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A SEARCH FOR CANDIDATE OLD OPEN CLUSTERS: PRELIMINARY PHOTOMETRY OF THE SAURER ET AL. CLUSTERS

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ABSTRACT

We have performed V and I CCD observations of the previously unstudied open cluster candidates proposed by Saurer et al. in 1994. Five of these clusters are found to be true clusters, with ages older than 1 Gyr, based on the "morphological age index" of Janes & Phelps, while effects of differential extinction make the identification of another as a true cluster inconclusive. The derived ages of the clusters range between a low of about 1 Gyr to a high of 7–8 Gyr for cluster A. Based on the derived parameters, cluster A is one of the oldest and the most distant of any Galactic open clusters studied to date.

Key words: Galaxy: fundamental parameters — Galaxy: structure — open clusters and associations: general

1. INTRODUCTION

The system of Galactic open clusters is an ideal sample for investigating the formation and evolution of the Milky Way. The small, but important, subset of the cataloged open clusters (Lyngå 1987) that are old allow the early history of the Galaxy to be investigated. In this context, "old" refers to ages greater than the Hyades (625 ± 50 Myr; Perryman et al. 1998). Unfortunately, the majority of open clusters that formed within the Galactic disk have been destroyed, primarily by interactions with molecular clouds (Spitzer 1958). However, given the proper circumstances (e.g., sufficient mass, an opportune location in the Galaxy) an open cluster can survive for thousands of millions of years, and a few may be as old as the disk of our Galaxy (Phelps, Janes, & Montgomery 1994). Old open clusters are therefore very important for investigating the age and star formation history of the Milky Way's disk, as well as its chemical evolution (Friel 1995).

Because of their importance, studies by various groups have been undertaken to find, and date, the Galaxy's population of old open clusters. Since a large number of open clusters remain unstudied, a significant number of old Galactic open clusters may remain undiscovered. Saurer et al. (1994) identified six previously unknown candidate open star clusters (Table 1) as a result of a systematic search of the Palomar Observatory Sky Survey. The published images of these candidate clusters have appearances suggesting an old age (see Fig. 6 of Saurer et al. 1994), since a young open 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 (King 1964).

2. OBSERVATIONS AND DATA REDUCTIONS

All of the Saurer et al. (1994) clusters have now been observed. The observation log is summarized in Table 2, with the dates of the observations listed in column (2). The cluster observations were carried out with the 60 inch (1.5 m) Oscar G. Meyer Telescope at the Palomar Observatory and with the 40 inch (1.0 m) Swope Telescope at Las Campanas Observatory (LCO), according to the respective entry in column (3). Each of the 2048 × 2048 CCDs has pixels that are 24 μm on a side, resulting in a pixel scale at Palomar of $0''.367$ pixel^{-1}, for a field of view of $12'.67$, and a scale of $0''.697$ pixel^{-1}, for a field of view of $23'.7$, at LCO (see cols. [4] and [5]). The observations, using the Johnson V and Cousins I filters, were conducted by taking short, medium, and long exposures (cols. [6] and [7]) of the cluster candidate to allow for bright and faint stars to be measured. All exposures were obtained under photometric conditions.

Preliminary processing of the data was undertaken using IRAF[3] using standard techniques as described in the IRAF CCDPROC documentation. The zero-level correction was determined by taking the median of approximately five zero-exposure frames per night. Flat-field corrections were obtained from dome flats in each of the V and I filers, by averaging five individual frames obtained in each filter, using the σ-clipping algorithm in IRAF.

Instrumental magnitudes were obtained by using the Stellar Photometry Software point-spread function photometry package (Janes & Heasley 1993). The instrumental magnitudes were transformed to the Landolt (1983, 1992) standard-stars system using observations on the nights that the clusters were observed. Standard stars, in the color range $-0.3 \leq V{-}I \leq 1.8$, were observed over an air-mass range of 1–2, yielding 40–50 standard-star measurements per night. The transformations to the Landolt system were undertaken using SPTR, which is a set of stellar photometry transform routines written by K. Janes at Boston University. Typical transformation errors of $\sigma < 0.02$–0.03 mag were achieved. For additional details regarding the transformation technique, the reader is referred to Phelps & Janes (1994).

