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BVI CCD PHOTOMETRY OF THE GLOBULAR CLUSTER M4[1]

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ABSTRACT

From 31 *BVI* CCD frames obtained with the 1.54 m Danish telescope at La Silla, ESO, we have constructed V versus $B-V$, V versus $V-I$, and V versus $B-I$ color-magnitude diagrams in a $4' \times 2'.5$ field of M4, the globular cluster closest to the Sun. The I band was included owing to the advantage of observing in a spectral region little influenced by metallic-line absorption when comparing our results with the *BVI* isochrones of VandenBerg and Bell (1985). The main-sequence turnoffs are found to be at $V_{\rm TO} = 16.90 \pm 0.05$, $B-V = 0.81 \pm 0.02$, $V-I = 0.96 \pm 0.02$, and $B-I = 1.77 \pm 0.02$. Both the turnoff and the fiducial main sequence in the $B-V$ color index are in good agreement with the results of Richer and Fahlman (1984), Alcaino and Liller (1984), and Fahlman (1987). The magnitude difference between the turnoff and the horizontal branch for the three diagrams, $\Delta M_v = 3.52 \pm 0.1$, is in excellent accord with the recent value of $\Delta M_v = 3.46 \pm 0.03$ given by Peterson for the 36 globular clusters with *BV* turnoff photometry. Using $Y = 0.2$, [Fe/H] $= -1.27$, $\alpha = 1.65$, a distance modulus $(m-M)_v = 12.7$, and $E(B-V) = 0.41$, we deduce from the location of the main-sequence turnoff a consistent age for M4 in all three color indices of $17 \pm 1.5 \times 10^9$ yr, similar to recent age determinations of other globular clusters studied by us using identical technique with data fitted to the same set of isochrones. These results provide strong evidence that the globular cluster system is coeval and that the epoch of galactic contraction was short, hence getting a lower limit for the age of the universe and thus an upper limit for the Hubble constant of $H_0 < 58 \pm 5$ km s^{-1} Mpc^{-1} assuming $q_0 = 0$.

Subject headings: clusters: globular — cosmology — photometry — stars: evolution

I. INTRODUCTION

To convert theoretical stellar log T_e–Log L diagrams to color-magnitude diagrams, it is necessary to know precisely the degree to which atomic and molecular absorptions depress and alter the computed emergent stellar flux. Great advances have been made in the calculation of these corrections, but still there exist uncertainties. Kurucz, van Dishoeck, and Tarafdar (1987) state quite bluntly, "Our knowledge of the contributions to the opacity in stellar atmospheres is still incomplete."

This uncertainty has led us to incorporate longer wavelength bands in our ongoing program of photometry of globular cluster stars, since in the red and infrared of solar-type and cooler stars the line opacity is substantially less than it is in the red. Indeed, we found for 47 Tucanae (Alcaino and Liller 1987*a*) some evidence that there are still minor problems along these lines.

The primary aim of our cluster photometry program is to derive ages of clusters, both globular and open. In the *BV* system, 36 globular clusters have been observed well onto the main sequence (Peterson 1986), and such color-magnitude diagrams can be compared to the recently improved set of isochrones developed by VandenBerg and Bell (1985) to derive ages. During the past five years the evidence has become increasingly strong that the spread in age among the known galactic globular clusters could be as small as 1 Gyr and that the average age of these objects is between 14 and 17 Gyr (Burstein 1985). Since metal-rich clusters have not been studied as thoroughly as metal-poor clusters, we are currently devoting more time to investigations of this former type of cluster.

CCD photometry is more than well suited for the usual two-color (*BV*) globular cluster research; the high sensitivity maintained in the red and infrared virtually begs extension to these longer wavelengths where stellar atmosphere calculations are more easily and more confidently made. Because the VandenBerg and Bell isochrones include the R and I bands, we have embarked on CCD *BVRI* photometry of globular clusters. To date we have reported on NGC 6362 (Alcaino and Liller 1986*a*), NGC 2298 (Alcaino and Liller 1986*b*), 47 Tuc (Alcaino and Liller 1987*a*), ω Cen (Alcaino and Liller 1987*b*). We present herewith *BVI* main-sequence CCD photometry for M4 (NGC 6121), ($\alpha_{1950} = 16^{\rm h}20^{\rm m}.6$, $\delta_{1950} = -26°24'$, $l = 351°.0$, $b = +16°.0$).

II. PREVIOUS RESEARCH ON M4

The globular cluster M4 at a distance of ~ 2 kpc is probably the globular cluster closest to the Sun (Alcaino 1975). As an object of low concentration, it can be studied to its very center. However, owing to its location behind the nebulosity in Scorpio-Ophiuchus, the extinction is larger than that normally encountered at the moderate Galactic latitude at which it lies.

With *BV* photometry, five CMDs down to the horizontal branch have been chronologically published by the following authors: Greenstein (1939), Alcaino (1975), Moshkalev (1976), Lee (1977), and Lloyd Evans (1977), who included a few bright stars with I photometry. Two CMDs have been reported down to ~ 3 mag beyond the turnoff; one by Richer and Fahlman (1984), who used a CCD to carry out *UBV* photometry of 469 stars, and one by Alcaino and Liller (1984), who presented *BVRI* photographic photometry of 1421 stars. The latter study was the first four-color investigation beyond the turnoff of a globular cluster. A summary of the basic conclusions obtained from all the works quoted above is presented in a section of Alcaino and Liller (1984) along with summaries of other rele-

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vant photometric and spectroscopic studies. Recently, two other papers concerning this cluster have appeared: Caputo (1987), using pulsational properties of the RR Lyrae stars, has derived the reddening and the distance modulus of M4 as a function of the mass of the variables and the adopted cluster metallicity. She concludes that both parameters vary within realistic limits and yield a low age range of 2×10^9 yr. She gives for the age of this object 16 ± 2 Gyr. Using high-resolution CCD spectra of stars in M4, Wallerstein, Leep, and Oke (1987) found the abundance of M4 to be [Fe/H] $= -1.2 \pm 0.1$, in close agreement with the value found in § V of this paper.

III. OBSERVATIONS

The observations reported here were carried out with the CCD camera at the Cassegrain focus of the 1.54 m Danish telescope at La Silla (see Pedersen and Cullum 1982) on 1984 April 22 and August 20. The camera is based on an RCA laminated thinned back-illuminated CCD, type SID 53612, composed of 512 × 320 pixels. The f/8.5 telescope system provides a plate scale of 15''.7 mm^{-1}, and, with pixel size 30 × 30 μm, corresponding to a sky area of 0.47 × 0.47 arcsec^2, the total field is 240 × 150 arcsec^2.

One field located 7' to the northwest of the cluster's center was observed in *BVI*. The field, centered at $\alpha_{1984} = 16^h22^m07^s$, $\delta_{1984} = -26°28'07''$, was chosen as the best compromise maximizing membership with workable contamination.

The filters are *BV* of Johnson's and *I* of Gunn's system. We used the Gunn *I* filter because the Kron-Cousins filters for the 1.54 m Danish telescope had not yet arrived. We chose it rather than the Johnson *I* on the basis of the transmission curves published in the *ESO Users Manual*, which showed that the passband and effective wavelength more nearly matched the Kron-Cousins system.

