

CCD PHOTOMETRY OF STARS IN THE OLD OPEN CLUSTER NGC 188

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ABSTRACT

We present CCD photometry for stars in three fields centered on the old open cluster NGC 188, with the aim of investigating the HR diagram distribution of cluster main-sequence stars. A sequence of subgiant, turnoff, and main-sequence stars has been detected, extending the observed lower main sequence down to about $m_v = 20$ mag. By relying on theoretical evolutionary tracks and by adopting recent estimates of the cluster reddening and distance modulus, we find that the observed color-magnitude diagram appears well fitted by a theoretical isochrone for an age $t \simeq 6 \times 10^9$ yr, provided that Yale transformations from the theoretical (luminosity versus effective temperature) into the observational plane (visual magnitude versus color) are assumed. The same age would be derived by using Vandenberg [Astrophys. J. Suppl. **58**, 711 (1985)] transformations, but with a discrepancy in color for the main-sequence stars, which grows for lower luminosities. From the distribution of the stellar luminosities one finds that the turnoff stars should have masses around $1.3 M_{\odot}$. Moreover, we find that the MS appears progressively depopulated in going toward lower masses. We finally discuss the cluster evolutionary scenario in connection with the reported luminosity of the clump of He-burning giants. A cluster original helium content of the order of $Y \simeq 0.28$ is derived, suggesting a "solar" chemical composition for NGC 188.

1. INTRODUCTION

Galactic open clusters provide fundamental clues for tracing the history of galactic matter from the time when the collapse of the original gaseous protohalo was followed by the galactic disk. The oldest among these stellar systems appears to be of particular relevance, addressing the problem of the evolutionary conditions of the "early disk." Old open clusters often appear characterized by a rather abundant stellar content and by a fairly spherical symmetry, thereby recalling well-known properties of the older halo globular clusters. Both these characteristics make old open clusters an interesting target for producing significant color-magnitude (C-M) diagrams. The interest is increased by the fact that some old open clusters occur much nearer to the Sun than globular clusters do, allowing for the detection of much fainter stars, and providing an opportunity for gaining relevant information on the distribution of low main-sequence (MS) stars.

As for stellar evolution theory, old open clusters give us the opportunity of testing the predictions of theoretical models of slightly more massive stars than those found in galactic globular clusters. However, both types of stellar systems appear to be populated by stars with similar evolutionary behavior, i.e., developing an electronically degenerate He core during the red giant (RG) phase and igniting central helium after a fairly violent He flash. Thus, one may hope to translate, at least in part, to old open clusters the well-defined scenario of procedures recently developed for the interpretation of globulars.

In this context, the open cluster NGC 188 deserves particular attention since it was suggested by Sandage (1962) to be the oldest known open cluster. Over the past two decades the

estimate of its age varied from 11 Gyr (Iben 1967) to 5 Gyr (Demarque and McClure 1977; Twarog 1978) and back up to 10 Gyr (Barbaro and Pigatto 1984; Vandenberg 1985, hereafter referred to as V85), with the most recent estimate (Twarog and Anthony Twarog 1989) leading to an age of 6.5 Gyr. As a whole, NGC 188 could represent a milestone for learning the history of the galactic disk as well as for the more general problem of the evolution of stellar populations within the galaxy.

Extensive photometric observations of stars in NGC 188 have already been carried out by Sandage (1962), Eggen and Sandage (1969), McClure and Twarog (1977), and Twarog (1978) leading to a color-magnitude diagram showing sufficiently well-defined sequences for giant, subgiant, and dwarf stars down to $V \simeq 19$ mag, roughly 4 mag below the MS turnoff. The present investigation intends to extend the previous results by the use of modern CCD detectors. The observations and data reduction will be reported in Sec. II, along with tables of all observed stars. The discussion of the C-M diagram (morphology, comparison with theoretical isochrones, age determination) will be presented in Sec. III, together with the discussion of the observed luminosity function. Evolutionary implications concerning the cluster's original composition will finally be discussed in Sec. IV.

II. PHOTOMETRY AND DATA REDUCTION

Observations have been performed at the Observatorio del Roque de los Muchachos (La Palma, Spain) using the prime focus GEC CCD camera (Wae and Laing 1986) of the 2.5 m Isaac Newton Telescope. Three partially overlapping frames have been observed in both B and V colors, covering the cluster central region and extending toward the southern

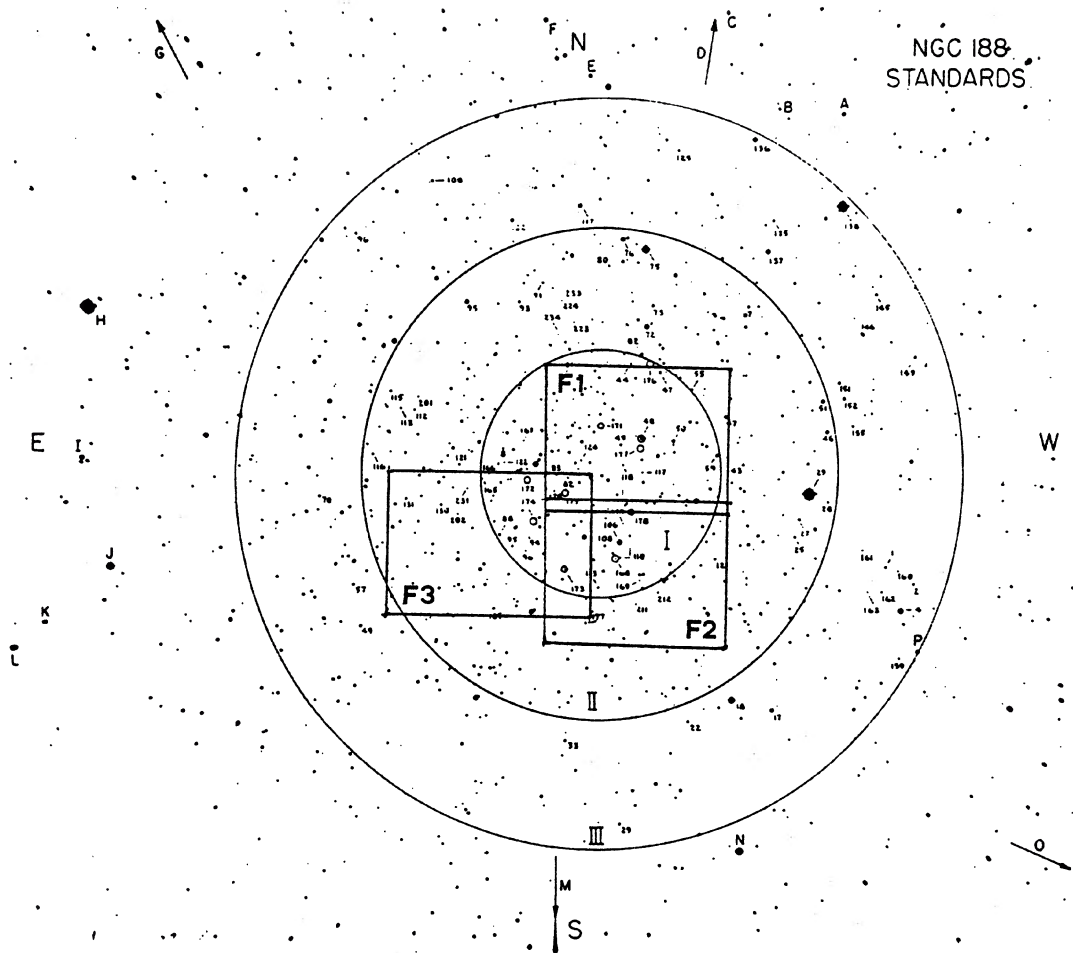


FIG. 1. Position of the sky of the three CCD frames *F1*, *F2*, *F3* in NGC 188. The field is from Sandage (1962), with his identification for Rings I–III.

region of the cluster. In this way we covered a large majority of Sandage (1962) Ring I together with a portion of Ring II (see Fig. 1).