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TABLE 1

Saurer Cluster Coordinates

Cluster	α (J2000)	δ (J2000)	l (deg)	b (deg)
Saurer A........	07 18 18	+01 53 43	214.606	+7.2083
Saurer B........	08 25 28	−39 38 02	257.952	−1.0612
Saurer C........	10 41 25	−55 18 20	285.052	+2.9808
Saurer D	12 13 50	−63 36 00	298.787	−1.0298
Saurer E........	19 39 35	+25 38 59	60.990	+1.8185
Saurer F........	19 49 05	+32 06 42	68.012	+2.8601

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

3. ESTABLISHING THE REALITY OF THE CLUSTERS

Figure 1 presents our V-band images of the regions identified by Saurer et al. (1994) as candidate clusters. Circles are centered on the area defined to represent the cluster candidate, with radii indicating the defined cluster extent in the subsequent analysis. A cluster's extent was defined solely by its visual appearance in the image. A second circle near the field edge represents the region used to analyze field star contamination in the cluster color-magnitude diagram (CMD). Field regions are defined to be equal-area regions in the CCD frames that are located outside the defined cluster region.

Figure 2 shows our derived CMDs for the candidate clusters, A–F, using the cluster regions defined in Figure 1. As revealed in the figure, the majority of the cluster candidates (A, B, C, D, and F), show a reasonably defined sequence, confirming the likely nature of these candidates as true clusters. The analysis of a typical open cluster CMD, however, is complicated by the presence of noncluster stars, or "field stars," in the CMD. The existence of clusters in Figure 2 is further strengthened by noting the enhancement in stellar density in the cluster region CMD, relative to that found in the field regions (Fig. 3). Only stars with photometric errors of $\sigma_V < 0.05$ mag and $\sigma_I < 0.05$ mag are plotted in Figures 2 and 3.

While candidates A, B, C, D, and F appear to be true clusters, the interpretation of the CMD for candidate E, is more problematic. Examination of Figure 1 (*bottom left*) reveals that the region suffers from a great deal of variable extinction, making it possible, and likely, that the appearance of a cluster is due solely to extinction effects. Positive identification of candidate E as a true cluster therefore is not possible with the current data, and we tentatively exclude it from further consideration as an open cluster.

4. CLUSTER PROPERTIES

A typical old open cluster CMD often reveals a fairly well defined main sequence along with a red giant branch, a distinctive red "clump," or both (Cannon 1970), where stars in the red clump are in the core helium burning phase of their evolution. Since the magnitude of the clump remains fairly constant while the main-sequence turnoff moves to fainter magnitudes and redder colors as a cluster ages, numerous attempts have been made to use the morphology of a cluster CMD to estimate the ages of open clusters. For the purposes of this study, we use the parameters δV and $\delta 1$ (Phelps et al. 1994), along with the morphological age index (MAI) of Janes & Phelps (1994) to estimate cluster ages. The parameter δV is constructed by measuring the difference in magnitudes of the main-sequence turnoff of a cluster and that of the red giant clump, while $\delta 1$ measures the difference in color between the main-sequence turnoff and a point on the red giant branch that is 1 mag brighter than the main-sequence turnoff. The values of the morphological parameters used to construct δV and $\delta 1$ for the Saurer et al. (1994) clusters were constructed from the CMD features listed in Table 3 and shown in Figure 4. These parameters are combined to construct the MAI, which is useful when ranking relative ages of old open clusters. Table 4 lists the derived values for δV (col. [3]) and $\delta 1$ (col. [5]), along with the MAI derived from both δV (col. [4]) and $\delta 1$ (col. [6]), as well as the adopted value of the MAI (col. [7]), which is taken to be the average of the MAI derived from δV and $\delta 1$. The radius listed in column (2) is the visually derived radius described in § 2. Error estimates are derived by considering the range in uncertainties derived for the morphological parameters in Table 3.