The number of exposures made for each color are given in Table 1. In order to cover a large range of magnitudes from giants (without saturation) to faint main-sequence stars, each frame was observed from 3 to 5 times with widely differing exposure times. The nights had no detectable transparency fluctuations, and the seeing stayed within the range 1''.1–1''.3.

In order to minimize errors produced by photometric transfer and differential extinction, we previously observed repeatedly and photoelectrically three *BVRI* standards in the same field using the 1 m telescope at La Silla (Alcaino and Liller 1984). These stars are listed in Table 2 and identified in Figure 1.

During both the late afternoon and early morning, a large set of exposures of the diffusely illuminated dome (flat fields) were taken for each filter.

IV. REDUCTIONS

All reductions were carried out at ESO/La Silla using the MIDAS VAX system program which has been fully described elsewhere (Ortolani 1986*a*, *b*; Gratton and Ortolani 1984; Ortolani 1984). Particular mention should be made of Ortolani's (1986*a*, *b*) papers in which he compares the performances of the well-known DAOPHOT reduction program and INVENTORY, developed by Kruszewski (see West and Kruszewski 1981) for photometry of faint extragalactic objects in crowded fields (clusters of galaxies). Ortolani concludes that the two programs give excellent and closely comparable results. Moreover, a comparison of our results on 47 Tuc (Alcaino and Liller 1987*a*) with those of Hesser *et al.* (1987) demonstrates that the two programs are equally effective. Although faint stars often lie close to the bright standards, the magnitude differences are sufficiently great for no significant errors due to crowding to be introduced, as can be seen from the small residuals of the magnitude and color determinations made photoelectrically and with the CCD (see Table 2). Each frame was reduced separately, and the zero points set to reproduce the magnitudes of the standard stars in the frames. The mean standard deviations of the two deepest frames for magnitude intervals are listed in Table 3.

TABLE 1

LOG OF OBSERVATIONS

Date	Filter	Exposure Time (s)	Air Mass
1984 Apr 22........	*B*	20.0	1.02
1984 Apr 22........	*B*	19.9	1.02
1984 Apr 22........	*B*	21.0	1.01
1984 Aug 20........	*B*	80.0	1.78
1984 Aug 20........	*B*	80.0	1.81
1984 Apr 22........	*B*	240.0	1.00
1984 Apr 22........	*B*	240.0	1.00
1984 Apr 22........	*B*	240.0	1.00
1984 Aug 20........	*B*	720.0	1.15
1984 Aug 20........	*B*	720.0	1.22
1984 Apr 22........	*V*	15.9	1.01
1984 Apr 22........	*V*	15.2	1.01
1984 Apr 22........	*V*	14.9	1.01
1984 Aug 20........	*V*	60.0	1.74
1984 Aug 20........	*V*	60.0	1.75
1984 Apr 22........	*V*	180.0	1.00
1984 Apr 22........	*V*	180.0	1.01
1984 Apr 22........	*V*	180.0	1.01
1984 Aug 20........	*V*	540.0	1.29
1984 Aug 20........	*V*	540.0	1.34
1984 Apr 22........	*I*	16.2	1.05
1984 Apr 22........	*I*	13.0	1.05
1984 Apr 22........	*I*	11.7	1.05
1984 Aug 20........	*I*	60.0	1.63
1984 Aug 20........	*I*	60.0	1.65
1984 Aug 20........	*I*	60.0	1.67
1984 Apr 22........	*I*	180.0	1.03
1984 Apr 22........	*I*	180.0	1.04
1984 Apr 22........	*I*	180.0	1.04
1984 Aug 20........	*I*	540.0	1.50
1984 Aug 20........	*I*	540.0	1.57

TABLE 2

PHOTOELECTRIC MAGNITUDES COLORS AND CCD RESIDUALS FOR STANDARD STARS IN M4

Star	Published Identification	*V*	*B−V*	*V−I*	*B−I*	*n*
1........	62	13.50	0.56	0.87	1.43	7
		0.00	+0.01	−0.01	0.00	
2........	G	13.50	0.96	1.25	2.21	4
		0.00	+0.02	−0.01	+0.01	
3........	H	13.59	0.91	1.16	2.07	8
		0.00	−0.02	0.00	−0.02	
4........	63	14.76	1.12	1.46	2.58	6
		+0.01	−0.02	+0.01	−0.01	
5........	N	15.13	0.86	1.19	2.05	8
		−0.02	−0.02	+0.02	0.00	
6........	70	15.41	1.15	1.45	2.60	4
		−0.01	0.00	0.00	0.00	

NOTE.—Previously published photoelectric values are those indicated by letters (Alcaino and Liller 1984). Residuals are in the sense, photoelectric minus CCD. They are the lower values in each row.