The open cluster NGC 188 is situated at a declination of 85° and, when observed from a 28° of north latitude observatory, there is always a minimum airmass around 2. The mean seeing in the two different nights was around 2 arcsec, as it was provided by the acquisition and guide camera of the telescope. Table I gives the log of the various exposures.

The data have been processed at the Instituto de Astrofísica de Canarias (La Laguna, Spain) adopting a computer program (IACFOT) based on the philosophy described by Buonanno *et al.* (1983) for photometry in crowded fields, but with the improvement that stellar images have been here best fitted by a two-dimensional Molfatt's function of the form,

$$f(x,y) = S + H * (1 + \{[(X - X_0)\cos A + (Y - Y_0)\sin A] / R_x\}^2 + \{[-(X - X_0)\sin A + (Y - Y_0)\cos A] / R_y\}^2)^{-B},$$

where S represents the sky level, H the height of the profile, A the inclination angle of the image, and B , R_x , and R_y are the

parameters defining the shape of the profile, as described in the abovementioned paper by Buonanno *et al.* (1983). Such a procedure allowed us to account for elliptical images that can be originated by autoguide problems when pointing near to the pole with an equatorial mounting telescope, and that can be particularly relevant for the faintest objects.

Relying on the extensive investigation by Eggen and Sandage (1969) we found 45 standards in Field *F1* and 24 in fields *F2* and *F3* each. On this basis, each CCD frame has been calibrated in terms of V magnitude and $(B - V)$ color, by a linear fit of the instrumental results with the photoelectric values. The standard deviation of the differences for V

TABLE I. The log of observations. Fields as labeled in Fig. 1.

Run	Date	Filter	Exp (sec)	Field
088	October 26, 1986	V	300	1
090	"	B	1000	1
335	October 28, 1986	V	300	2
337	"	B	1000	2
343	"	V	300	3
345	"	B	1000	3

and $(B - V)$, respectively, was 0.040 and 0.034 for field $F1$, 0.050 and 0.040 for field $F2$, and 0.049 and 0.034 for field $F3$. Figures 2(a) and 2(b) report the V_s and $(B - V)_s$ values by Eggen and Sandage (1969) versus the present results V_c and $(B - V)_c$, after calibration. Figures 2(c) and 2(d) show the corresponding discrepancies in magnitude and color versus the standard magnitude. As a whole, the standard deviation of such discrepancies results in 0.05 for V and 0.04 for $(B - V)$ over the total of 87 calibrating stars. As a result, we finally obtained B and V photometric values for 121 stars in $F1$, 90 in $F2$, and 93 in $F3$.

The stars in common between different frames allowed us to reach a direct estimate of the intrinsic error of our measurements. Fields $F1$ and $F2$ have only one star in common, with a difference of less than 0.01 both in color and magnitude. From the five stars in common between fields $F1$ and $F3$, and the 13 stars in common between $F2$ and $F3$, a mean systematic difference ($F1 - F3$ and $F2 - F3$) of 0.02 in V and 0.04 in $(B - V)$ is derived, with a standard deviation of 0.02 and 0.04, respectively. However, due to the small number of common stars (less than the number of photoelectric standards in each frame) we kept field $F3$ with the calibration obtained through the standards, without applying any further unessential shift.

To assess the completeness of the luminosity function, we compared the stars detected and fitted by the program, with

the objects present in the frame. We conclude that the program begins to reject some images at a magnitude of about 19.5. After subtraction of stars common to two frames, 285 stars remained whose photometric values are listed in Table II. Figures 3(a)–3(c) report the sky map of all these objects.

III. THE COLOR-MAGNITUDE DIAGRAM

Figure 4 shows the C–M diagrams for all the program stars in the various frames. As already indicated from a careful analysis of the frames, we estimated that the diagrams should be complete down to, at least, $V \simeq 19$ mag, with no, or only minor, problems of crowding. Inspection of Fig. 4 reveals that the turnoff region merges in a sufficiently well-defined, though poorly populated, main sequence that becomes progressively depopulated and vanishes around $V \simeq 20$ mag, an occurrence that deserves further comment (see Sec. IV).

In order to compare the observed C–M diagram with theoretical isochrones, three fundamental quantities have to be determined, namely the cluster metal content, and the reddening and distance modulus. However, if one fixes the metallicity and the reddening (the distance modulus), the distance modulus (the reddening) can be, at least in principle, derived by the fitting of the observed main sequence to the theoretical one.

