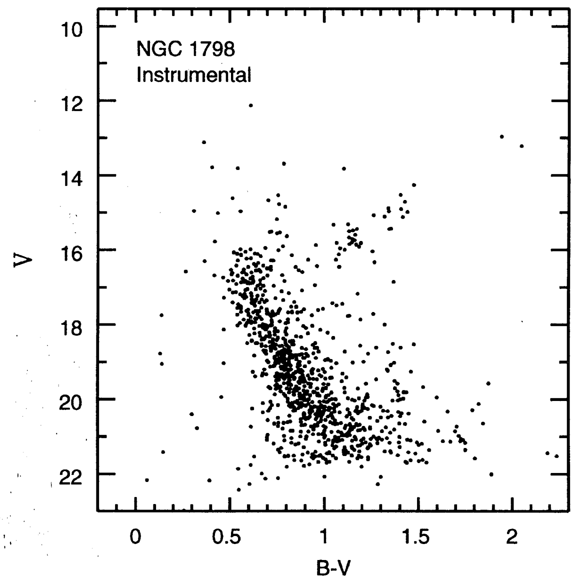

FIG. 9. Instrumental *BV* CMD for NGC 1798.

In this way it was possible to derive up to three versions of δV; one an average of the measured δV from the *BV* and/or *VI* photometry, one a conversion of $\delta 1(BV)$ into δV using the relation in Fig. 2, and one a conversion of $\delta 1(VI)$ into δV using the relation in Fig. 3. The adopted value of δV, taken to be the average of the directly measured value and the computed value(s) (see Fig. 4), is listed in Table 5 for each of the clusters was found to be old. We have also included in Table 5, the equatorial and galactic coordinates for each cluster and a quality grade, "*q*," which represents our qualitative estimate of the reliability of δV. Clusters with the best-defined CMDs were assigned a value of "*a*," those that were moderately well defined were given a "*b*," and the most difficult clusters to evaluate were given a "*c*." The reliability grade was affected in a few cases by the overall photometric quality, but more likely by problems such as the richness of the cluster, interference by field stars, or large reddening. The δV values for the *a* clusters are in general defined with a precision of better than 0.1 mag, the *b* clusters with a precision between 0.1 and 0.2 mag and the *c* clusters are generally worse than 0.2 mag.

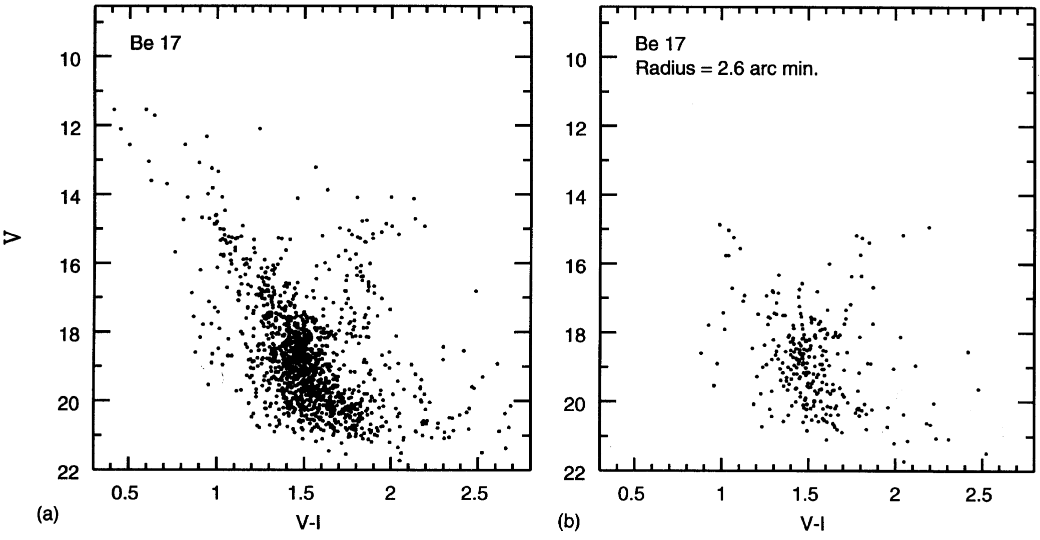

FIG. 10. *VI* CMDs for all stars (a) and stars within 2.6 arcmin of the center (b) of Berkeley 17 (Be 17).

4. DISCUSSION

4.1 The Oldest Open Clusters

Table 5 lists 72 clusters with δV similar to or larger than the Hyades. At least 15 clusters (and perhaps as many as 19, considering the uncertainties in δV) are approximately the age of M67 or older. For the first time, there is a significant sample of very old clusters suitable for probing the history of the Galactic disk. Our systematic ranking of cluster ages, based on δV, also allows us to address several controversies about individual clusters which have appeared in the literature.

As discussed by Demarque *et al.* (1992) the clusters M67, NGC 188, and NGC 6791 have played a significant role in shaping our ideas of the chronology of the Galaxy, particularly whether or not a significant gap in time existed between the formation of the globular clusters in the halo and the formation of the first disk stars. The controversy arises primarily because of the large differences in age that have been cited for NGC 188 and NGC 6791. NGC 188, for example, was found to be 10 Gyr by VandenBerg (1985), but Twarog & Anthony-Twarog (1989) suggested that its age can differ by no more than 2 Gyr from that of M67 which has an age of 3.5–6 Gyr (Montgomery *et al.* 1993). Anthony-Twarog & Twarog (1985) also pointed out the similarity between the CMDs of NGC 188 and NGC 6791, indicating that the two clusters have similar, nearly solar metallicities, a result also suggested by DDO photometry (Janes 1988) and Washington photometry (Canterna *et al.* 1986) of giants in NGC 6791. Assuming a solar metallicity, NGC 6791 is about 1 Gyr older than NGC 188 (Demarque *et al.* 1992). A higher metallicity (e.g., Friel & Janes 1993), however, could change the relative ages of NGC 188 and NGC 6791. In their own study based on new isochrones, Demarque *et al.* find ages of $4^{+1.0}_{-0.5}$ Gyr for M67, $6.5^{+1.5}_{-0.5}$ Gyr for NGC 188, and 6.5–9 Gyr for NGC 6791.