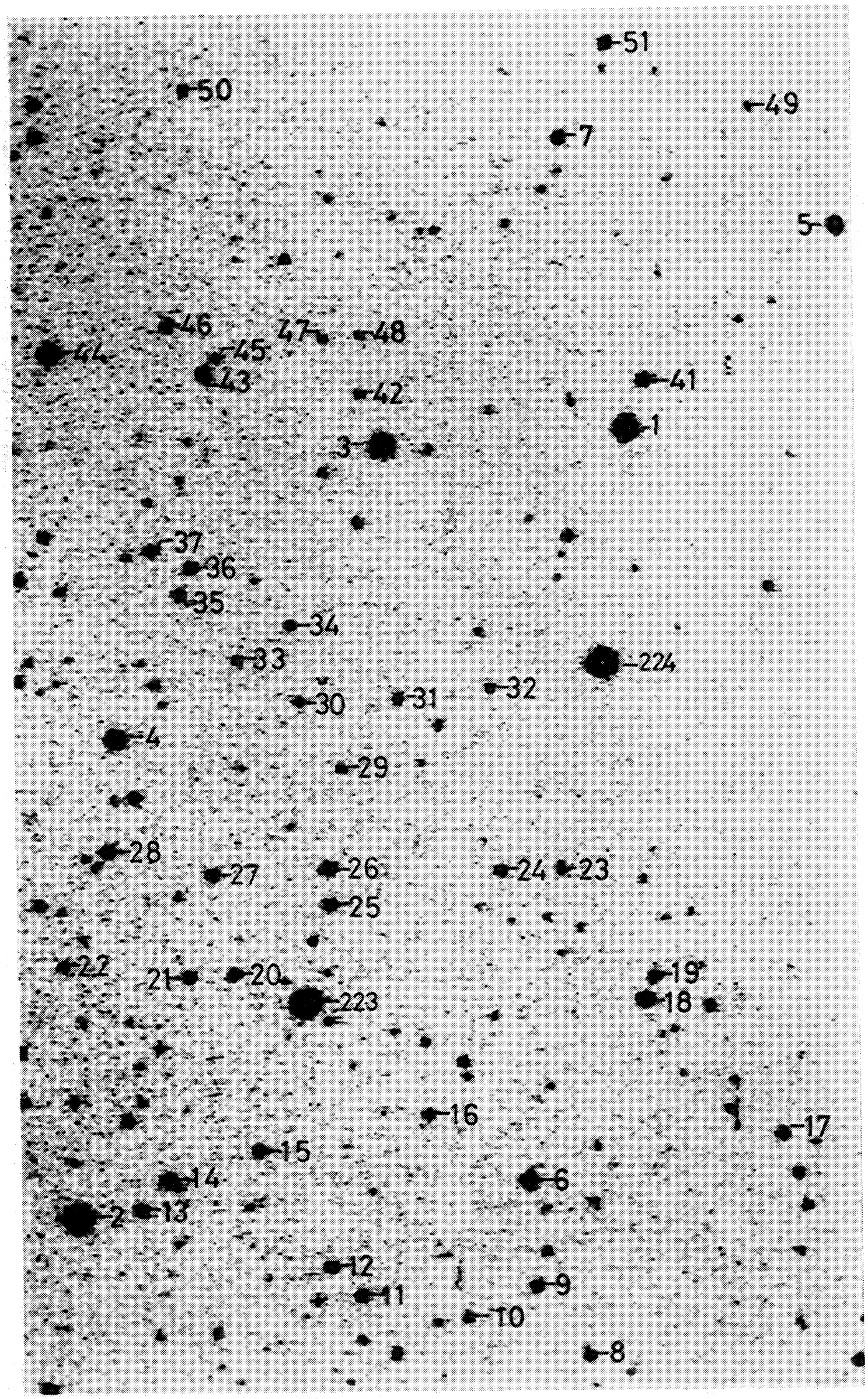

FIG. 1.—The identification chart for the bright stars, where the standard stars are indicated. The chart is from a 15 s visual CCD frame obtained with the 1.54 m Danish telescope at La Silla, ESO. The field covers 4′ × 2′.5. North is up and east is left.

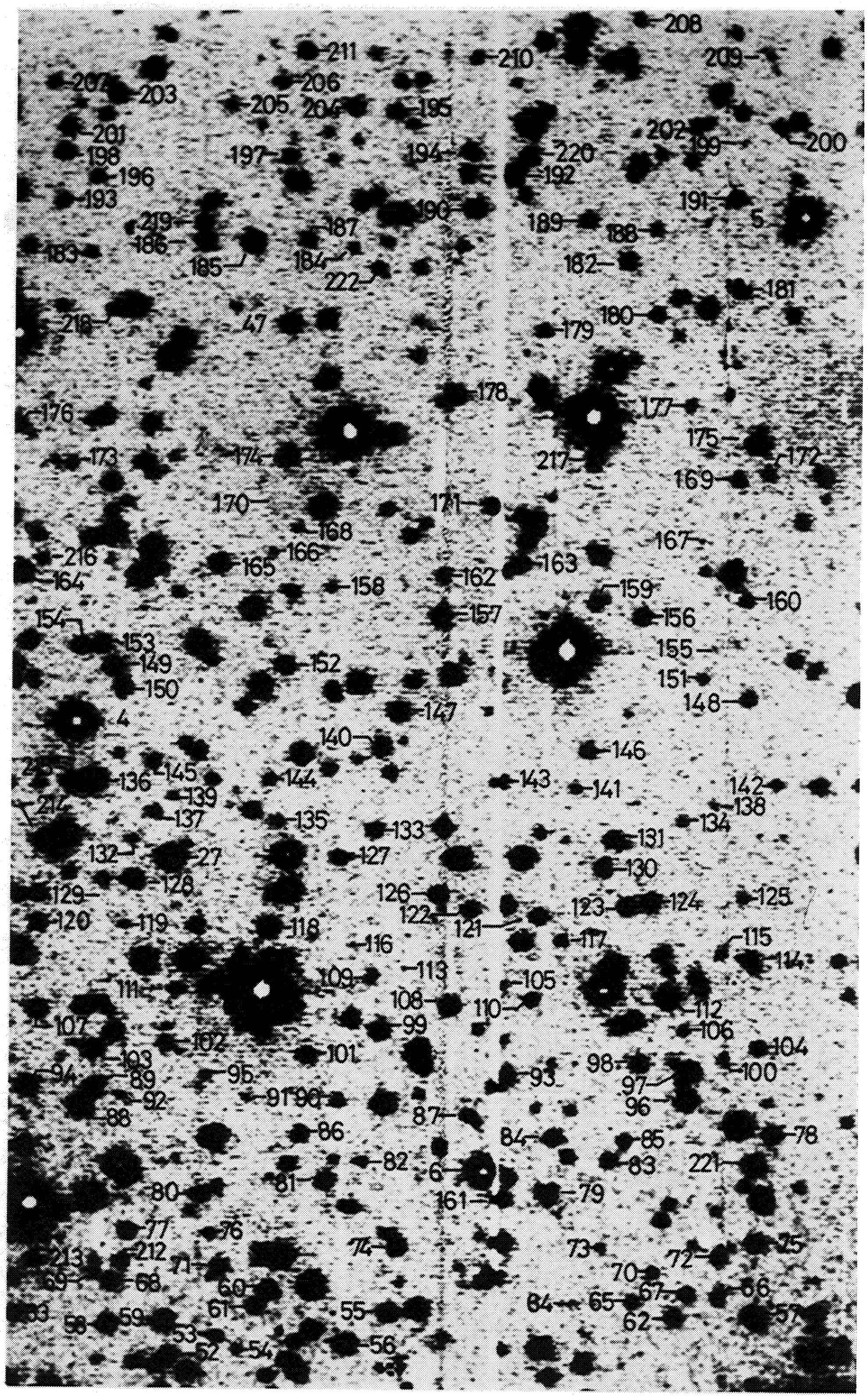

FIG. 2.—Identification chart of the fainter stars. The chart is from a 9 minute visual CCD frame obtained with the 1.54 m Danish telescope at La Silla, ESO. The field covers 4′ × 2′.5. North is up and east is left.

TABLE 3

STANDARD DEVIATION FOR THE MEAN OF TWO FRAMES PER MAGNITUDE INTERVALS

Range of V	σ_V	σ_{B-V}	σ_{V-I}	σ_{B-I}
13–16........	0.005	0.007	0.006	0.007
16–17........	0.005	0.007	0.006	0.007
17–18........	0.007	0.012	0.010	0.013
18–19........	0.013	0.025	0.018	0.023
19–20........	0.018	0.030	0.021	0.030
20–21........	0.019	0.036	0.029	0.032

In order to improve the transformations from the instrumental (b, v, i) colors and magnitudes to the standard *BV* (Johnson), *I* (Kron-Cousins) system, we incorporated, beside the standard stars observed in M4, 140 *BVI* frames obtained with the same equipment in fields that included other previously observed standard stars calibrated with Cousins's standards (see, e.g., Cousins 1980*a*, *b*). All data were first reduced to outside the atmosphere using the mean extinction coefficients adopted at ESO. For V we used 40 stars with $0.14 < (B-V) < 1.65$; for B, 38 stars with $0.14 < (B-V) < 1.65$; and for I, 34 stars with $0.59 < (V-I) < 1.57$. The transformations were determined to be

$$V = v + 0.06(\pm 0.01)(b - v) - 0.05(\pm 0.01)\,,$$

$$B-V = 1.12(\pm 0.01)(b - v) - 0.11(\pm 0.01)\,,$$

and

$$V-I = 1.10(\pm 0.01)(v - i) - 0.11(\pm 0.01)\,,$$

in excellent agreement with those derived for the ESO tests by Motch (1983), who used the same telescope and CCD and the *BVI* Johnson filters. Moreover, our mean color equation is in very good agreement with that derived by Ortolani (1985) and Stobie, Rager, and Gilmore (1985).