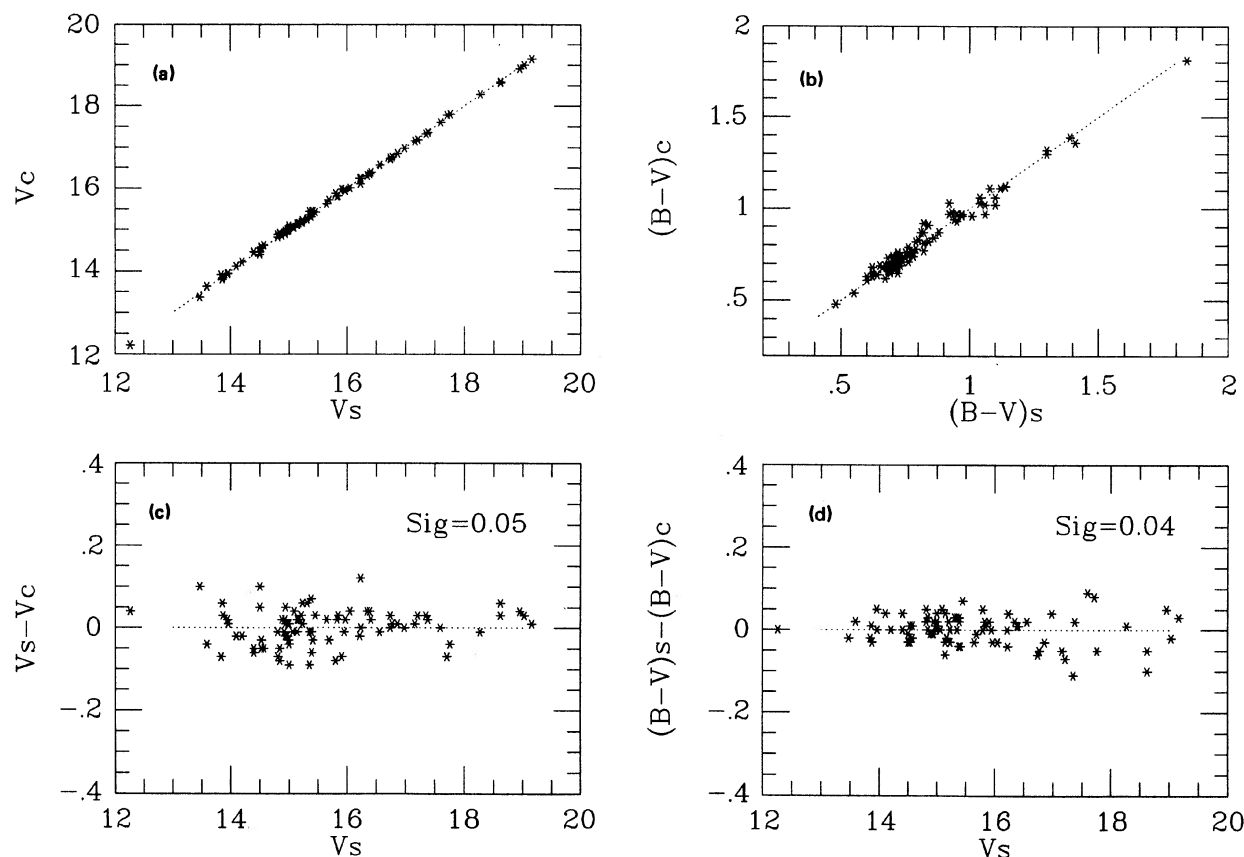


FIG. 2. (a) V calibrated vs V standard; (b) $(B - V)$ calibrated vs $(B - V)$ standard; (c) magnitude difference vs V standard; and (d) color difference vs V standard.

TABLE II. V magnitudes and $(B - V)$ colors for all the program stars. Stars are identified with the number given in the maps of Fig. 3.

FIELD 1								
#	B-V	V						
3.I	.48	13.95	57.I	1.12	13.63	150.I	1.49	18.86
12.I	.67	15.09	58.I	.73	16.76	151.I	1.08	17.67
13.I	1.12	16.89	59.I	.96	13.93	152.I	1.17	18.19
14.I	.65	15.42	60.I	.69	15.15	153.I	1.78	18.68
15.I	.77	14.88	61.I	1.06	14.12	155.I	1.04	18.59
16.I	.82	15.98	62.I	.76	14.82	162.I	.62	17.03
17.I	.69	15.02	63.I	.71	15.82	163.I	.96	17.93
18.I	.60	15.59	64.I	.86	16.29	170.I	1.36	18.91
19.I	.76	16.21	65.I	.68	15.36	171.I	1.33	18.64
20.I	.94	14.22	66.I	.87	14.99	175.I	2.11	19.81
21.I	.70	15.73	67.I	.74	16.02	177.I	1.44	18.49
22.I	.82	16.62	68.I	.69	15.92	E1.I	.83	17.08
23.I	.83	16.67	69.I	1.30	12.22	E2.I	.74	15.63
24.I	.69	14.91	70.I	.75	14.81	E3.I	1.67	14.38
25.I	.65	15.31	74.I	.72	15.68	E5.I	.93	16.47
27.I	.80	15.08	75.I	1.11	13.84	E6.I	.99	17.59
28.I	.68	15.94	76.I	.69	14.96	E8.I	1.25	17.95
31.I	.74	16.24	79.I	.71	15.75	E11.I	.58	19.13
32.I	.64	14.45	80.I	.69	15.44	E13.I	1.08	20.23
33.I	.79	14.56	81.I	.76	15.88	E14.I	.76	17.13
34.I	.71	15.81	82.I	.87	16.74	E15.I	1.64	19.66
35.I	.88	16.19	83.I	.87	16.71	E16.I	1.19	19.58
36.I	.64	16.41	84.I	.80	16.12	E17.I	.84	20.12
37.I	.71	15.19	85.I	1.06	14.62	E18.I	2.48	19.88
38.I	.72	15.27	117.I	1.03	17.32	E19.I	2.22	19.70
39.I	.73	16.02	118.I	1.02	16.98	E23.I	1.67	19.71
40.I	.69	15.21	120.I	.86	17.05	E25.I	1.78	20.00
41.I	.73	15.22	121.I	.89	17.03	E26.I	1.65	19.26
42.I	.97	15.07	128.I	.87	16.95	39.II	.71	15.00
43.I	.63	14.91	131.I	1.49	19.21	47.II	.68	13.37
45.I	.68	14.99	136.I	1.06	17.67	48.II	.68	15.71
46.I	.92	16.58	137.I	1.01	17.45	55.II	.69	15.31
47.I	.73	14.93	138.I	.89	17.24	56.II	.73	16.17
48.I	.76	14.86	139.I	1.16	18.21	57.II	.84	16.42
49.I	.75	15.63	140.I	1.46	19.25	E7.II	1.11	17.62
50.I	.54	13.80	141.I	1.21	17.73	E9.II	1.02	17.70
52.I	.70	14.89	142.I	1.09	17.89	E10.II	1.41	19.51
53.I	.75	15.69	145.I	.97	17.02	E11.II	1.15	19.53
54.I	.70	15.00	147.I	1.13	17.91	E12.II	.63	18.11
55.I	.80	14.91	148.I	1.49	17.28			
56.I	.81	16.39	149.I	.91	18.69			
FIELD 2								
#	B-V	V						
67.I	.74	16.02	E31.I	1.44	19.93	212.II	.98	15.15
71.I	.63	15.05	E32.I	1.38	19.39	E15.II	.84	16.39
91.I	.72	14.92	E34.I	1.57	20.39	E16.II	1.15	17.18
99.I	.71	14.93	E35.I	.98	16.46	E17.II	1.51	19.33
101.I	.66	15.09	E36.I	.70	15.85	E18.II	1.55	19.17
102.I	.64	14.45	E37.I	1.25	19.10	E19.II	.68	16.36
103.I	.69	15.15	E38.I	1.25	20.85	E20.II	1.13	18.67
104.I	.66	15.45	E39.I	2.32	20.66	E21.II	1.06	17.64
107.I	1.41	15.96	E40.I	1.66	19.80	E22.II	1.63	19.94
108.I	.69	15.13	1.II	.76	15.93	E23.II	.98	17.75
109.I	.76	16.24	2.II	.72	15.30	E24.II	1.23	19.81
110.I	.83	16.85	7.II	.79	16.13	E25.II	1.58	20.85
111.I	.66	15.18	8.II	.69	15.02	E26.II	1.61	19.77
112.I	.66	14.46	9.II	.72	15.25	E27.II	1.76	20.23
113.I	.83	15.95	10.II	.69	15.56	E28.II	1.29	18.94
114.I	.70	14.84	11.II	.82	16.49	E29.II	2.12	20.34
115.I	.76	15.72	12.II	.76	16.11	E32.II	1.82	20.20
116.I	.98	13.91	13.II	.52	15.17	E33.II	.74	19.39
132.I	.33	18.65	15.II	1.01	15.09	E34.II	1.70	19.09
133.I	1.26	18.16	17.II	.80	15.84	E36.II	1.30	20.80
134.I	.98	17.60	34.II	.59	15.60	E38.II	.79	15.36
154.I	1.78	19.20	35.II	.75	16.24	E39.II	1.01	14.96
156.I	1.17	18.29	37.II	.71	16.04	E40.II	.94	17.07
157.I	1.13	18.27	177.II	.82	16.13	E41.II	1.03	17.59
158.I	1.39	19.22	178.II	.72	14.99	E44.II	.93	16.96
168.I	.99	17.80	179.II	1.03	14.01	E45.II	.71	19.91
173.I	.93	18.59	183.II	.76	16.24	E46.II	1.28	19.50
178.I	1.82	19.15	186.II	.88	15.85	E47.II	.72	19.50
179.I	1.12	18.28	190.II	.69	15.98	E48.II	.67	18.46
E29.I	1.58	19.82	211.II	.94	17.36	E49.II	1.50	18.91