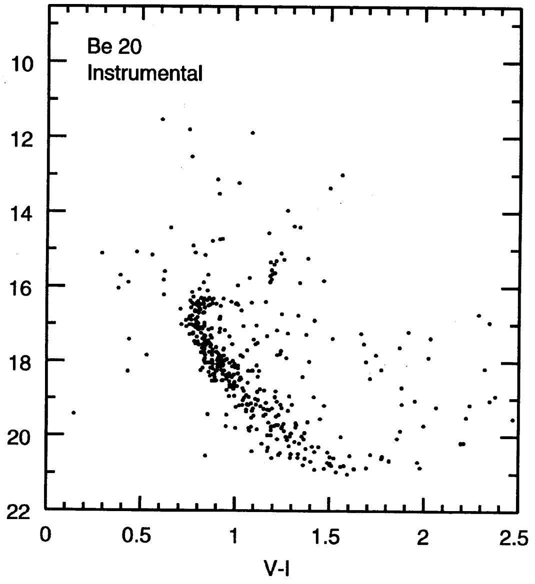

FIG. 11. Instrumental *VI* CMD for Berkeley 20 (Be 20), obtained with the KPNO 2.1 m telescope.

The morphological age parameters are less sensitive to metallicity effects than age determinations by isochrone fitting (Buonanno *et al.* 1989) and provide a ranking of the *relative* ages of clusters. Our value of $\delta V=2.6$ for NGC 6791 confirms that it is among the very oldest of open clusters, but NGC 188 ($\delta V=2.4$) is only a little older than M67 ($\delta V=2.3$).

Among the clusters thought to be very old is NGC 1193. Kaluzny (1988) derived an age range of 5–8 Gyr, based on the VandenBerg (1985) isochrone fits to the *BV* CMD. However, the value of $\delta V=2.1$ indicates that it may be less than 5 Gyr, assuming an age for M67 ($\delta V=2.3$) of 3.5–6 Gyr (Montgomery *et al.* 1993).

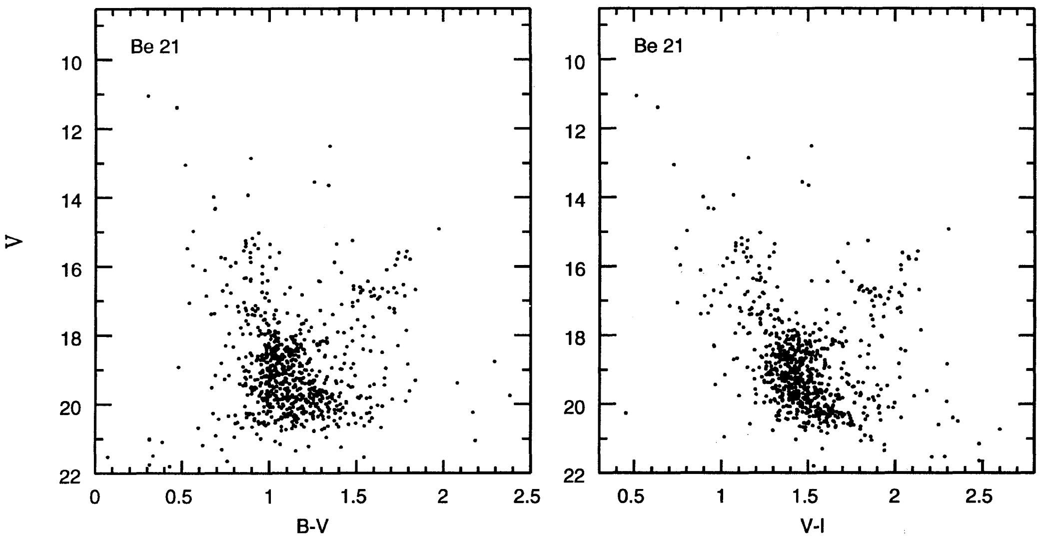

FIG. 12. *BV* and *VI* CMDs of Be 21.

Our new list of the oldest clusters (Table 6) adds several clusters to the category of the oldest open clusters in the Galaxy; they are Be 17, Cr 261, NGC 6791, Be 54, and AM 2. Be 17, with $\delta V=2.8$ is perhaps *the* oldest open cluster yet discovered in the Galaxy. To this list might also be added Lyngå 7, which has recently been put forward by Ortolani *et al.* (1993) as being either a young metal-rich globular cluster or their candidate for the oldest open cluster. Unfortunately, it is not possible to make a quantitative measurement of δV from their published CMDs, but the appearance of the CMD does indeed suggest that the cluster is quite old.

This increase in the number of the very oldest open clusters has major implications for our understanding of the formation of the Galactic disk. While NGC 6791, previously identified as the oldest open cluster in the disk with an age of ~9 Gyr (Garnovich *et al.* 1993), remains younger than the youngest globulars (Chaboyer *et al.* 1992), the addition of other clusters about the same age, and at least one (Be 17) and perhaps another (Lyngå 7) distinctly older cluster apparently closes the gap between the time of formation of the old open clusters and the globulars. Further discussion of the connection between the open clusters in the disk and the globulars in the halo

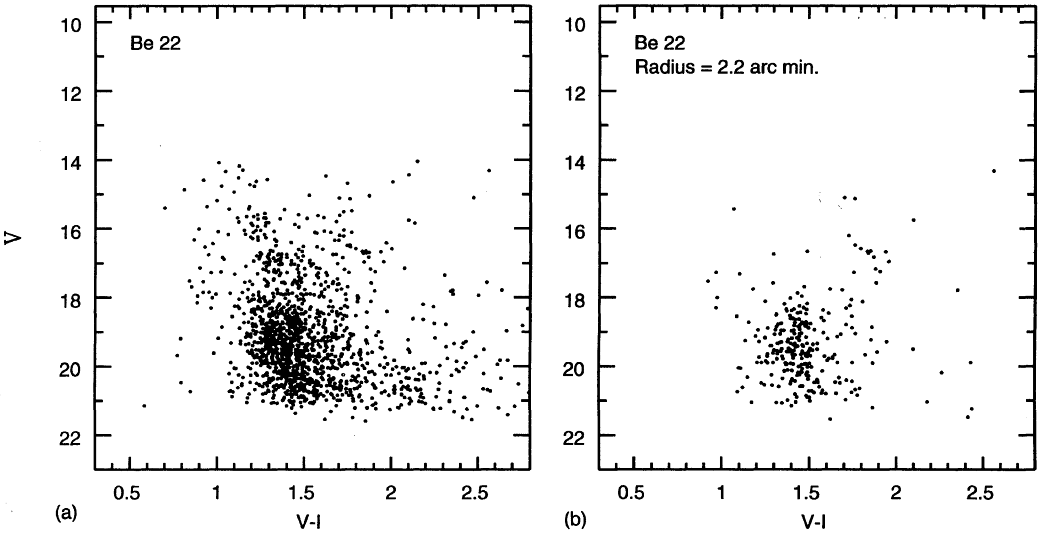

FIG. 13. *VI* CMDs for all stars (a) and stars within 2.2 arcmin of the center (b) of Berkeley 22 (Be 22).