The final results for the *BVI* magnitudes and colors of 224 stars are listed in Table 4. The brighter stars are identified in Figure 1; the fainter stars in Figure 2. Stars with standard deviation ≥ 0.05 mag have been dropped from further consideration.

V. COMPARISON WITH ISOCHRONES, AND THE AGE OF M4

In Figures 3, 4, and 5 we show, respectively, the V, $B-V$, V, $V-I$, and V, $B-I$ diagrams. These CMDs can be compared directly with the isochrones of VandenBerg and Bell (1985), which are shown on the same plots. In these figures, we can see that, besides a single giant-branch star, four horizontal-branch stars are at $V \sim 13.5$. About 20 subgiant stars, defined their branch in the three diagrams well. About seven field stars appear to the redward side of the subgiant branch. The presence of field stars in this region of color and magnitude is also clearly shown in Figure 31 of Alcaino and Liller (1984).

The magnitudes of the main-sequence turnoff points in the three colors all fall very close to $V_{\rm TO} = 16.90$, with an uncertainty of ± 0.05. The colors and estimated uncertainties of the main-sequence turnoffs are $B-V = 0.81 \pm 0.02$, $V-I = 0.96 \pm 0.02$, and $B-I = 1.77 \pm 0.02$.

From photometry of 11 measured RR Lyrae stars, Cacciari (1979) deduced a mean visual magnitude of $(V)_{\rm RR} = 13.34 \pm 0.06$. From 28 measured RR Lyrae stars we previously deduced $(V)_{\rm RR} = 13.42 \pm 0.05$ (Alcaino and Liller 1984). If we

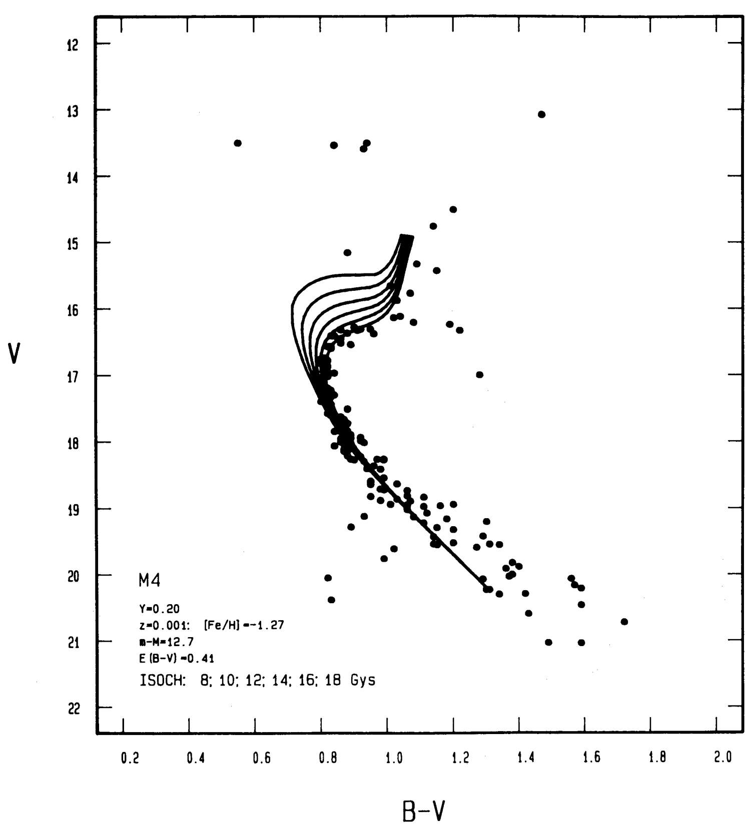

FIG. 3.—The observed V vs. $B-V$ color-magnitude diagram of M4 fitted to the isochrones of VandenBerg and Bell (1985) for $Y = 0.2$, $Z = 0.001$ ([Fe/H] $= -1.27$), $\alpha = 1.65$, and ages 8–18 Gyr. The isochrones were shifted to represent a cluster with $(m-M)_V = 12.7$ and $E(B-V) = 0.41$.

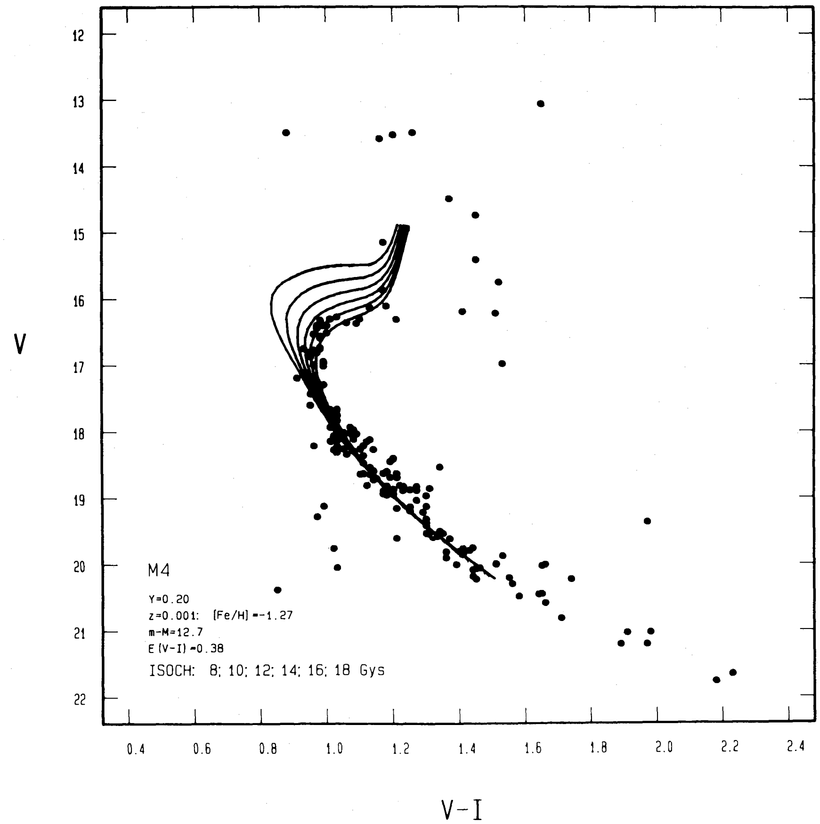

FIG. 4.—The observed V vs. $V-I$ color-magnitude diagram of M4 fitted to the isochrones of VandenBerg and Bell (1985) for $Y = 0.2$, $Z = 0.001$ ([Fe/H] $= -1.27$), $\alpha = 1.65$ and ages 8–18 Gyr. The isochrones were shifted to represent a cluster of $(m-M)_V = 12.7$ and $E(V-I) = 0.38$.