TABLE II. (continued)

FIELD 3								
#	B-V	V						
81.I	.71	15.88	175.I	1.74	19.76	183.II	.76	16.22
85.I	1.03	14.62	E37.I	1.05	19.09	184.II	.73	15.84
86.I	.84	15.77	E42.I	.71	15.04	185.II	.74	15.44
87.I	.83	16.30	E43.I	.28	14.04	186.II	.79	15.86
88.I	.91	15.03	E44.I	2.12	19.84	192.II	.69	15.60
90.I	.76	15.72	E45.I	.98	16.99	202.II	.91	17.18
91.I	.68	14.89	E46.I	1.54	17.63	203.II	.91	17.28
92.I	.67	15.45	127.II	.55	15.32	205.II	1.09	18.11
93.I	.69	14.58	128.II	.68	16.40	206.II	1.40	16.93
94.I	.78	16.35	129.II	.75	14.84	231.II	1.02	17.78
95.I	.75	16.01	130.II	.79	16.65	232.II	.89	17.15
96.I	.84	16.57	131.II	.74	16.31	E45.II	.47	19.84
97.I	.96	14.97	132.II	.61	15.34	E53.II	1.40	19.28
98.I	.75	16.33	137.II	.67	15.19	E54.II	.86	17.05
99.I	.74	14.89	138.II	.61	14.26	E55.II	.99	17.68
100.I	.73	15.17	143.II	.94	16.83	E56.II	1.27	18.73
101.I	.67	15.04	144.II	.76	16.30	E58.II	1.16	18.60
102.I	.61	14.40	145.II	.69	15.57	E59.II	1.11	18.06
103.I	.65	15.12	146.II	.68	16.02	E64.II	.96	19.71
104.I	.67	15.40	147.II	.74	16.53	E65.II	.82	17.42
130.I	.98	19.10	148.II	.86	16.29	E68.II	1.19	18.50
132.I	.16	18.60	150.II	1.29	13.68	E70.II	1.40	19.17
158.I	1.76	19.29	151.II	.54	14.63	E71.II	1.30	19.07
160.I	.97	17.62	152.II	1.17	13.62	E72.II	.60	20.09
161.I	1.26	17.66	153.II	.73	14.90	E78.II	1.41	18.50
162.I	.58	17.02	154.II	.72	16.01	E79.II	.87	17.04
165.I	.98	17.63	155.II	.73	16.00	E81.II	.93	17.32
170.I	1.30	18.86	156.II	.70	15.90	E83.II	1.44	19.42
172.I	1.32	19.00	158.II	.77	14.79	E84.II	1.80	17.65
173.I	.87	18.56	180.II	.73	16.05	E86.II	1.47	19.47
174.I	1.59	18.68	182.II	.79	16.65	E87.II	1.56	19.48

As for the metallicity, NGC 188 is widely assumed to have a composition similar to that of the Sun (i.e., $[\text{Fe}/\text{H}] = 0$) although until now no spectroscopic determination has been carried out for its stars. Following the metallicity indices listed by Twarog (1978) and Janes (1979), one can derive a mean value $[\text{Fe}/\text{H}] = 0.02 \pm 0.11$.

As far as the reddening and distance modulus are concerned, the values $E(B - V) = 0.09$ and $(m - M) = 11.12$ originally found by Eggen and Sandage (1969) are consistent with the values $E(B - V) = 0.08$ and $(m - M) = 11.10$ adopted by V85 for his isochrone fitting, which led to a cluster age of about 10 Gyr. However, in a recent paper by Twarog and Anthony-Twarog (1989) both the above parameters have been revised, reporting convincing evidence for $E(B - V) = 0.12$ and $(m - M) = 11.5$.

By adopting these new values and with the above metal content, we compared the cluster C-M diagram with the set of isochrones recently computed by Chieffi and Straniero (1989) for metallicity $Z = 0.02$ and helium content $Y = 0.23$. The left panel of Fig. 5 shows this comparison by using the Yale transformations (see Green, Demarque, and King 1987) from the theoretical into the observational plane, while the right panel refers to the V85 relations. In both cases one finds that the upper portion of the MS, the turnoff, and the subgiant regions appear well fitted with the 6 Gyr isochrone, in complete agreement with the result reported by Twarog and Anthony-Twarog (1989). It is interesting to note that decreasing the cluster age implies an increased difference in temperature between the turnoff and the red giant branch base, thus removing the discrepancy on the color of the subgiant branch found when trying to fit the cluster C-M diagram with a 10 Gyr isochrone (see, e.g.,

V85). Finally, it is worth noting that the derived age is not critically dependent on the assumed amount of original helium. With $Y = 0.28$, as generally adopted for the Sun, the isochrone should be blueward shifted by roughly $\delta(B - V) = 0.02$ (see Vandenberg and Bell 1985), a fact that leaves no hope of discussing the original helium on the basis of present data for the cluster main sequence.

As for the faint region of the main sequence, Fig. 5 discloses that the agreement between theory and observations becomes progressively unsatisfactory, even with depending on the assumed transformation from the theoretical into the observational plane. It appears difficult to illuminate the origin of such a discrepancy, since the transformation of theoretical into observational parameters is still a debated problem. Nor can we exclude the intervention of systematic errors in the photometry of fainter stars. However, we note that a recent empirical determination of the color-temperature transformation (Arribas and Martinez Roger 1988) for solar metallicity stars seems to support the Yale transformations at least at the low temperature we are dealing with, and may in turn support the theoretical evaluations.

What appears surprising in Fig. 5 is the apparent lack of stars populating the lower portion of the cluster main sequence. The luminosity function for our sample of stars is given in Fig. 6, showing that in NGC 188 the lower MS appears much less populated than the turnoff region, at variance with normal expectations. Moreover, the data in Fig. 6, which refers to all the measured stars, include the contribution of field stars that are mainly affecting the low luminosity portion of the distribution. One may obtain a rough estimate of such a contribution following the simple photometric criterion of treating as field stars all the objects falling well