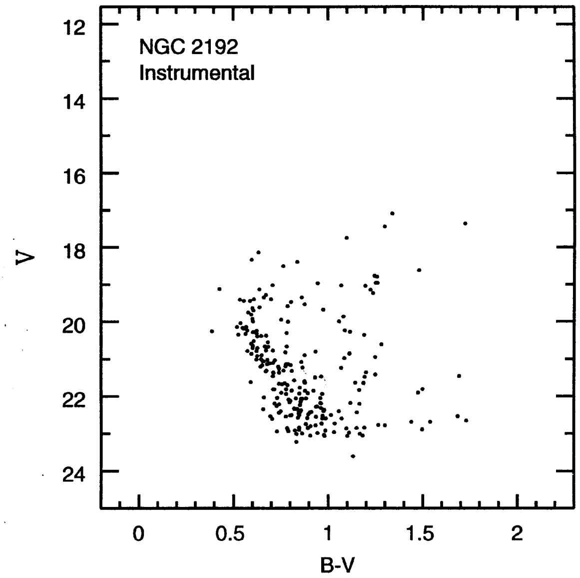

FIG. 14. Instrumental *BV* CMD for NGC 2192.

will be presented in Janes & Phelps (1994) (Paper 2).

4.2 *Frequency Distribution of Old Open Clusters*

Figure 5 shows the number of old open clusters as a function of δV. This diagram shows first that there was substantial cluster formation back to at least 10 Gyr ago, assuming the Garnovich *et al.* (1993) value of 9 Gyr for the age of NGC 6791 ($\delta V=2.6$), and also that a significant number of clusters have actually survived from that time. Since the typical lifetime of open clusters is about 100 mil yr (Janes *et al.* 1988), it is particularly striking to see a distinct peak in the number of clusters near $\delta V=2.3$, corresponding to an age near 5 Gyr, or 50 times the typical cluster lifetime. The peak in the distribution near $\delta V=2.3$ is at least partly the result of the strongly nonlinear relation between δV and age, but shows that there was extensive cluster formation at early times in the Galaxy. The gap in the cluster distribution near $\delta V=1.6$–20 (corresponding to an age of roughly 3 Gyr) corresponds to a gap in the star-formation rate discussed by Noh & Scalo (1990). A more detailed interpretation of this distribution will be presented in Paper 2, but Fig. 5 does demonstrate that the star-formation rate in the Galactic disk has not proceeded uniformly with time.

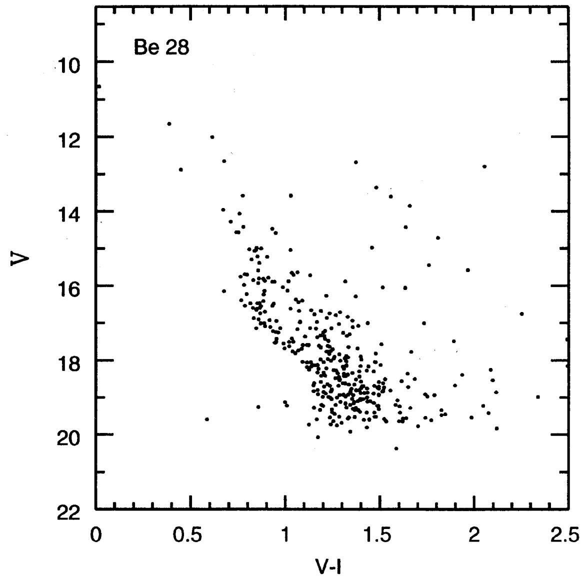

FIG. 15. *VI* CMD for Berkeley 28 (Be 28).

4.3 *Individual Clusters*

The CMDs for the clusters in our program which have not previously been studied, and for a few clusters where our data represent a major improvement in the previous photometry are presented in Figs. 6–33. Several of the clusters were observed under nonphotometric conditions and the resulting CMDs are presented on the instrumental system, as indicated in the figures. Three clusters deserve individual mention because we find that they have significantly different ages than has previously been thought or because their CMDs pose special problems in interpretation.

Be 42. Our value of δV (Table 5) indicates that Be 42 is similar in age to the Hyades, a result which contrasts with the age of 6 ± 2 Gyr suggested by Aparicio *et al.* (1991).

Be 21. The derived value of δV (Table 5) indicates that Be 21 is old, with an age significantly greater than the ~100 Myr age assumed in the Christian & Janes (1979) photographic study of the cluster.

Pi 19. The CMDs reveal a young cluster ($\delta V=0$) and an overlapping sequence of hot, blue stars, likely representing stars from the nearby young cluster NGC 5617, with $E(B-V)=0.53$ (Lyngå 1987). The large spread in the Pi 19 sequence, and its location far to the red of the presumed NGC 5617 sequence, indicates that Pi 19 is a heavily reddened cluster.

5. SUMMARY

In a comprehensive survey of old open clusters, we obtained new CCD photometry for 37 clusters, including 24 clusters with no previous photometry. From this new photometry, together with previously published photometry we have compiled a list of 72 clusters that are similar in age to, or older than, the Hyades based on the morphology of the cluster CMDs. As many as 19 clusters are as old or older than the classic old open cluster M67 (about 5 Gyr in age), and several, including Be 17, Cr 261, and possibly Lyngå 7 are as old or older than the well-known old open cluster NGC 6791. Based on its morphology, Be 17 appears to be the oldest open cluster yet found in the Galaxy.