It is also possible to derive preliminary distances and reddening to old clusters by measuring the colors and magnitudes of the red giant clump. Assuming a mean absolute magnitude ($M_V = 0.95 \pm 0.10$) of clump stars with $\delta V \geq 1$ (Janes & Phelps 1994), and a mean intrinsic color of the clump of $V-I = 1.0$, as is found for M67 (Montgomery, Marschall, & Janes 1993), an estimate of the reddening $E(V-I)$ for each cluster can be made. Using the Dean, Warren, & Cousins (1978) relation $E(V-I) = 1.25E(B-V)$ allows for conversion of $E(V-I)$ to the more commonly expressed $E(B-V)$ reddening. These reddening measurements can then be used to correct the $(m-M)_V$ for reddening, using $R_V = 3.0$ (Patriarchi et al. 2001), and hence estimate the distance to the clusters. The derived reddening $E(V-I)$ (col. [2]), interstellar extinction (col. [3]), true distance modulus (col. [4]), and distance from the Sun (col. [5]) for each cluster are listed in Table 5. The Galactocentric

TABLE 2

Summary of Observations

Cluster (1)	Date (UT) (2)	Telescope (3)	Scale (arcsec pixel^{-1}) (4)	FOV (arcmin) (5)	V Exp. Time (s) (6)	I Exp. Time (s) (7)
A...........	1996 Nov 4	Palomar 1.5 m	0.367	12.7	1, 300	1, 300
B...........	2000 Jan 9	LCO 1.0 m	0.697	23.7	3, 30, 360	3, 30, 300
C...........	2000 Jan 9	LCO 1.0 m	0.697	23.7	3, 30, 360	3, 30, 300
D	2000 Jan 9	LCO 1.0 m	0.697	23.7	3, 30, 360	3, 30, 300
E...........	1999 Aug 6	Palomar 1.5 m	0.367	12.7	3, 30, 360	3, 30, 300
F...........	1998 Oct 20	Palomar 1.5 m	0.367	12.7	3, 30, 300	3, 30, 300