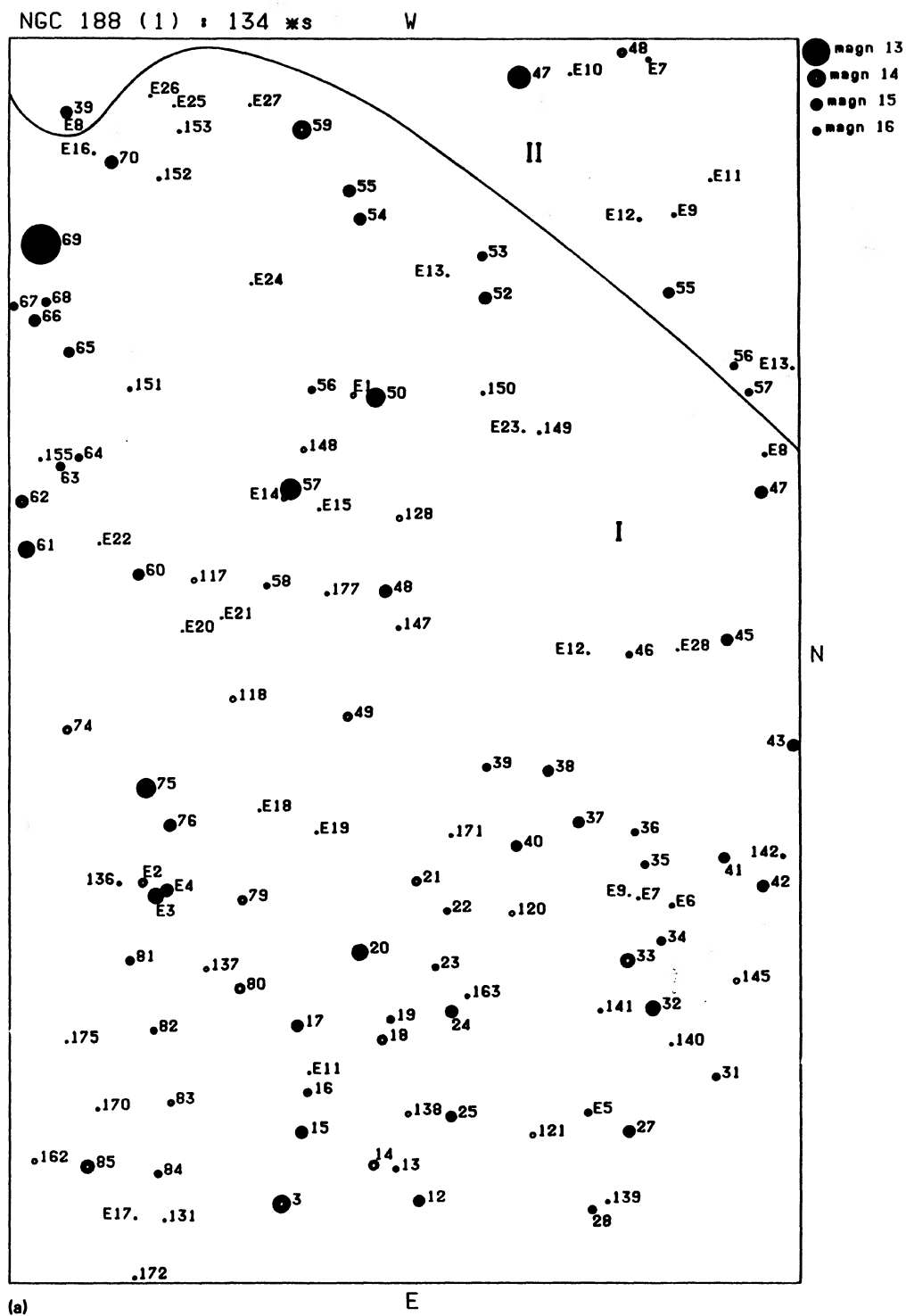


FIG. 3. (a) Map of the observed objects in field $F1$; (b) the same but for field $F2$; and (c) the same but for field $F3$.

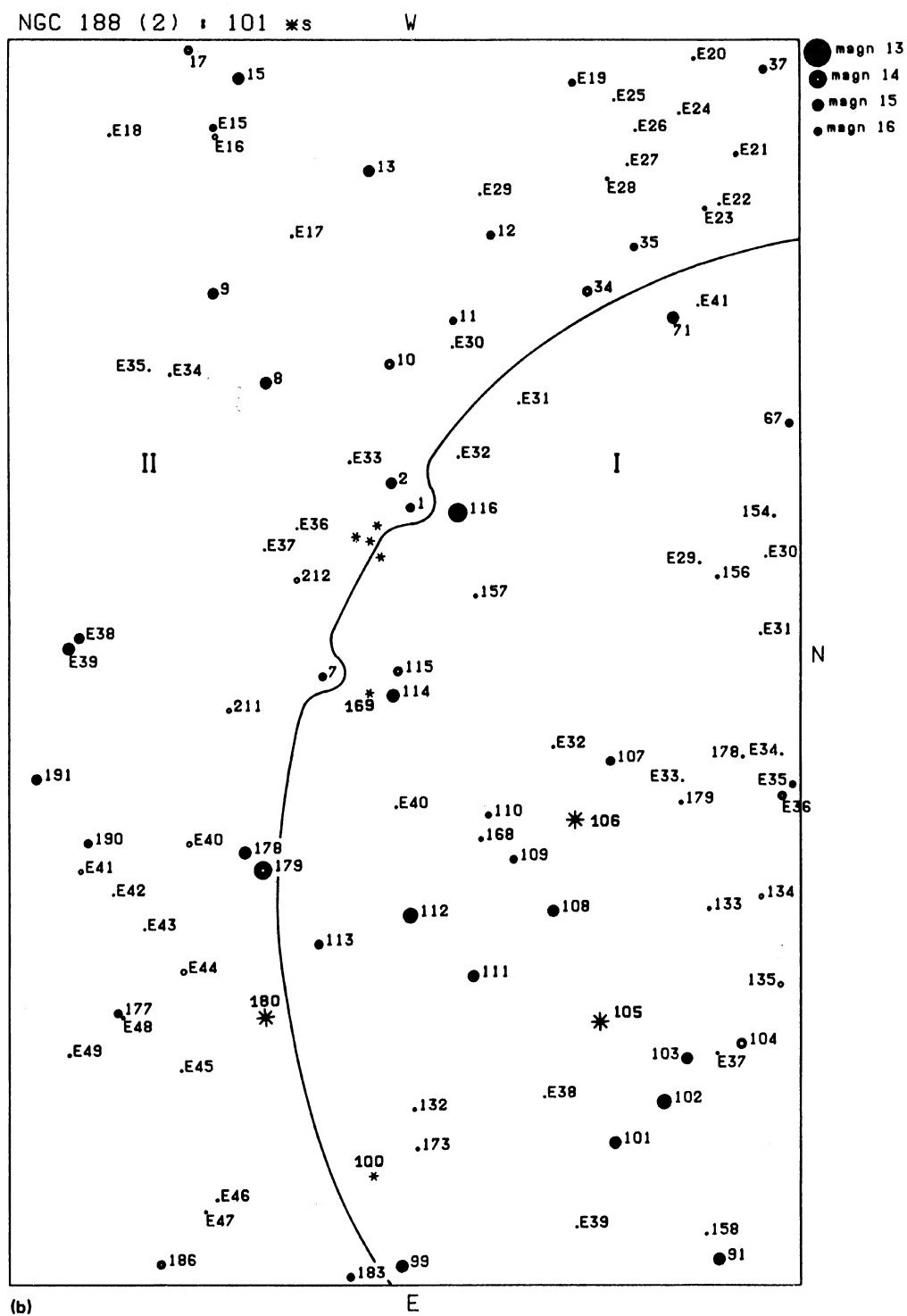


FIG. 3. (continued)