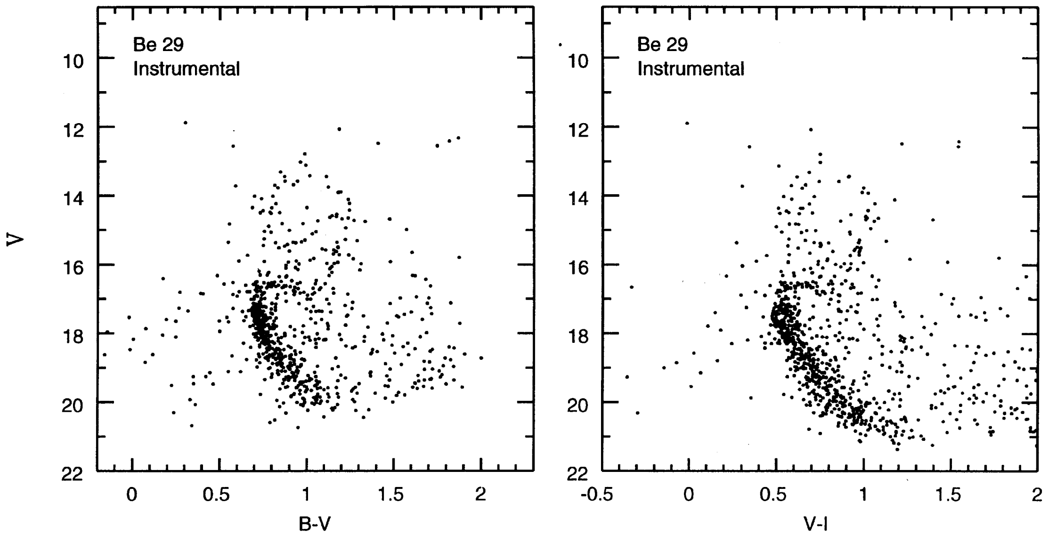

FIG. 16. Instrumental *BV* and *VI* CMDs of Berkeley 29 (Be 29) obtained with the 2.1 m KPNO telescope.

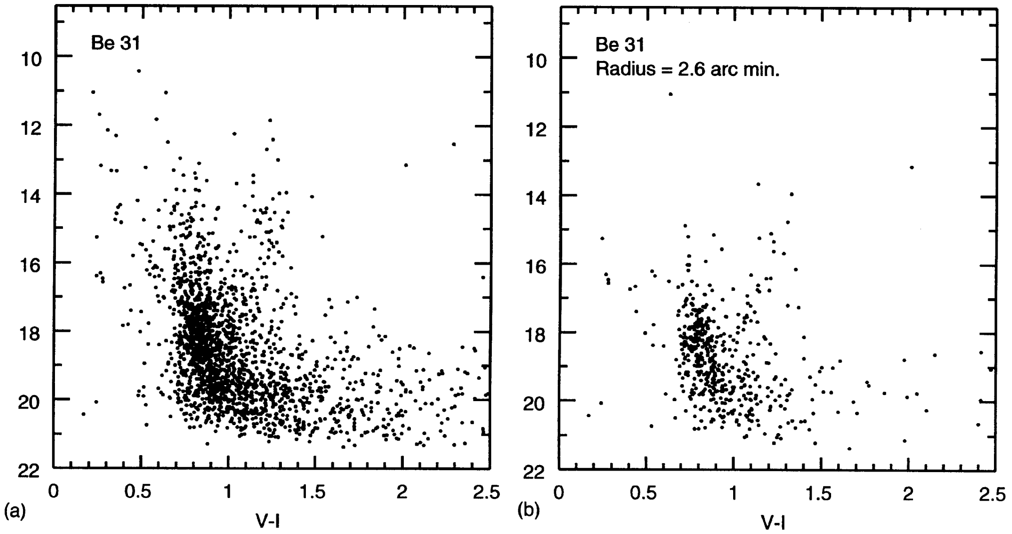

FIG. 17. *VI* CMDs for all stars (a) and stars within 2.6 arcmin of the center (b) of Berkeley 31 (Be 31).

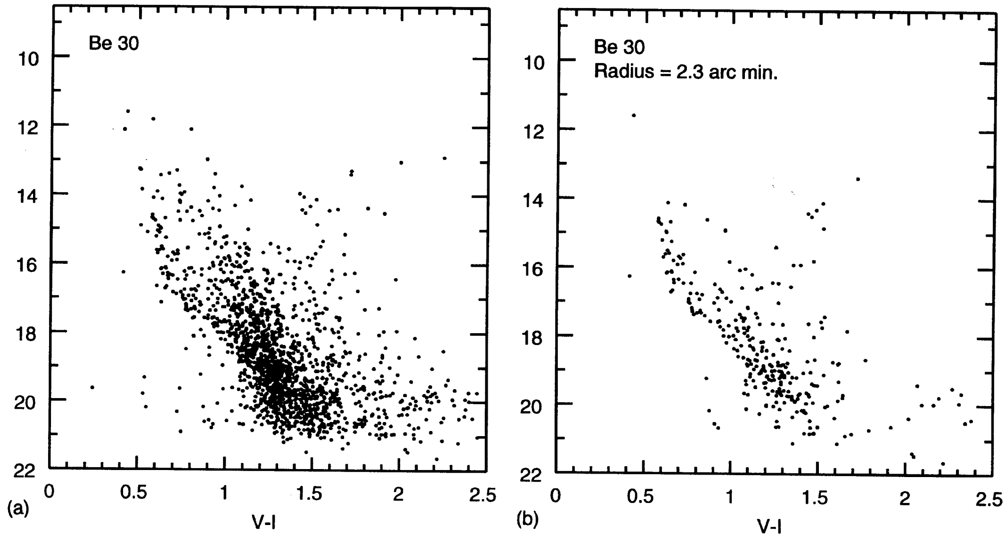

FIG. 18. *VI* CMDs for all stars (a) and stars within 2.3 arcmin of the center (b) of Berkeley 30 (Be 30).

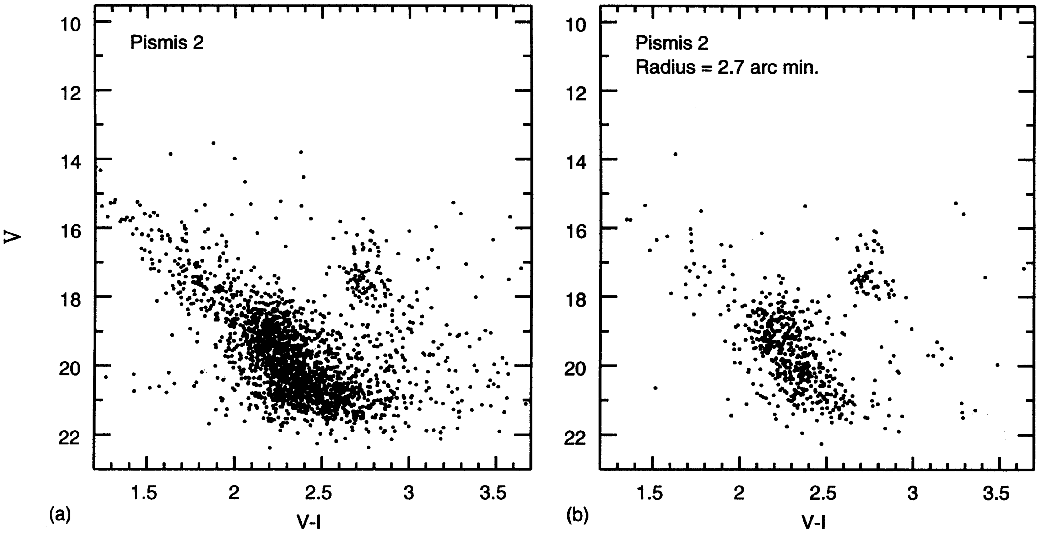

FIG. 19. *VI* CMDs for all stars (a) and stars within 2.7 arcmin of the center (b) of Pismis 2 (Pi 2).