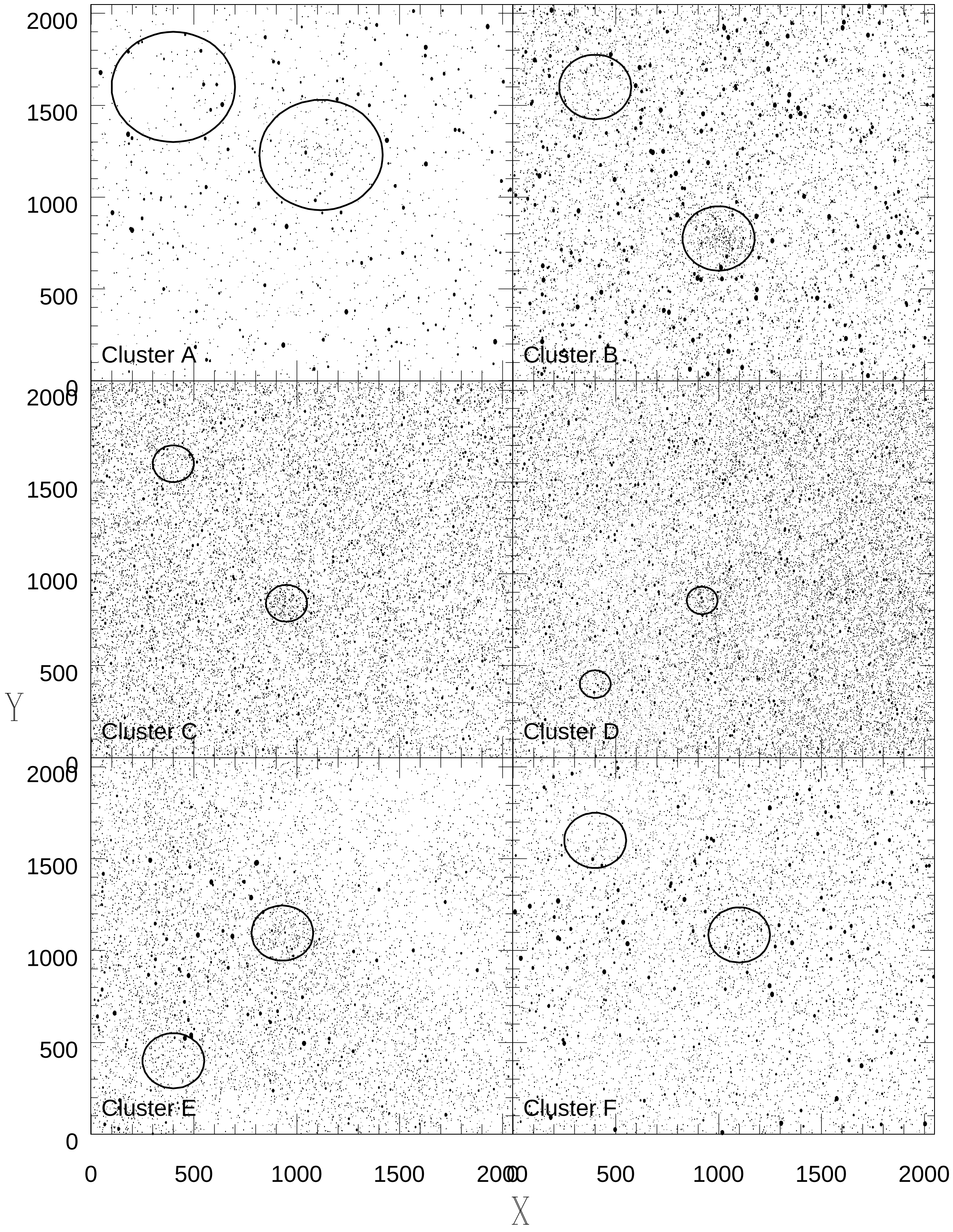

FIG. 1.—Cluster photometry fields

location for each cluster, calculated using $R_{\odot} = 8.0$ kpc (Reid et al. 1999), is listed in column (6), as is the scale height above or below the Galactic plane (col. [7]).

4.1. *Cluster A*

Analysis of the CMD for Saurer A reveals that it is an old open cluster, with a derived MAI of 7.20 ± 3.05 Gyr. This makes Saurer A a prime candidate for further study, as the number of open clusters with ages greater than 4 Gyr is only approximately 20, thus making Saurer A one of the oldest open clusters known (Phelps et al. 1994). The derived distance of 11.97 ± 1.1 kpc, corresponding to $R_{\rm gc} = 19.1$ kpc and a scale height $z = 1.50$ kpc, indicates that Saurer A is the most distant Milky Way open cluster found to date and a cluster with among the largest displacements from the Galactic plane.