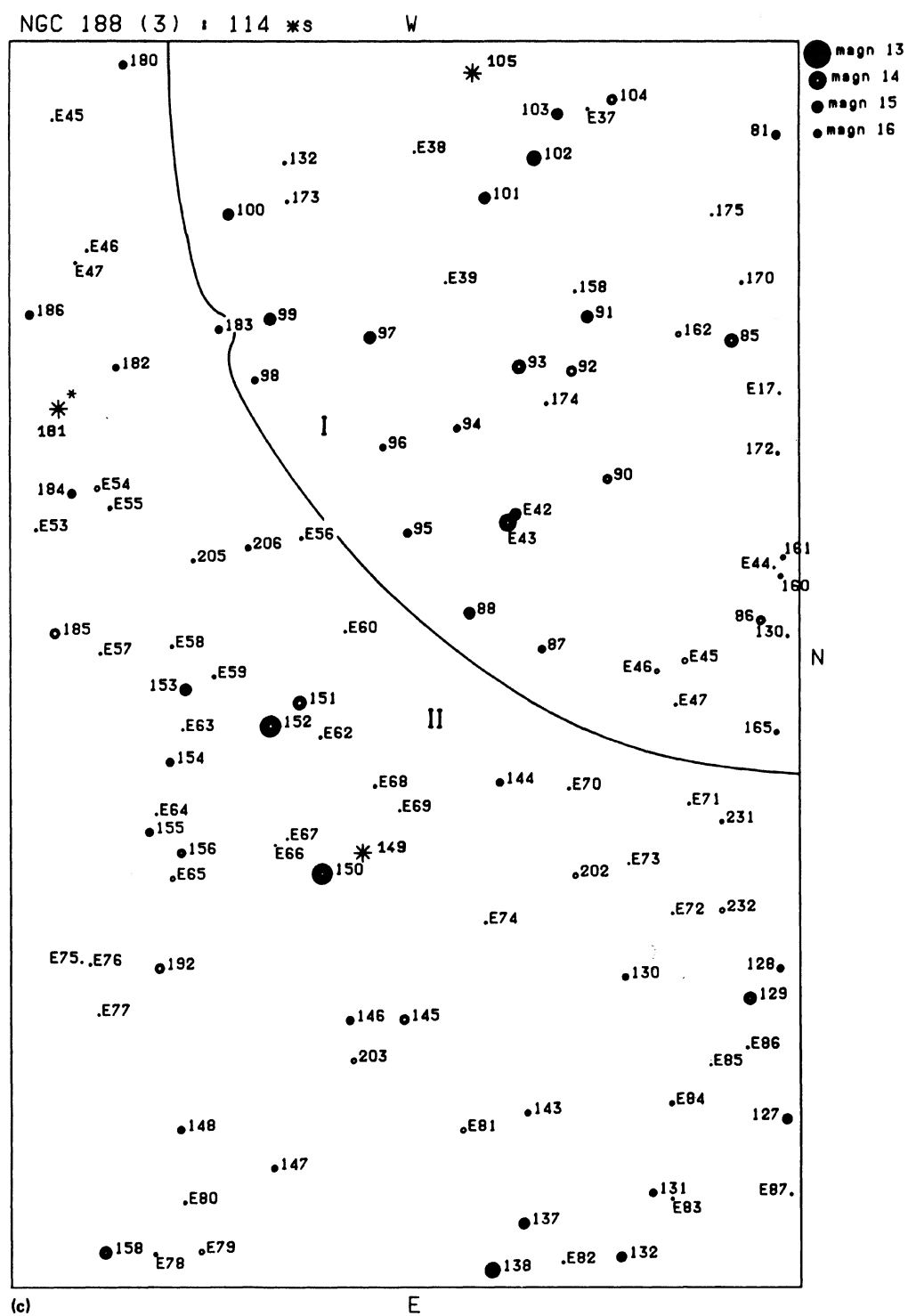


FIG. 3. (continued)

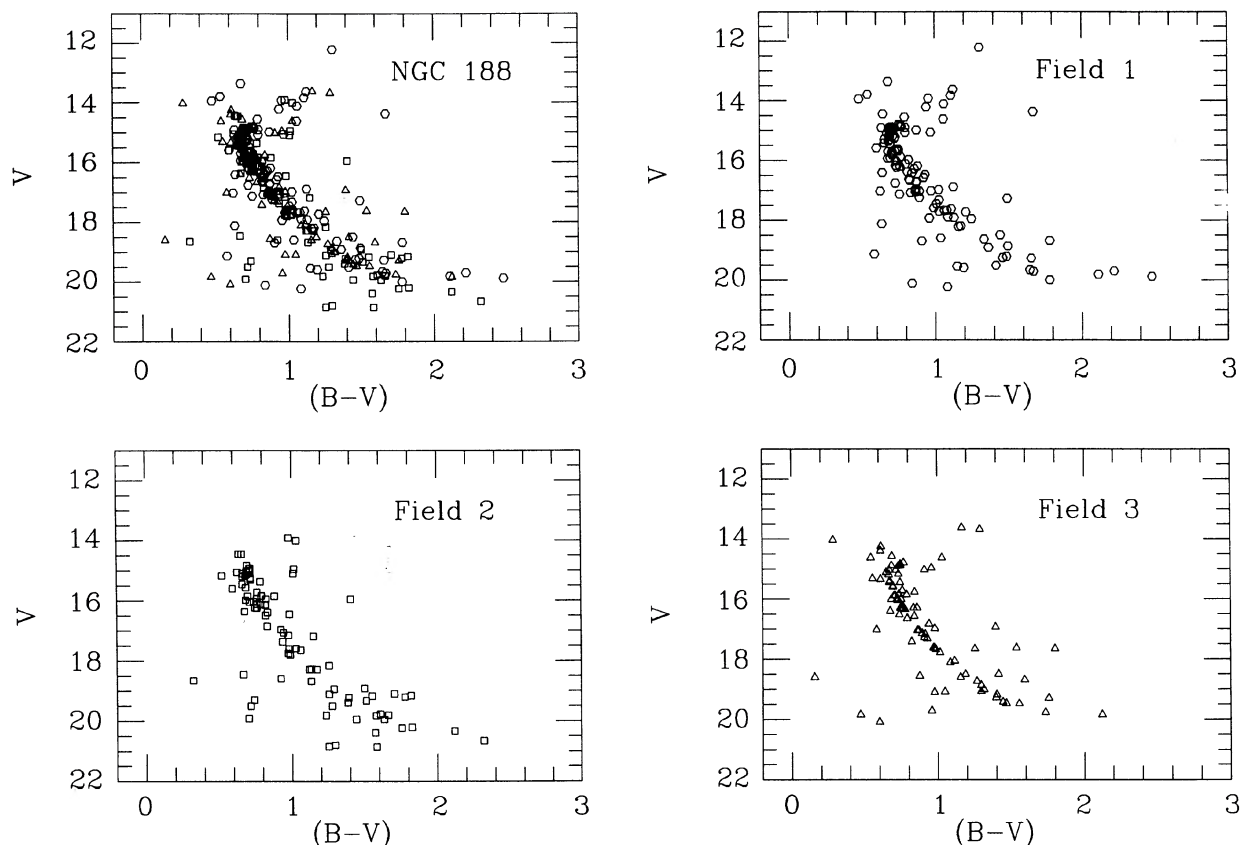


FIG. 4. Color-magnitude diagram for the three fields separately and for all the fields.

outside the cluster main loci in the C-M diagram. Figure 6 reports the resulting luminosity distribution after all the stars lying more than $\delta(B - V) = \pm 0.2$ mag from the average cluster main sequence have been removed as field stars. Even greater evidence for the lack of cluster low luminosity MS stars is now seen.