The old open clusters identified in this survey provide a powerful dataset for investigating the formation and evolution of the Galactic disk. Studies of the chemical evolution of the disk using open clusters (Friel & Janes 1993; Geisler *et al.* 1992) require large samples of open clusters, spanning the age of the disk, with well-determined relative ages. Comparison of the age distribution of old open clusters in the disk can now be compared to that of halo globular clusters to help establish the connection between the formation of the Galactic disk and halo (Janes & Phelps 1994).

Because the aim of the project was to survey as many clusters as possible and to identify those that might be old, the observations were made with small telescopes, sometimes under marginal weather conditions. Consequently, many of the more interesting clusters should be reobserved with larger telescopes, first to define more precisely the principal sequences of their CMDs but also to derive esti-

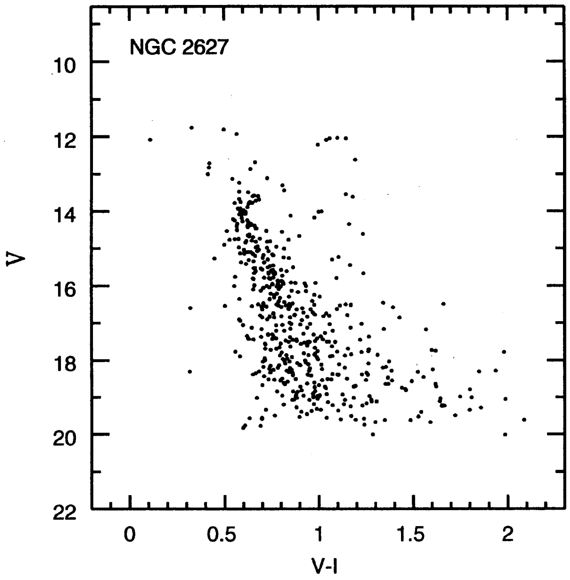

FIG. 20. *VI* CMD for NGC 2627.

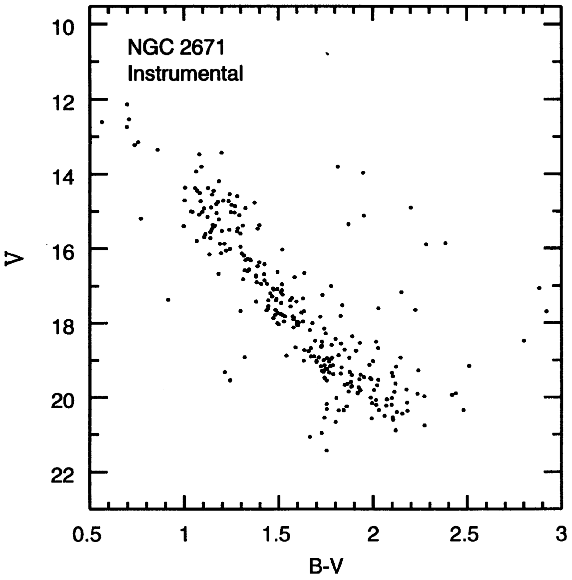

FIG. 21. Instrumental *BV* CMD for NGC 2671.

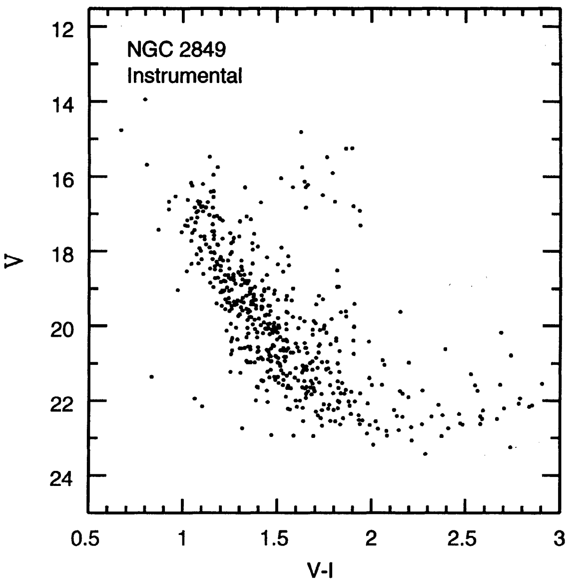

FIG. 22. Instrumental *VI* CMD for NGC 2849.

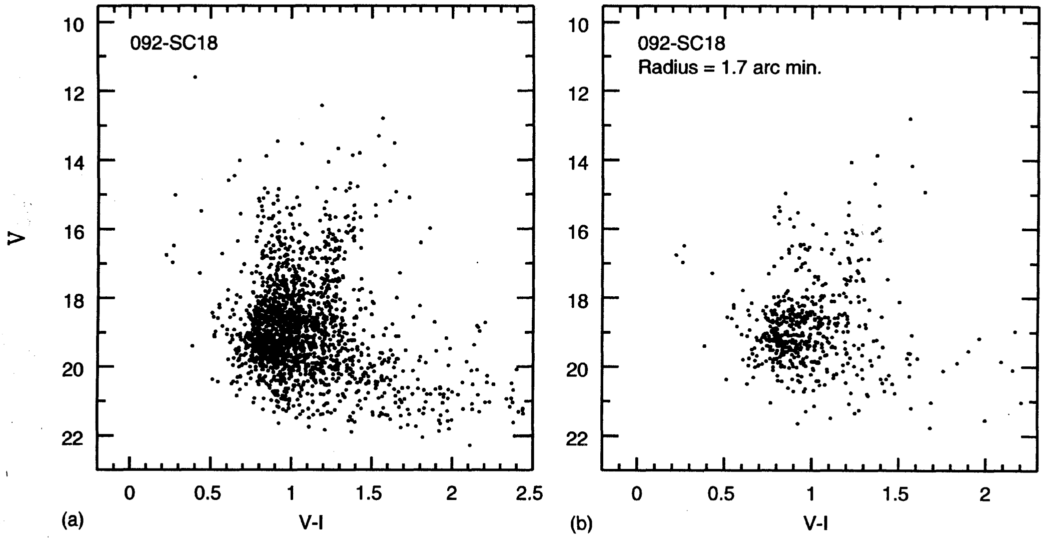

FIG. 23. *VI* CMDs for all stars (a) and stars within 1.7 arcmin of the center (b) of the cluster 092-SC18.