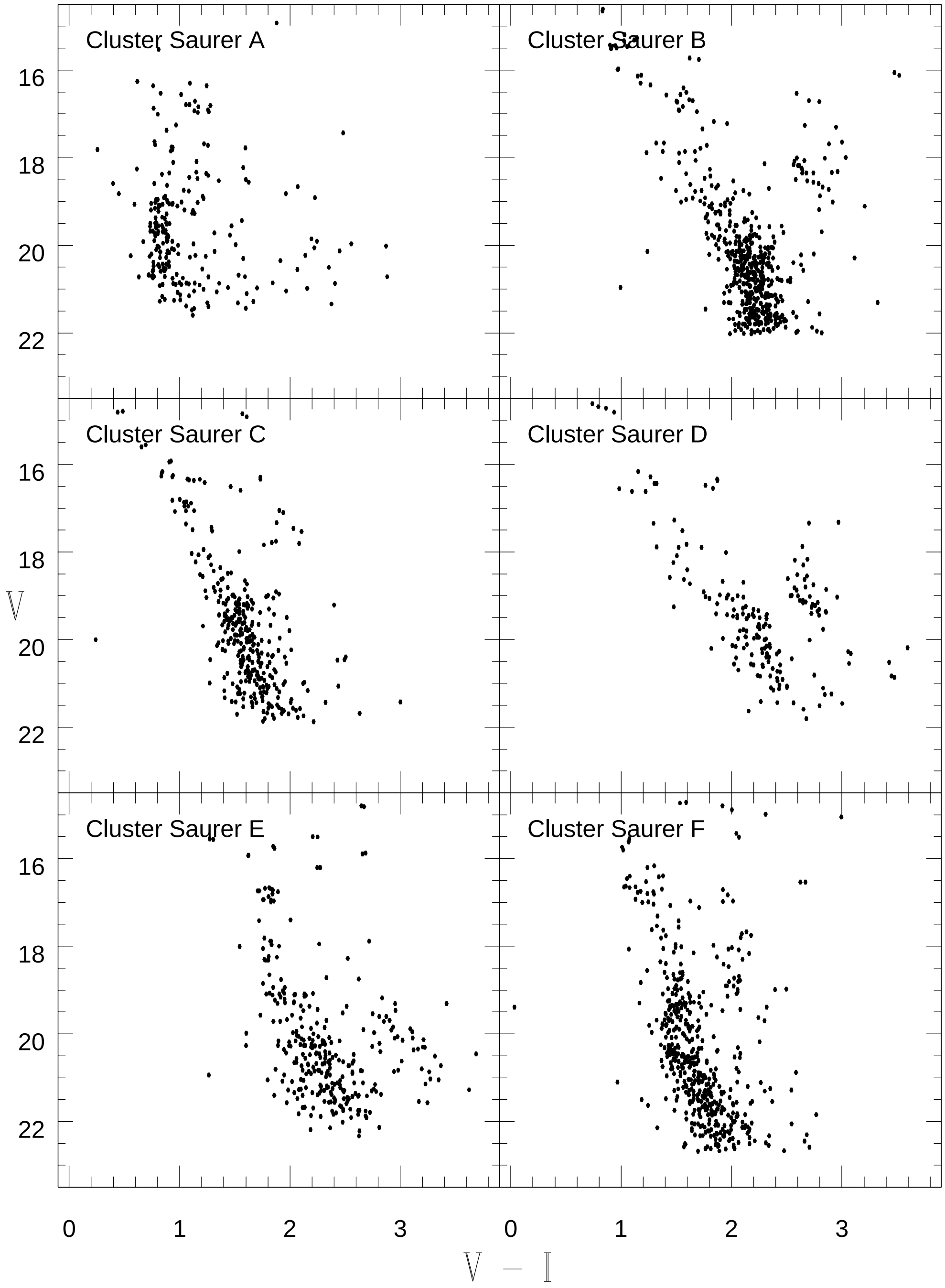

FIG. 2.—Calibrated cluster CMDs

TABLE 3

CMD MORPHOLOGICAL PARAMETERS

Cluster	V_{turnoff}	$(V-I)_{\mathrm{turnoff}}$	V_{clump}	$(V-I)_{\mathrm{clump}}$	V_{giant}	$(V-I)_{\mathrm{giant}}$
A............	19.00	0.80	16.70	1.15	18.00	1.15
B............	19.80	2.05	18.15	2.60	18.80	2.60
C............	19.25	1.45	17.60	1.80	18.25	1.95
D	19.74	2.05	18.75	2.60	. . .	. . .
E............	. . .	. . .	. . .	. . .	. . .	. . .
F............	19.40	1.50	18.20	2.00	18.40	2.05