To approach the cluster luminosity function in a very general way, let us derive from our theoretical isochrone the expected distribution of star luminosities from MS up to the red giant branch, for a cluster with the assumed age and chemical composition, and when a flat distribution of the initial mass function (IMF) is assumed (see Fig. 7). To discuss now the observed distribution, let us take as reference the number NTO of stars in half a magnitude interval, between $V = 15$ and $V = 15.5$, in the upper MS. By looking at the data in Fig. 7 one finds that the poorly populated red giant branch that characterizes NGC 188 is just what one expects from theoretical constraints. As a matter of fact, Fig. 7 shows that around $M_v = 1.5$ mag ($V = 13$ mag) one expects in the same interval of magnitude about 1/30 of NTO. In our sample $NTO = 35$, thus the theoretical expectation leads to just one star, as observationally found. It is much more interesting to apply such a procedure to the extensive photographic investigation by McClure and Twarog (1977). Since they found $NTO = 56$, about two stars are expected around $V = 13$, against the three stars actually observed. Note that all these considerations are independent of any assumption on the initial mass function, since the distribution in luminosity of stars around and beyond the turnoff

point is essentially dependent only on the evolutionary lifetimes (see Castellani, Chieffi, and Norci 1989 for a detailed discussion on the red giant luminosity function).

On the contrary, the luminosity distribution along the main sequence is essentially governed by the mass distribution of MS stars. To discuss such a distribution we report in Fig. 8 the observed luminosity function of stars below $V = 14$ mag, compared with the corresponding theoretical expectations along the adopted isochrone ($t = 6$ Gyr) when a flat mass distribution ($dN/dM = \text{const}$) is assumed. The theoretical distribution has been normalized to the observed number of stars in the interval $15 < V < 16$, i.e., in the upper portion of the MS, just below the turnoff region. The figure shows that at larger luminosities than such an interval, where the evolutionary effects are expected to be dominant, there is a good agreement between theory and observations. This again supports the derived age (for the given distance modulus), since the decline of the luminosity function is a well-known age indicator (Paczynski 1984; Chieffi and Gratton 1986).

As for the lower portion of MS, one finds clear evidence for an increasing deficiency of stars with respect to the adopted flat distribution. This implies that dN/dM is decreasing when the stellar mass decreases. From the values displayed in Fig. 8 one roughly evaluates that a dependence $(dN/dM) \propto M$ is needed to account for the observed behavior. As a result, it appears difficult to escape the conclusion that at least the central observed region of NGC 188 is at present largely populated by stars near $1.2 M_{\odot}$, with a de-

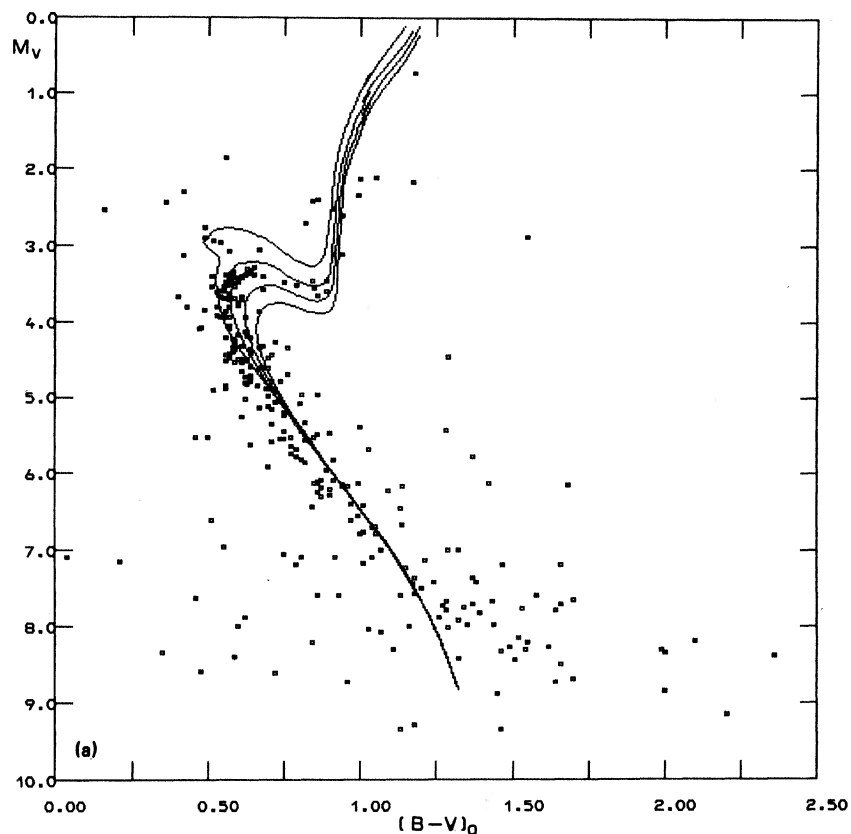
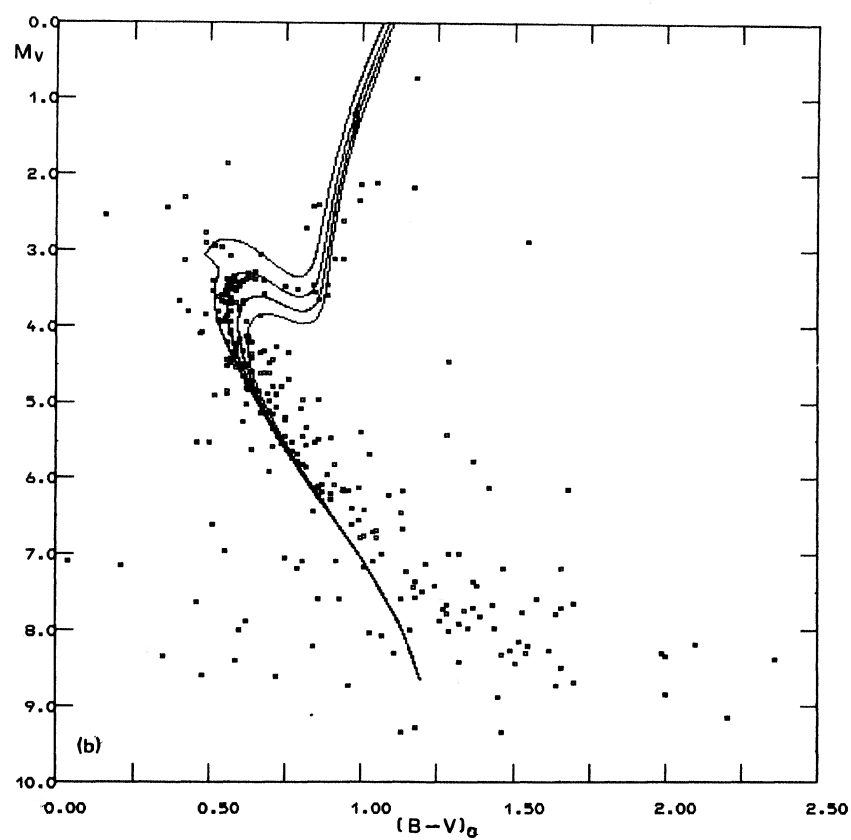


FIG. 5. Color-magnitude diagram for the total observed stars superimposed with the isochrones with solar metallicity and ages from 4 to 10 Gyr. In the upper panel (a) the Yale transformations have been used, while in the lower panel (b) the V85 ones have been used.