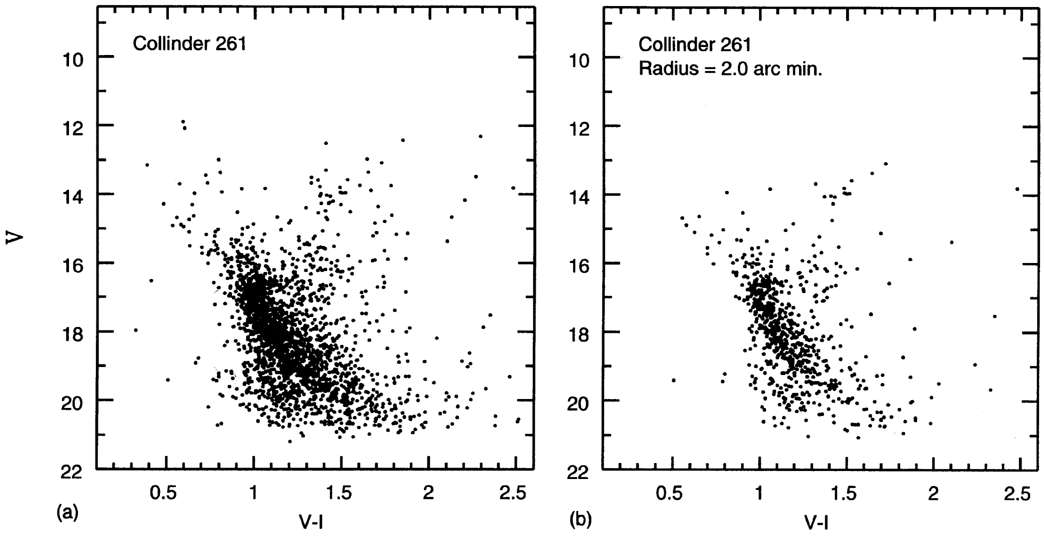

FIG. 24. *VI* CMDs for all stars (a) and stars within 2.0 arcmin of the center (b) of Collinder 261 (Cr 261).

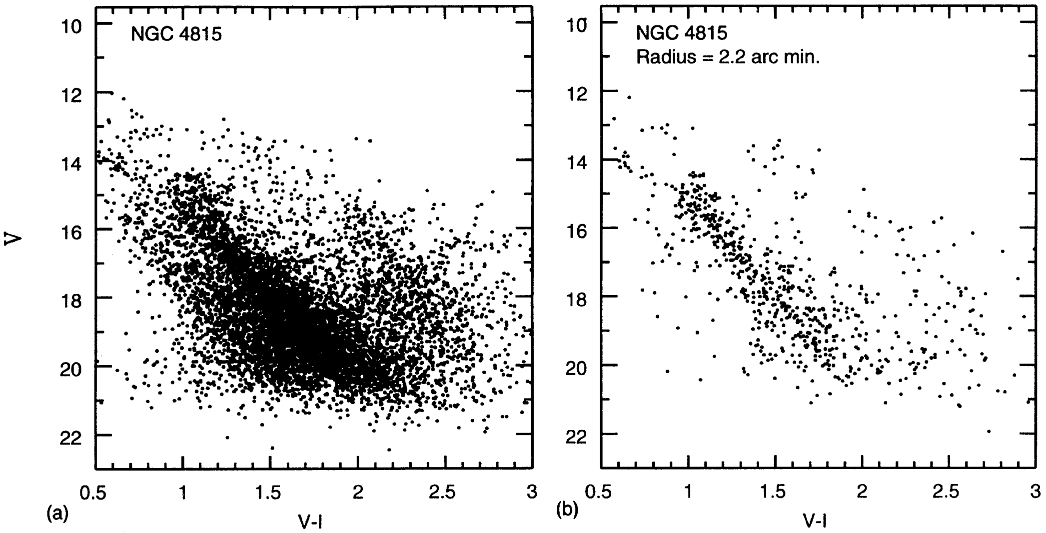

FIG. 25. *VI* CMDs for all stars (a) and stars within 2.2 arcmin of the center (b) of NGC 4815.

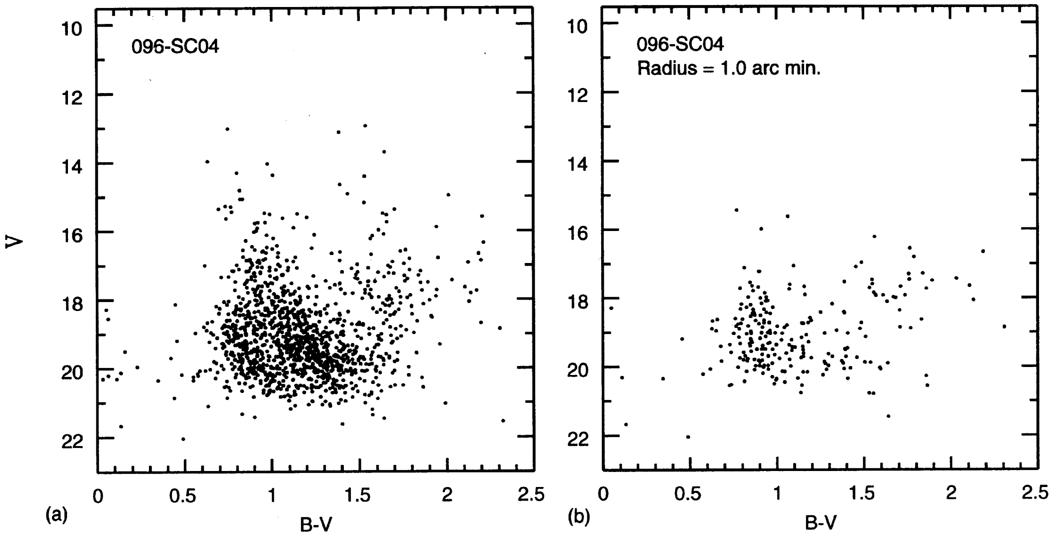

FIG. 26. *BV* CMDs for all stars (a) and stars within 1.0 arcmin of the center (b) of 096-SC04.