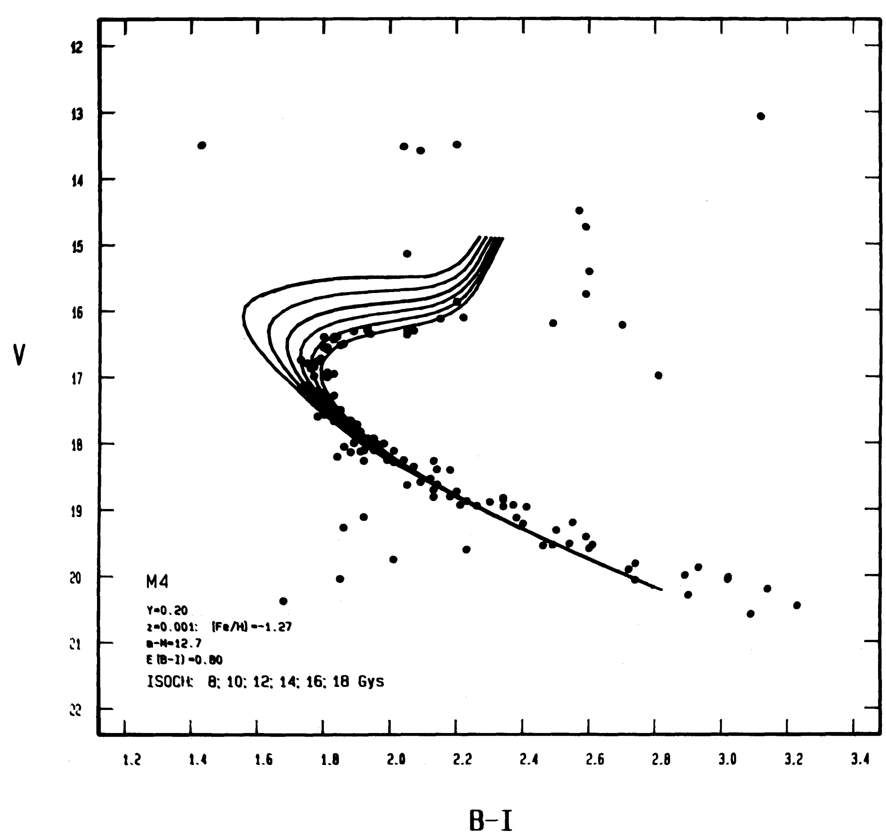

FIG. 5.—The observed V vs. $B-I$ color-magnitude diagram of M4 fitted to the isochrones of VandenBerg and Bell (1985) for $Y = 0.2$, $Z = 0.001$ ([Fe/H] $= -1.27$), $\alpha = 1.65$ and ages 8–18 Gyr. The isochrones were shifted to represent a cluster of $(m-M)_V = 12.7$ and $E(B-I) = 0.80$.