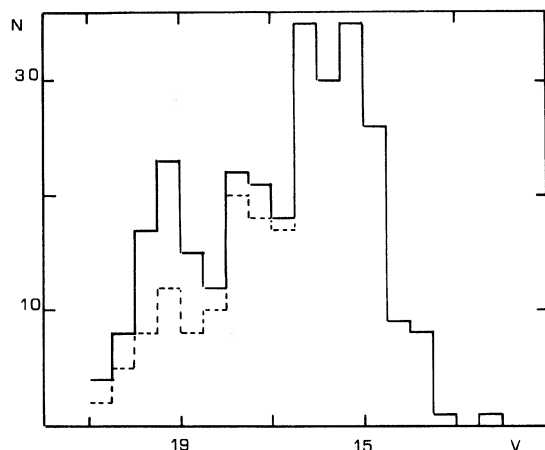


FIG. 6. Luminosity function for all the observed stars (solid line) and after removing all the objects lying more than $\delta(B - V) = 0.20$ from the cluster main sequence (dashed line).

creasing contribution of stars of lower masses along the MS. We note that the effect of increasing the helium content up to $Y = 0.28$ would slightly decrease the mass by roughly $0.09 M_{\odot}$.

The spatial distribution of NGC 188 stars has already been explored and discussed by McClure and Twarog (1977) in connection with the cluster dynamics. We compare in Fig. 9 our luminosity function for stars fainter than $V = 15$ mag with similar results we derived from the data given by McClure and Twarog (1977) for Sandage's Rings I and II. It appears that our luminosity function agrees well down to $V = 19$ mag with the one of McClure and Twarog for the more central region of the cluster, which is the one our CCD frames are essentially referring to. Although these authors do not discuss their limiting magnitude for completeness, we take the abovementioned agreement as evidence that the photographic investigation is essentially complete down to $V = 19$ mag. Thus good photographic photometry appears to be still competitive with a CCD investigation, at least as far as the cluster luminosity function is concerned. The major improvement given from the present investigation is the better definition of the main sequence

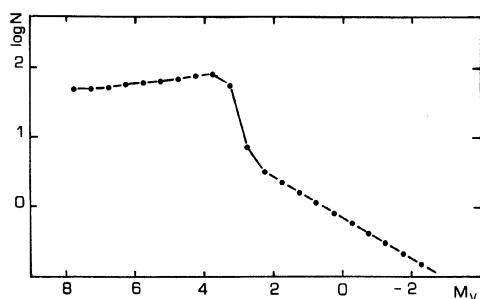


FIG. 7. Distribution of the theoretical luminosity function from the isochrone with $Z = 0.02$, $Y = 0.23$, and $t = 6$ Gyr, normalized to an arbitrary number of stars.

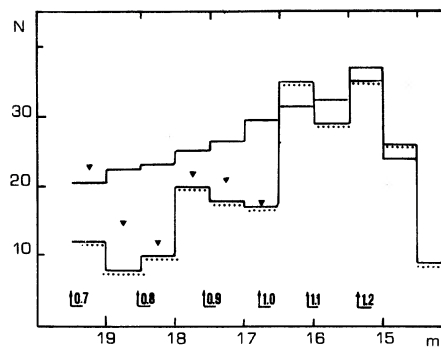


FIG. 8. Comparison between the theoretical luminosity function (solid line) and the observed one after removing the contribution of the field stars (dotted line). The small triangles show the counts including field stars. The two distributions have been normalized in the interval $15 < V < 16$. The corresponding values of stellar mass are labeled for some selected luminosities.

down to $V = 19$ mag against the $V = 17$ mag given from the photographic photometry.

Made confident in the results of the abovementioned photographic investigation, we note in Fig. 9 that the lack of low-mass MS stars is dramatically enhanced when passing from Ring I to II, i.e., when going outward from the cluster center. In our opinion, this supports the conclusion that the lack of less massive stars should likely be connected with the dynamical history of the cluster rather than reflecting a real characteristic of the cluster IMF.

IV. DISCUSSION AND CONCLUSION

As shown in the previous section, overimposing theoretical isochrones to the NGC 188 observed C-M diagram corrected for a reddening of $E(B - V) = 0.12$ and a distance modulus of 11.50 leads to a good fitting for a cluster age of 6 Gyr. One may estimate that the error should not exceed ± 1 Gyr.

Note that we found that the star distribution along all the red giant branch agrees with theoretical expectations, over-

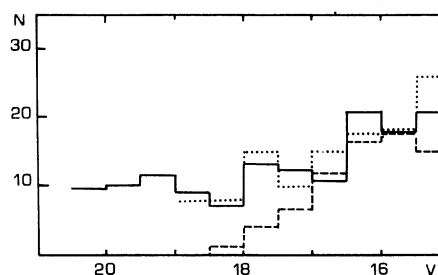


FIG. 9. Luminosity function for all the measured stars (solid line) compared with those derived from the McClure and Twarog (1977) photometry of Ring I (dotted line) and Ring II (dashed line) stars. All the distributions are normalized to $N = 18$, which is the observed number of stars in Ring I between $V = 15.5$ and $V = 16.0$.

coming the argument advanced by Barbaro and Pigatto (1984) for a rather anomalous luminosity at the bottom of the RG branch, with respect to the expected evolutionary behavior of such H-shell burning stars.

It is worth noting that the new determination of the cluster distance modulus used in this paper has been based on the evidence for a clump of giants at approximately $V = 12.35$ mag, which should be interpreted as the observational evidence for He-burning "horizontal branch (HB)-like" stars. It is interesting to discuss whether or not such an assumption is compatible with the adopted evolutionary scenario.

From the observed color of the clump, $(B - V) = 1.2$, one would derive a correct color of $(B - V)_0 = 1.08$. Both V85 and the Yale computations give for such stars a bolometric correction $BC \approx 0.6$, so that one may assume for the observed He-burning clump $m_{\text{bol}} = 11.75$ mag, $M_{\text{bol}} = 0.25$ mag and then $\log L/L_0 = 1.79$. The comparison with theoretical prescriptions is shown in Fig. 10, where the quoted clump luminosity is presented with the expected luminosity of red HB stars for various assumptions on the original chemical composition. The theoretical data are from Sweigart (1987), except the case with $Y = 0.23$ and $Z = 0.02$ (Pulone, private communication). These HB models have been computed with a He-core mass M_c appropriate to the age of globular clusters (14–16 Gyr), but, given the well-known negligible dependence of M_c on age, the variation of the RHB luminosity with age can also be assumed as negligible.

Given the solar metallicity of NGC 188, in order to reconcile the observed clump luminosity with the theoretical constraints, one is driven to accept a large amount of original helium content, likely nearer to $Y = 0.30$ rather than to $Y = 0.23$, which is the value generally assumed for metal-poor galactic globular clusters. This indication should support the coupling between the evolutionary increases of helium and metals in the galactic matter, an argument already suggested in the literature (see, e.g., Lequeux *et al.* 1979).

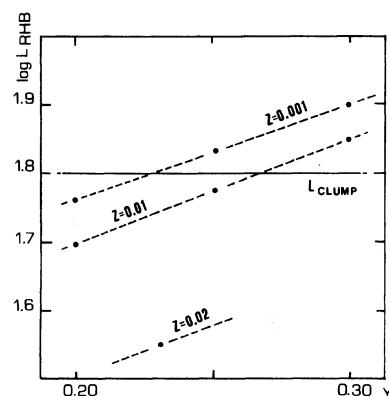


FIG. 10. The observed luminosity of the red giant clump compared with the theoretical value for red HB stars with various chemical compositions.

Let us finally note that if NGC 188 is still among the oldest open clusters, its decreased age should leave a gap of at least 6 Gyr between disk and halo systems, leading to some intriguing questions on the history of galactic matter in this very large interval of time.

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