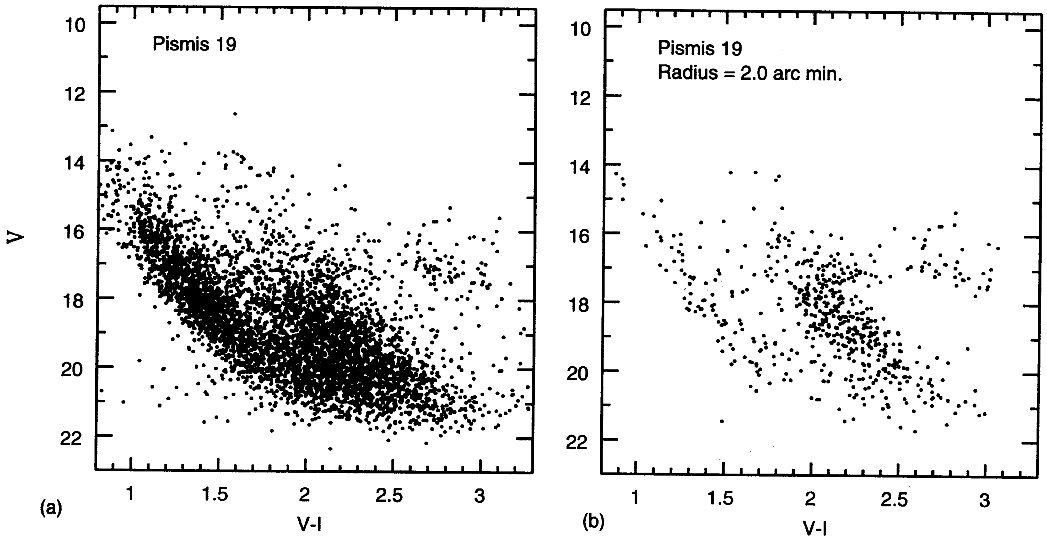

FIG. 27. *VI* CMDs for all stars (a) and stars within 2.0 arcmin of the center (b) of Pismis 19 (Pi 19). Although there is a clump in the CMD, the derived value of $\delta V=0$ implies that the cluster is significantly younger than the Hyades.

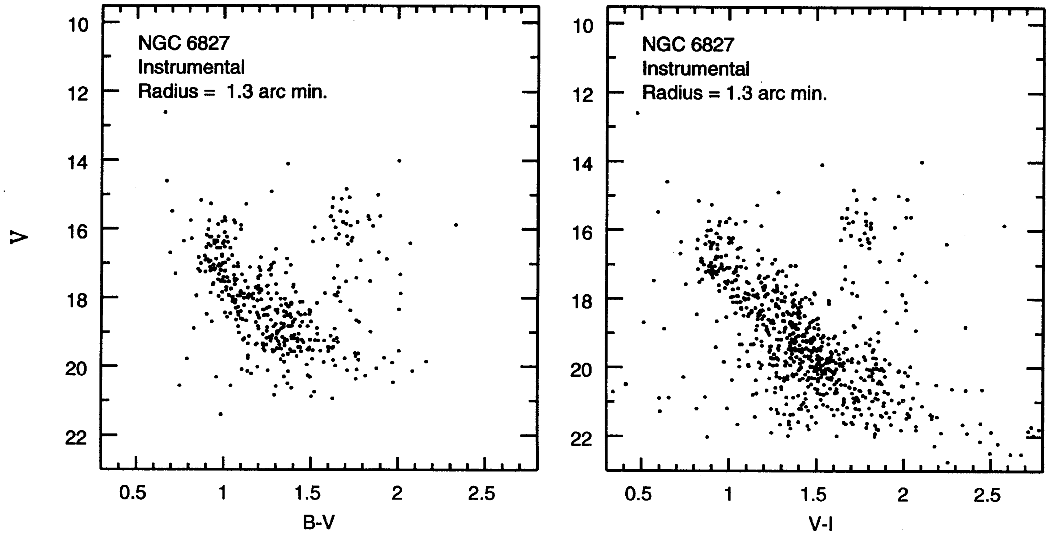

FIG. 28. Instrumental *BV* and *VI* CMDs for stars within 1.3 arcmin of the center of NGC 6827.

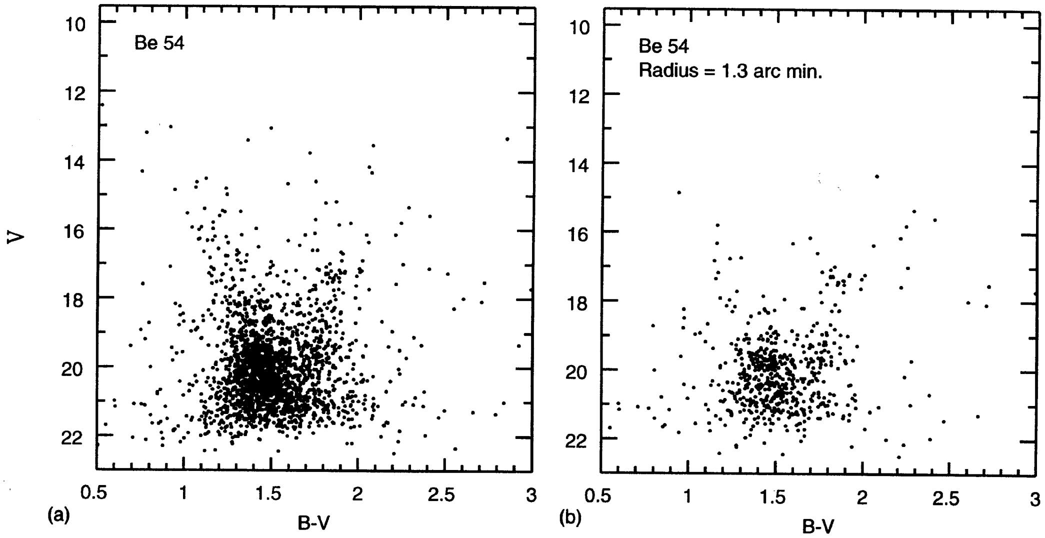

FIG. 29. *BV* CMDs for all stars (a) and stars within 1.3 arcmin of the center (b) of Berkeley 54 (Be 54).