TABLE 4

CCD Magnitudes and Colors for 224 Stars in M4

Star	V	$B-V$	$V-I$	$B-I$
1	13.50	0.55	0.88	1.43
2	13.50	0.94	1.26	2.20
3	13.59	0.93	1.16	2.09
4	14.75	1.14	1.45	2.59
5	15.15	0.88	1.17	2.05
6	15.42	1.15	1.45	2.60
7	16.23	1.19	1.51	2.70
8	16.75	0.80	0.93	1.73
9	16.73	0.81	0.98	1.79
10	17.19	0.82	0.91	1.73
11	16.40	0.84	1.00	1.84
12	16.77	0.82	0.96	1.78
13	16.36	0.88	1.06	1.94
14	15.65	1.01	...	...
15	16.51	0.86	1.00	1.86
16	16.94	0.82	0.99	1.81
17	16.31	0.86	1.21	2.07
18	15.32	1.09	...	...
19	16.32	1.22	...	...
20	16.30	0.92	1.01	1.93
21	16.40	0.83	0.97	1.80
22	16.80	0.80	0.95	1.75
23	16.99	1.28	1.53	2.81
24	16.59	0.83	0.98	1.81
25	16.30	0.95	1.10	2.05
26	15.87	1.03	1.17	2.20
27	16.32	0.91	0.98	1.89
28	16.11	1.04	1.18	2.22
29	17.25	0.81	0.95	1.76
30	16.75	0.81	0.98	1.79
31	17.01	0.82	0.99	1.81
32	17.39	0.80	0.97	1.77
33	16.81	0.80	0.97	1.77
34	16.87	0.81	0.95	1.76
35	16.37	0.96	1.09	2.05
36	16.44	0.86	0.97	1.83
37	16.40	0.84	0.99	1.83
38	16.56	0.83	0.98	1.81
39	16.53	0.89	0.96	1.85
40	16.86	0.82	0.95	1.77
41	15.76	1.07	1.52	2.59
42	17.29	0.84	0.99	1.83
43	16.13	1.02	1.13	2.15
44	14.50	1.20	1.37	2.57
45	17.22	0.83	0.95	1.78
46	16.56	0.82	0.98	1.80
47	17.32	0.83	0.98	1.81
48	17.83	0.88	1.03	1.91
49	17.60	0.83	0.95	1.78
50	17.28	0.82	0.99	1.81
51	16.20	1.08	1.41	2.49
52	18.54	0.99	1.13	2.12
53	19.76	...	1.44	...
54	20.46	1.59	1.64	3.23
55	17.82	0.87	...	...
56	17.19	0.82	0.94	1.76
57	17.57	0.82	0.98	1.80
58	18.12	0.88	1.13	2.01
59	17.93	0.92	1.01	1.93
60	18.06	0.84	...	...
61	18.63	...	1.17	...
62	18.86	1.03	1.31	2.34
63	18.69	...	1.19	...
64	21.36	1.59	1.91	3.50
65	19.76	0.99	1.02	2.01
66	19.16	...	1.21	...
67	19.22	1.11	1.29	2.40
68	18.73	1.06	1.14	2.20
69	19.77	...	1.41	...
70	19.61	1.02	1.21	2.23
71	18.96	1.16	1.18	2.34
72	17.30	0.80	...	...
73	20.45	...	1.65	...
74	18.26	0.97	...	...
75	17.94	0.89	1.03	1.92
76	20.23	...	1.45	...
77	18.29	0.93	1.08	2.01
78	17.84	0.84	...	...
79	17.93	0.92	...	...
80	18.36	0.96	1.11	2.07
81	18.27	0.99	1.14	2.13
82	20.01	...	1.66	...
83	18.64	0.95	1.10	2.05
84	18.11	0.87	1.08	1.95
85	19.13	1.08	1.30	2.38
86	18.95	1.06	1.20	2.26
87	18.89	...	1.19	...
88	16.99	0.81	0.96	1.77
89	17.81	0.86	...	...
90	19.16	1.18	...	...
91	21.21	...	1.97	...
92	21.03	...	1.98	...
93	17.97	0.88	...	...
94	17.34	0.81	0.97	1.78
95	20.21	1.59	1.55	3.14
96	16.96	0.84	0.99	1.83
97	20.29	1.42	...	...
98	18.13	0.88	1.03	1.91
99	17.76	0.87	...	...
100	19.91	1.36	1.36	2.72
101	18.26	0.99	1.05	2.04
102	19.29	1.15	...	...
103	17.77	0.87	1.02	1.89
104	18.71	0.98	1.15	2.13
105	20.01	...	1.51	...
106	20.00	1.38	1.51	2.89
107	18.08	...	1.08	...
108	17.71	0.87	1.02	1.89
109	19.07	1.12	...	...
110	18.97	1.11	1.30	2.41
111	19.82	1.38	1.36	2.74
112	16.75	0.81	...	...
113	20.23	...	1.74	...
114	18.40	0.94	1.20	2.14
115	20.09	...	1.44	...
116	21.77	...	2.18	...
117	19.52	1.20	1.34	2.54
118	17.50	0.88	0.97	1.85
119	20.38	0.83	0.85	1.68
120	18.31	...	1.03	...
121	18.34	...	1.06	...
122	18.63	...	1.21	...
123	17.89	0.89	...	...
124	17.95	0.86	...	...
125	20.05	0.82	1.03	1.85
126	18.21	...	1.11	...
127	18.89	1.07	1.23	2.30
128	17.93	0.88	1.07	1.95
129	19.32	1.20	1.30	2.50
130	18.03	0.87	1.09	1.96
131	18.03	0.89	...	...
132	20.23	1.30	...	...
133	18.41	0.98	1.20	2.18
134	20.30	1.34	1.56	2.90
135	19.62	...	1.37	...
136	16.27	0.90	1.03	1.93
137	19.55	1.34	...	...
138	20.82	...	1.71	...
139	20.23	1.31	...	...
140	18.01	0.93	1.05	1.98
141	19.80	...	1.43	...
142	20.01	...	1.39	...
143	18.47	...	1.11	...
144	19.86	...	1.41	...
145	18.90	...	1.17	...
146	18.81	...	1.22	...
147	17.32	0.83	0.97	1.80
148	18.94	1.01	1.20	2.21
149	17.67	0.84	0.99	1.83
150	18.22	0.92	...	...
151	20.03	1.37	1.65	3.02
152	17.98	0.92	...	...
153	17.84	0.87	1.02	1.89
154	18.22	...	1.03	...
155	21.66	...	2.23	...
156	18.11	0.87	1.05	1.92
157	17.62	0.86	...	...
158	20.16	1.57	...	...
159	19.02	1.06	...	...
160	19.12	0.93	0.99	1.92
161	18.21	0.88	0.96	1.84
162	19.60	...	1.32	...
163	18.15	...	1.12	...
164	17.32	...	0.96	...
165	18.02	0.89	1.07	1.96
166	20.72	1.72	...	...
167	21.03	1.49	...	...
168	20.49	...	1.58	...
169	18.82	0.95	1.18	2.13
170	21.78	...	2.05	...
171	17.83	0.85	1.03	1.88
172	19.54	1.14	1.35	2.49
173	19.28	0.89	0.97	1.86
174	17.36	0.81	0.97	1.78
175	17.66	0.87	1.01	1.88
176	17.97	0.86	1.08	1.94
177	20.07	1.29	1.45	2.74
178	17.66	0.84	1.03	1.87
179	19.43	1.14	...	...
180	19.04	...	1.27	...
181	18.06	0.84	1.02	1.86
182	18.26	0.89	1.10	1.99
183	20.06	1.56	1.46	3.02
184	20.19	...	1.44	...
185	17.24	0.83	0.97	1.80
186	18.27	0.90	1.02	1.92
187	18.94	1.20	1.17	2.37
188	19.55	1.15	1.31	2.46
189	18.59	0.95	1.14	2.09
190	17.75	0.86	1.03	1.89
191	18.63	1.03	1.11	2.14
192	17.72	0.88	1.02	1.90
193	19.54	1.31	1.30	2.61
194	18.65	...	1.13	...
195	18.83	1.11	1.23	2.34
196	19.42	1.29	1.30	2.59
197	18.83	...	1.27	...
198	18.81	1.06	1.12	2.18
199	21.21	...	1.89	...
200	19.54	...	1.34	...
201	18.89	...	1.27	...
202	19.14	...	1.25	...
203	18.45	...	1.19	...
204	18.72	0.99	...	...
205	19.98	1.40	1.53	2.93
206	19.59	1.27	1.33	2.60
207	19.85	...	1.41	...
208	18.00	0.86	1.03	1.89
209	20.59	1.43	1.66	3.09
210	19.51	...	1.34	...
211	18.60	...	1.18	...
212	19.20	1.30	1.25	2.55
213	19.38	...	1.30	...
214	17.43	0.83	0.95	1.78
215	17.69	0.85	1.02	1.87
216	19.81	...	1.40	...
217	18.88	0.98	1.25	2.23
218	18.87	...	1.20	...
219	18.69	...	1.21	...
220	18.14	0.87	1.01	1.88
221	17.13	0.80	0.94	1.74
222	19.37	2.42	1.97	4.39
223V35	13.53	0.84	1.20	2.04
224	13.07	1.47	1.65	3.12

TABLE 5

MAIN-SEQUENCE FIDUCIAL POINTS FOR M4

V	$B-V$	$V-I$	$B-I$	V	$B-V$	$V-I$	$B-I$
16.00........	1.02	1.17	2.19	18.10........	0.90	1.07	1.97
16.10........	1.01	1.13	2.14	18.20........	0.92	1.09	2.01
16.20........	0.99	1.08	2.08	18.30........	0.93	1.11	2.05
16.30........	0.90	1.01	1.90	18.40........	0.95	1.13	2.09
16.40........	0.85	0.99	1.84	18.50........	0.97	1.14	2.12
16.50........	0.83	0.98	1.81	18.60........	0.99	1.16	2.16
16.60........	0.82	0.97	1.79	18.70........	1.02	1.18	2.20
16.70........	0.81	0.97	1.78	18.80........	1.04	1.20	2.24
16.80........	0.81	0.96	1.77	18.90........	1.06	1.22	2.28
16.90........	0.81	0.96	1.77	19.00........	1.08	1.24	2.32
17.00........	0.81	0.96	1.77	19.10........	1.10	1.26	2.36
17.10........	0.82	0.97	1.78	19.20........	1.13	1.28	2.41
17.20........	0.82	0.97	1.78	19.30........	1.15	1.30	2.45
17.30........	0.82	0.97	1.79	19.40........	1.18	1.32	2.49
17.40........	0.83	0.98	1.81	19.50........	1.20	1.34	2.54
17.50........	0.83	0.99	1.82	19.60........	1.23	1.36	2.58
17.60........	0.84	1.00	1.84	19.70........	1.26	1.38	2.63
17.70........	0.85	1.01	1.87	19.80........	1.28	1.40	2.68
17.80........	0.86	1.03	1.89	19.90........	1.31	1.42	2.73
17.90........	0.88	1.04	1.92	20.00........	1.35	1.44	2.79
18.00........	0.89	1.05	1.94				

adopt a value of V(HB) = 13.38 ± 0.04, the ΔV (turnoff-HB) = 3.52 ± 0.1, in excellent agreement with Sandage (1982), who derives $\overline{\Delta V} = 3.40 \pm 0.12$ for eight clusters, and, more recently, with Peterson (1986), who derives $\overline{\Delta V} = 3.46 \pm 0.03$ for 36 clusters.