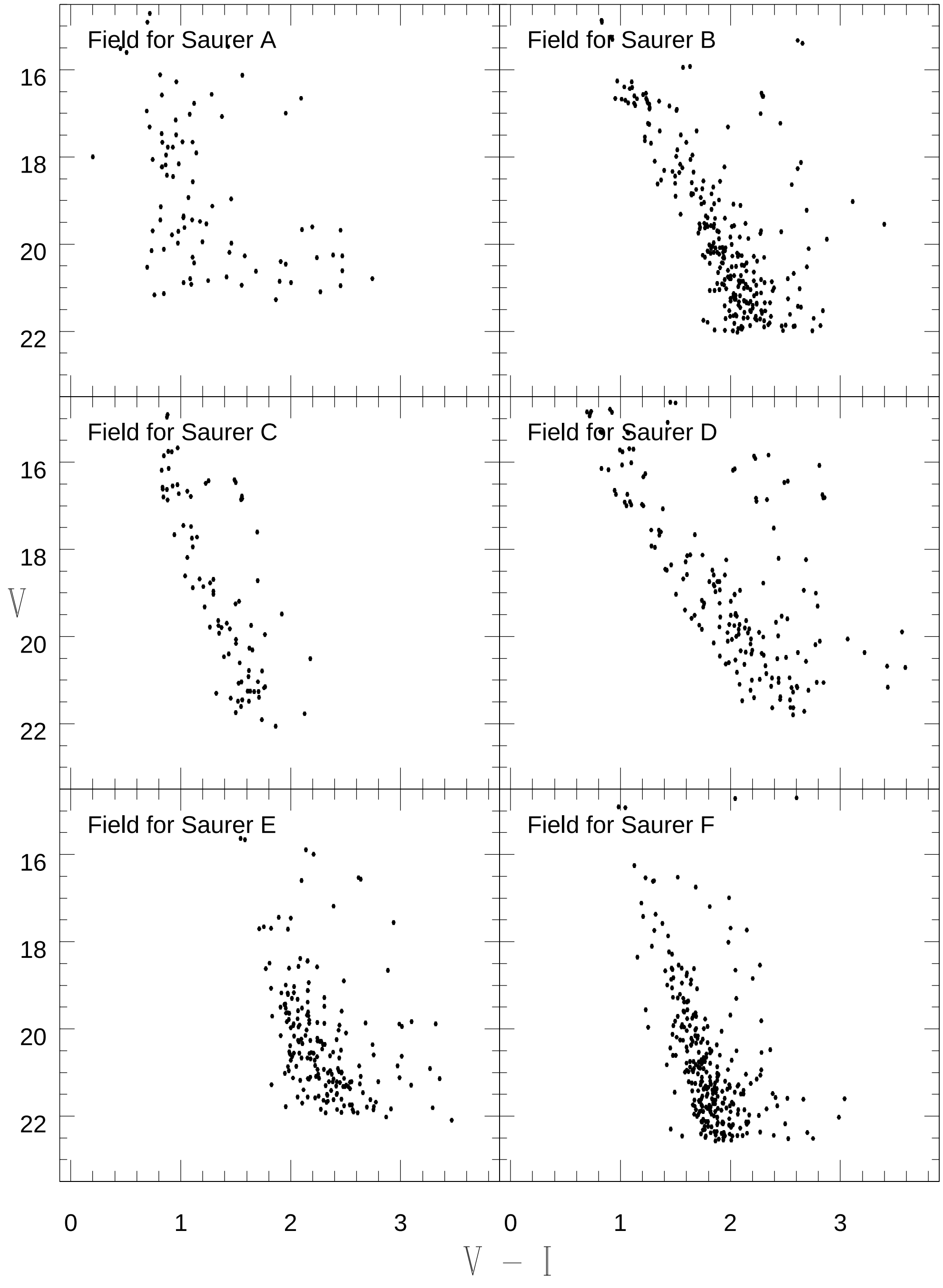

FIG. 3.—Calibrated field CMDs

TABLE 4
OBSERVED CLUSTER PROPERTIES

Cluster (1)	Radius (arcmin) (2)	δV (3)	MAI (δV) (4)	$\delta 1$ (5)	MAI ($\delta 1$) (6)	Adopted MAI (Gyr) (7)
A............	1.8	2.30 ± 0.05	6.34 ± 1.65	0.35 ± 0.02	8.06 ± 2.56	7.20 ± 3.05
B............	2.0	1.65 ± 0.10	2.92 ± 0.65	0.55 ± 0.03	2.07 ± 0.73	2.50 ± 0.97
C............	1.2	1.65 ± 0.10	2.92 ± 0.64	0.55 ± 0.03	2.83 ± 1.08	2.88 ± 1.26
D	0.9	1.00 ± 0.10	1.53 ± 0.28	...	...	1.53 ± 0.28
E............	0.9	...	...	...	...	...
F............	0.9	1.20 ± 0.10	1.84 ± 0.35	0.60 ± 0.03	2.07 ± 0.73	1.96 ± 0.81