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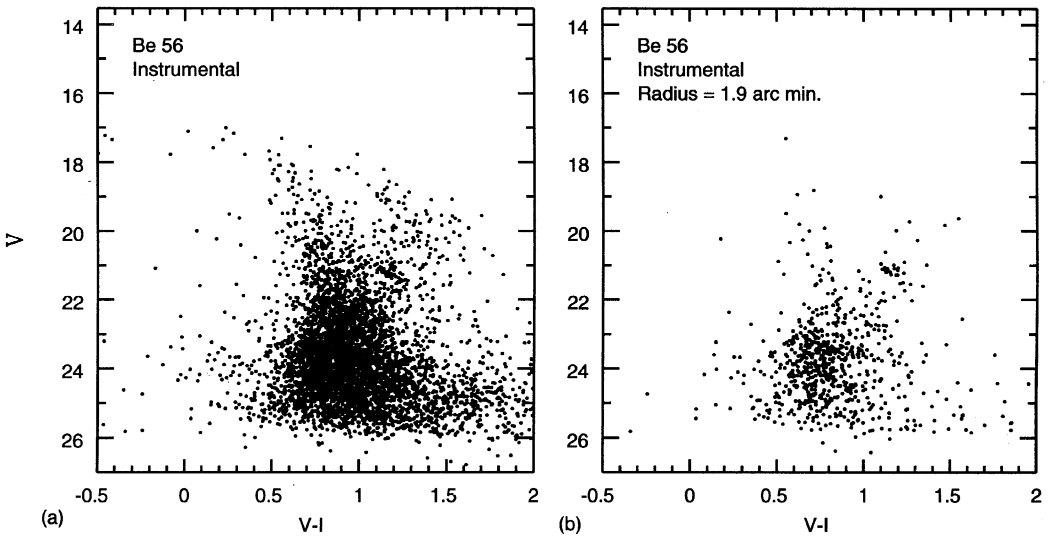

FIG. 30. Instrumental *VI* CMDs for all stars (a) and stars within 1.9 arcmin of the center (b) of Berkeley 56 (Be 56).

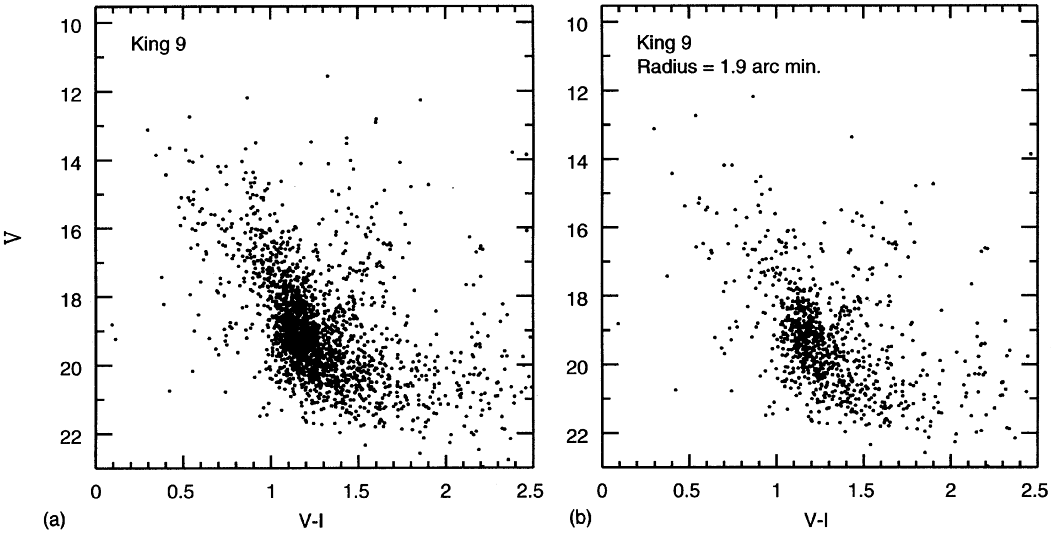

FIG. 31. *VI* CMD for all stars (a) and stars within 1.9 arcmin of the center (b) of King 9.

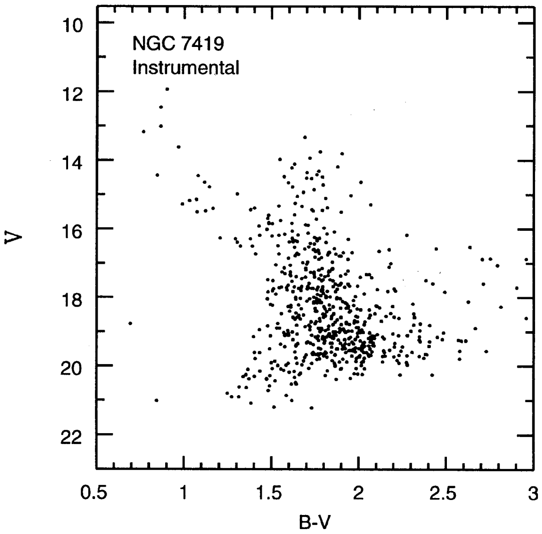

FIG. 32. Instrumental *BV* CMD for NGC 7419.

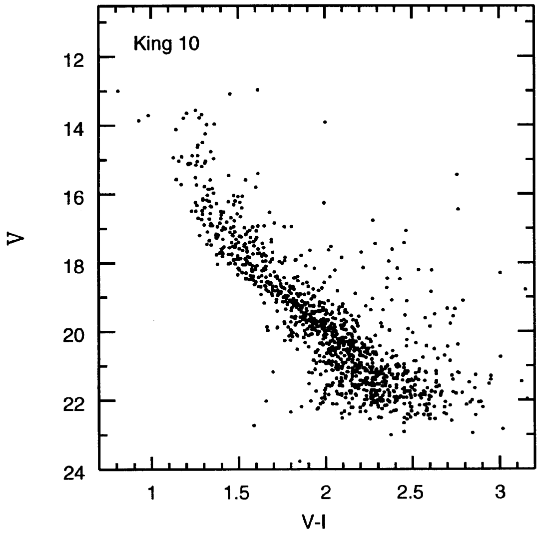

FIG. 33. *VI* CMD of King 10.

mates of the reddening, metallicity and the numbers of cluster members.

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