Table 5 gives the fiducial points of the main sequence of M4 every 0.1 visual magnitude steps in $B-V$, $V-I$, and $B-I$. Above $V = 19$ our main-sequence turnoff values and fiducial points for the V, $B-V$ CMD are in excellent agreement with the CCD results of Richer and Fahlman (1984), with our previous photographic work (Alcaino and Liller 1984), and with a recent investigation by Fahlman (1987). However, for the faintest magnitudes, our main-sequence deviates from that of Richer and Fahlman, becoming $\Delta(B-V) = 0.07$ at $V = 20$. The cause of this discrepancy is not known, but might be related to the different reduction programs used

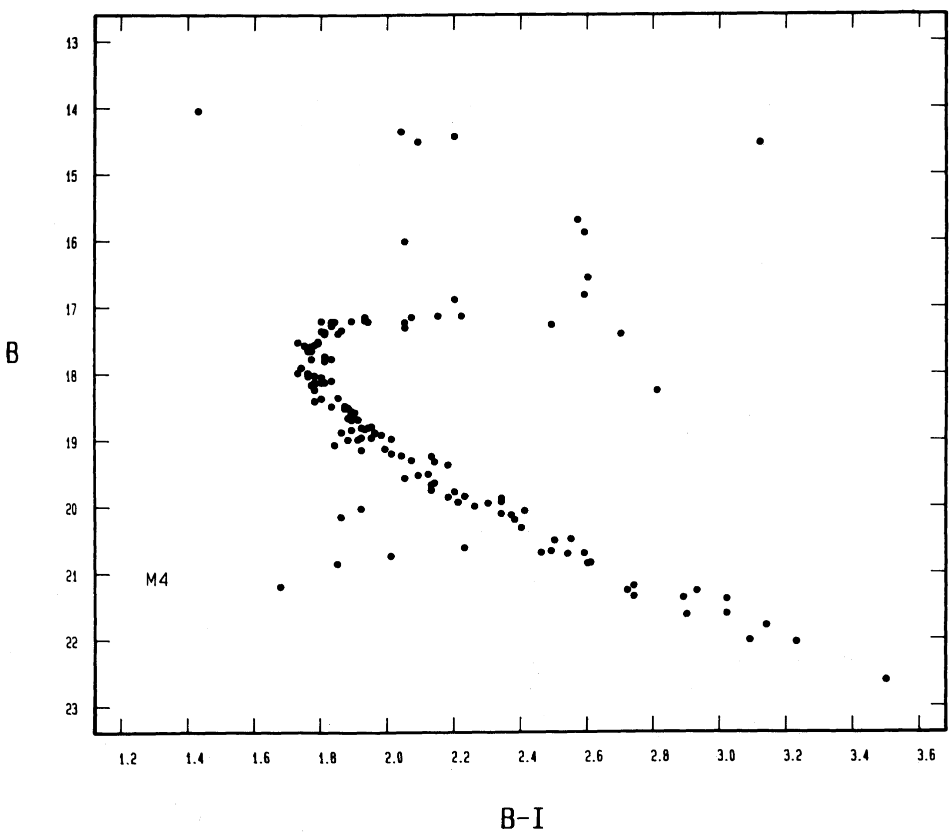

FIG. 6.—The observed B versus $B-I$ color-magnitude diagram

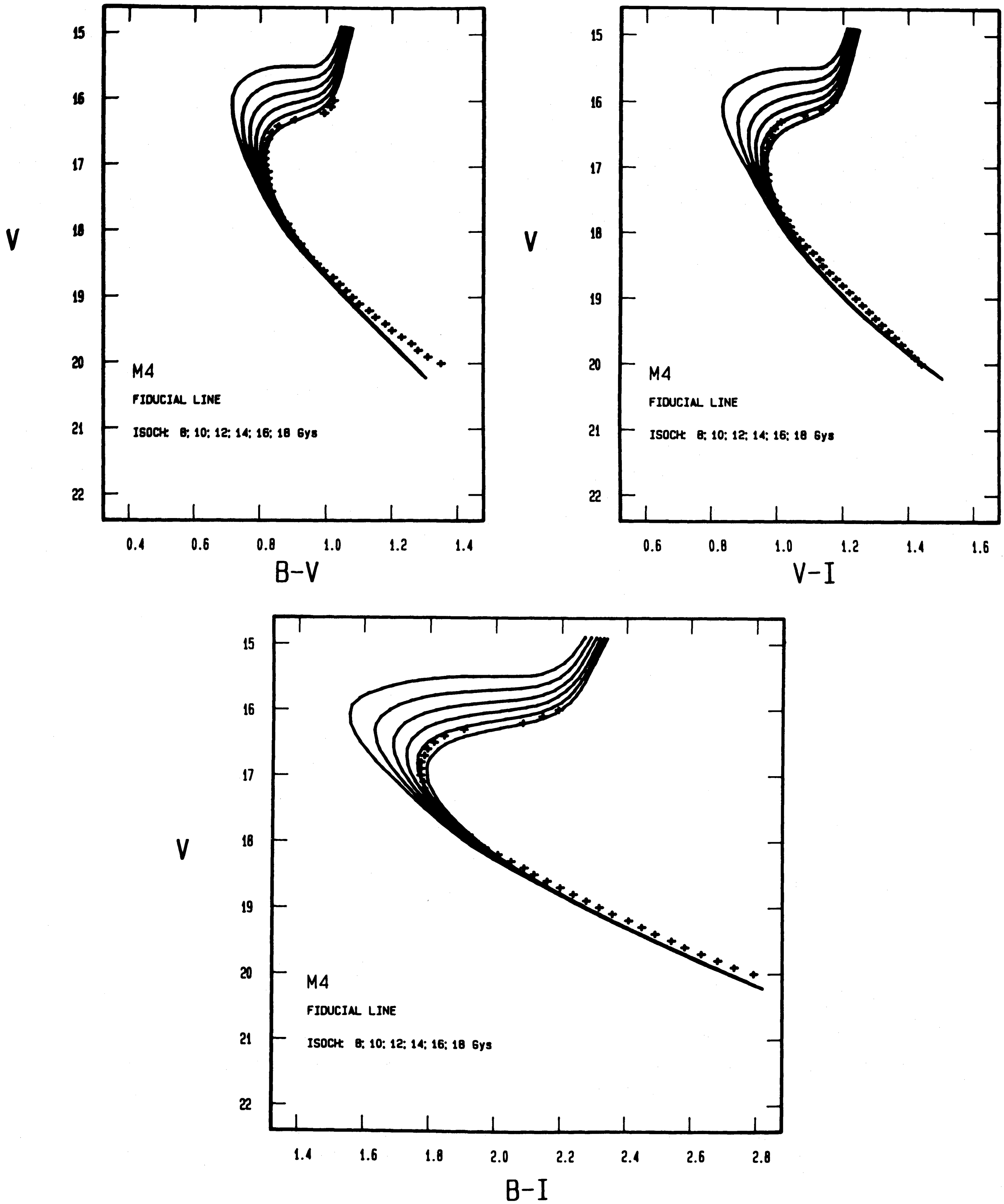

FIG. 7.—The fiducial lines of the three CMDs listed in Table 5 superposed on the isochrones of VandenBerg and Bell (1985). The best mean age estimation is 17 ± 1.5 Gyr.

(INVENTORY and DAOPHOT) or to the different manner of transferring standard magnitudes to the cluster stars.