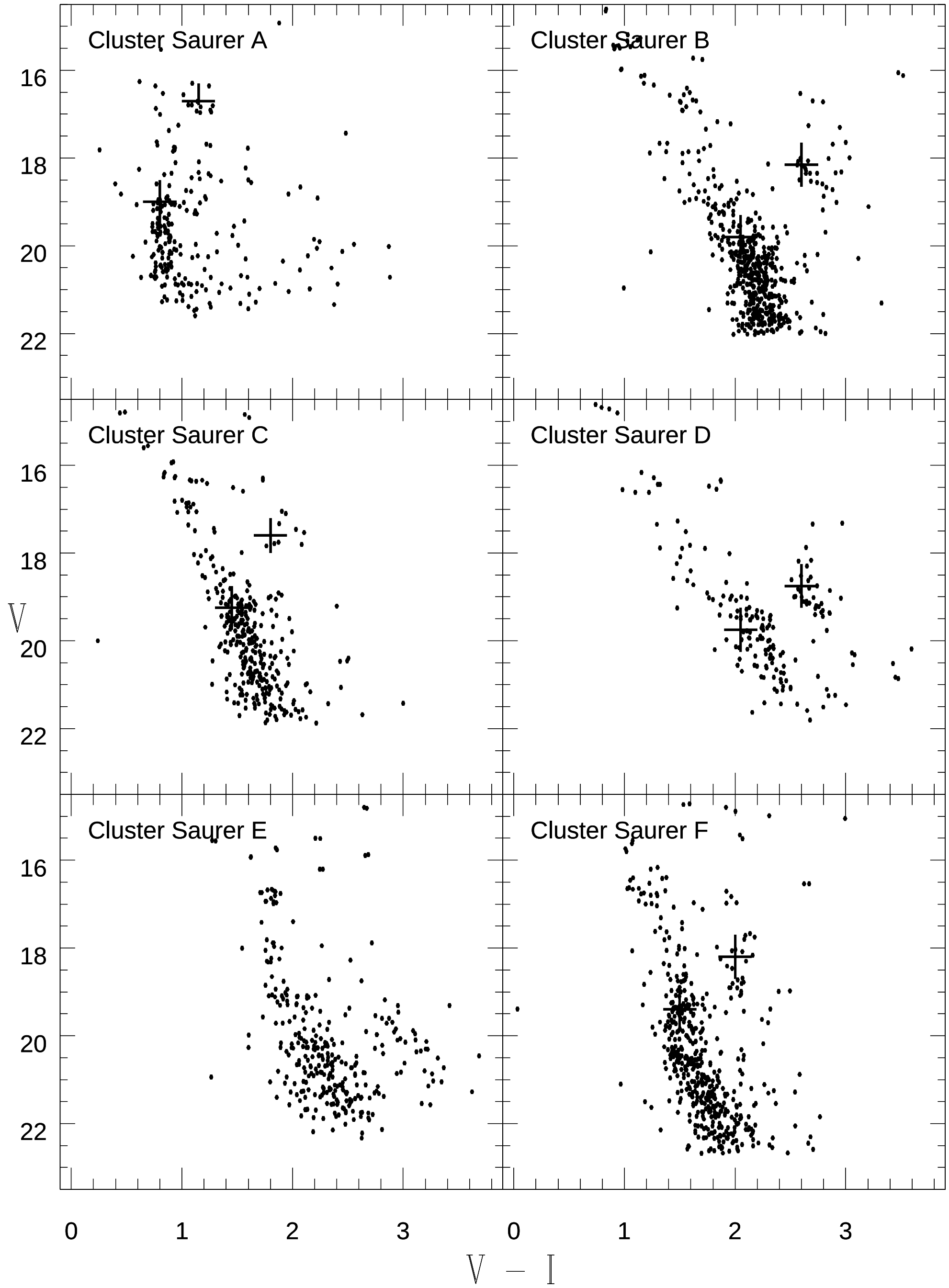

FIG. 4.—Cluster CMDs, with plus signs denoting the measurement of parameters

TABLE 5
DERIVED CLUSTER PROPERTIES

Cluster (1)	$E(V{-}I)^{\rm clump}$ (2)	$A_V^{\rm clump}$ (3)	$(m-M)_0^{\rm clump}$ (4)	d (kpc) (5)	$R_{\rm gc}$ (kpc) (6)	z (kpc) (7)
A............	0.15	0.36	15.39 ± 0.10	11.97 ± 1.10	19.1 ± 1.05	+1.50
B............	1.60	3.84	13.36 ± 0.10	4.70 ± 0.43	10.1 ± 0.30	−0.09
C............	0.80	1.92	14.73 ± 0.10	8.83 ± 0.81	10.3 ± 0.55	+0.46
D	1.60	3.84	13.96 ± 0.10	6.19 ± 0.57	7.4 ± 0.20	−0.11
E............	...	...	...	...	...	...
F	1.00	2.40	14.85 ± 0.10	9.33 ± 0.86	9.8 ± 0.60	+0.47

4.2. *Clusters B, C, D, and F*

The remaining candidates that were found to be true clusters are also found to be older than the Hyades, thereby increasing the numbers of old open clusters to nearly 80. The derived parameters are listed in Tables 3–5. These clusters are found to have ages between 1 and 3 Gyr, with two (C and F) having moderate scale heights of approximately 500 pc.

5. SUMMARY AND CONCLUSIONS

The discovery of five new open cluster with ages above 1 Gyr increases the sample size for investigations of the formation and population history of the Milky Way. Cluster A is particularly noteworthy, as it is the most distant open cluster found to date, in addition to being one of the oldest. Its age and large $R_{\rm gc}$, along with its large scale height, make Saurer A a very interesting cluster for further study. Clusters C and F are also interesting for further study as a result of their large scale heights.

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