In Figure 3, we have fitted the isochrones to the V, $B-V$ fiducial line diagram by shifting both vertically and horizontally. We found the best match to be produced with $Y = 0.2$, $Z = 0.001$ ([Fe/H] $= -1.27$), $\alpha = 1.65$, with a distance modulus of $(m-M)_V = 12.7 \pm 0.1$, and $E(B-V) = 0.41 \pm 0.03$. We note that the reddening is in good agreement with the unweighted mean of $E(B-V) = 0.39 \pm 0.07$ obtained from 16 independent reddening estimates (Table 6 of Cacciari 1979). The metallicity also agrees with the value [Fe/H] $= -1.2 \pm 0.1$ found spectroscopically by Wallerstein, Leep, and Oke (1987). In Figures 4 and 5 we have similarly superposed the isochrones with the same parameters as in Figure 4, for V versus $V-I$, and V versus $B-I$, respectively. From consideration of the three color indices we find that all the isochrones match the CMDs beat for an age of 17 ± 1.5 Gyr. Figure 6 show the excellent definition of the sequences in the B versus $B-I$ diagram. Figure 7 shows the fiducial lines of the three CMDs superposed in the isochrones.

The agreement between observation and theory appears to be equally good (or bad) in the three diagrams of Figure 7, and unlike our finding for 47 Tuc (Alcaino and Liller 1987*a*), it does not appear that agreement can be improved by varying the parameters such as Y, Z, α, E, and $(m-M)$. For example, in the V, $(B-I)$ diagram moving the isochrones to the right would produce agreement at the red end of the main sequence, but then the derived age would be substantially different than what is derived from the other diagrams. Because our values of V, $B-V$ around the turnoff agree essentially perfectly with those of Fahlman (1987) and Richer and Fahlman (1984) we are inclined to suspect that problems still exist with the isochrones. Perhaps the difficulty comes in the conversion from the theoretical plane to V, $B-V$ since stars with $(B-V) \sim 1.0$, both on the subgiant branch at $V \sim 16$ and on the main sequence at $V \sim 19$, lie consistently redward of the theoretical tracks.

Separation of the theoretical and observational main sequence continues to fainter magnitudes when the B band is included, but not when it is excluded (in the V, $V-I$ diagram, see Fig. 7). Owing to the increased influence of metallic-line absorption in the B band at $(B-V) > 1.0$, one suspects that the blanketing correction is the culprit.

VI. SUMMARY

We have presented CCD *BVI* main-sequence photometry of M4, matched to the *BVI* isochrones of VandenBerg and Bell (1985). Our main conclusions are as follows:

1. The main-sequence turnoffs are found to be at $V = 16.90 \pm 0.05$, $B-V = 0.81 \pm 0.02$, $V-I = 0.96 \pm 0.02$, and $B-I = 1.77 \pm 0.02$. Both the main-sequence turnoff point and the fiducial main sequence of the $B-V$ color index are in good agreement with the values derived by Richer and Fahlman (1984), Alcaino and Liller (1984), and Fahlman (1987).

2. The magnitude difference between the main-sequence turnoff and the horizontal branch is $\Delta M_V = 3.52 \pm 0.1$ for all three color indices; $B-V$, $V-I$, and $B-I$ are in general agreement with mean values of 3.40 ± 0.12 for eight clusters (Sandage 1982) and of 3.46 ± 0.03 for 36 clusters derived by Peterson (see Alcaino and Liller 1986*c*).

3. Using $Y = 0.2$, [Fe/H] $= -1.27$, and $\alpha = 1.65$, with a distance modulus of $(m-M)_V = 12.7$ and $E(B-V) = 0.41$, we deduce a consistent age for M4 in all three color indices of 17 ± 1.5 Gyr, very close to recent age determinations of all the other globular clusters studied by us using the same technique with data fitted to the same set of isochrones. These results suggest, as advocated by Sandage (1982), that the globular clusters are coeval and that the time of the galactic collapse was short. The corresponding limit on the Hubble constant becomes $H_0 < 58 \pm 5$ km s^{-1} Mpc^{-1} assuming $q_0 = 0$.

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REFERENCES

Alcaino, G. 1975, *Astr. Ap. Suppl.*, **21**, 5.
———. 1984, *Ap. J. Suppl.*, **56**, 19.
———. 1986*a*, *A.J.*, **91**, 303.
———. 1986*b*, *Astr. Ap.*, **161**, 61.
———. 1986*c*, *Mem. Soc. Astr. Italiana*, Vol. **57**, No. 3, p. 321.
———. 1987*a*, *Ap. J.*, **319**, 304.
———. 1987*b*, *A.J.*, **94**, 1585.
Burstein, D. 1985, *Pub. A.S.P.*, **97**, 89.
Cacciari, C. 1979, *A.J.*, **84**, 1542.
Caputo, F. 1987, *Astr. Ap.*, **172**, 67.
Cousins, A. W. J. 1980*a*, *South Africa Astr. Obs. Circ.*, **1**, 166.
———. 1980*b*, *South Africa Astr. Obs. Circ.*, **1**, 234.
ESO Users Manual, 1983 (ESO).
Fahlman, G. 1987, private communication.
Gratton, R. G., and Ortolani, S. 1984, *Astr. Ap. Suppl.*, **57**, 177.
Greenstein, J. L. 1939, *Ap. J.*, **90**, 387.
Hesser, J. E., Harris, W. E., VandenBerg, D. A., Allwright, J. W. B., Schott, P., and Stetson, P. 1987, *Pub. A.S.P.*, submitted.
Kurucz, R. L., van Dishoeck, E. F., and Tarafdar, S. P. 1987, *Ap. J.*, submitted.
Lee, S. W. 1977, *Astr. Ap. Suppl.*, **27**, 367.
Lloyd Evans, T. 1977, *M.N.R.A.S.*, **178**, 353.
Motch, C. 1983, private communication.
Moshkalev, V. G. 1976, *Soviet Astr.*, **19**, 495.
Ortolani, S. 1984, *Astr. Ap.*, **137**, 269.
———. 1985, private communication.
———. 1986*a*, *ESO Messenger*, No. **43**, p. 23.
———. 1986*b*, *Proc. ESO-OHP Workshop on The Optimization of the use of CCD Detectors in Astronomy*, ed. J. P. Baluteau and S. D'Odorico (ESO Conf. and Workshop Proc., No. 25) p. 183.
Pedersen, H., and Cullum, M. 1982, *ESO Messenger*, No. **30**, p. 26.
Peterson, C. 1986, *Pub. A.S.P.*, **98**, 1258.
Richer, H. B., and Fahlman, G. 1984, *Ap. J.*, **277**, 227.
Sandage, A. R. 1982, *Ap. J.*, **252**, 553.
Stobie, R. S., Rager, R., and Gilmore, G. 1985, *Astr. Ap. Suppl.*, **60**, 503.
VandenBerg, D. A., and Bell, R. A. 1985, *Ap. J. Suppl.*, **58**, 561.
Wallerstein, G., Leep, E. M., and Oke, J. B. 1987, *A.J.*, **93**, 1137.
West, R., and Kruszewski, A. 1981, *Irish Astr. J.*, **15**, 25.

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