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NEW PHOTOMETRIC DATA FOR THE OLD GALACTIC CLUSTER NGC 188: THE PRESENCE OF A GAP, CHEMICAL COMPOSITION, AND DISTANCE MODULUS

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ABSTRACT

New photoelectric *UBV* photometry has been combined with rereduced previous photometry for the old galactic cluster NGC 188. A gap on the rising branch of the evolving main sequence has been found in a place similar, relative to the luminosity at the turnoff from the main sequence, to the gap previously found in M67. The gap in NGC 188 occurs at $4.33 \geq M_V \geq 4.53$, which is fainter than gaps found in other clusters of old to intermediate age and which cannot be explained by some of the available theoretical evolutionary tracks.

The C-M diagram extends from $V = 9.8$ ($M_V{}^0 = -1.3$) to fainter than $V = 19$ ($M_V{}^0 = 7.9$). The main sequence termination point occurs near $M_V \simeq +3.8$, $(B - V)_{0,c} \simeq 0.62$. These values are 0.8 mag fainter and 0 08 mag redder than the termination point in M67.

The two-color diagram shows the presence of a small ultraviolet excess relative to the Hyades for stars near the main sequence. Separation of the effects of reddening and blanketing gives $E(B - V) = 0.09$ mag and $\Delta(B - V)_{bl} = 0.03$ (in the sense of line weakening for main-sequence stars). A photometric modulus of $(m - M)_0 = 10.85 \pm 0.15$ is obtained by fitting the C-M diagram to the zero-age main sequence by the use of a new curve of evolutionary deviation.

Comparison of NGC 188 and M67 with old subgiants of known chemical composition reaffirms previous conclusions that old disk stars whose ages are between 5×10^9 and 10^{10} years have solar abundances *in the mean*, but with variations of Fe/H between 0.5 and 2 times the solar value. About 85 percent of all old disk stars in the solar neighborhood lie within this range. The data emphasize again that the metal content of the galactic disk has been nearly fixed since the time of its formation, with no systematic trend of Fe/H with age.

Photometry of three of the four known contact binaries in NGC 188 is discussed in the Appendix.

I. INTRODUCTION

Continued study of the group of old galactic clusters promises solutions to certain yet-unsolved problems of stellar evolution and the chemical history of the Galaxy. Recent work by Kinman (1965) and Eggen (1969) has added two new clusters (NGC 6791 and NGC 3680) to the group defined by M67 (Johnson and Sandage 1955; Eggen and Sandage 1964) and NGC 188 (Sandage 1962*a*, hereinafter called Paper I), which remains the oldest disk cluster isolated so far. Because certain questions remained unanswered in Paper I, we have made a new study of NGC 188 ($\alpha = 0^h41^m6$, $\delta = +85°12'$ [1975]; $l^{II} = 123°$, $b^{II} = +22°$) to test and to extend the previous results.

New photometry was obtained to discuss (1) the reddening, (2) the metal abundance, (3) the presence or absence of a gap on the evolving main sequence, (4) the extension of the giant branch toward bright M_V values, (5) the presence or absence of blue stragglers, (6) the four recently discovered contact binaries which are cluster members, and (7) the C-M diagram for NGC 188 compared with that of M67 and certain field subgiants.

II. PHOTOMETRY

To make the best combination of new 200-inch observations by Eggen with the older data by Sandage, we adopted the following procedure. Eggen observed seventy-five cluster stars during the course of other programs where observations of external *UBV*

TABLE 1

PHOTOELECTRIC DATA FOR 154 STARS IN AND NEAR NGC 188

Ring I	V	B-V	U-B	n
1	11.88	1.14	0.82	2E
3	13.96	0.48	0.07	2E
4	16.28	0.83	0.27	1E
5	14.79	0.64	(0.34)	1E
6	14.85	0.95	0.61	1E
8	16.43	0.72	0.25	1S
9	15.48	0.84	0.38	2E
10	14.90	0.76	0.22	2E
11}v	15.87	0.98	0.69	1E
11	16.24	0.98	0.69	1E
14	15.45	0.72	0.13	1E
15	14.81	0.82	0.33	2E
16	15.91	0.84	0.38	1E
17	14.99	0.69	0.17	2E
20	14.20	0.94	0.51	3E
31	16.24	0.78	0.30	1S
32	14.40	0.64	0.14	2E
33	14.53	0.76	0.26	2E
34	15.83	0.73	0.22	1E
41	15.23	0.73	0.19	2E
42	15.06	0.97	0.66	2E
43	14.93	0.62	0.13	2E
44	16.36	0.75	0.29	1S
45	15.00	0.72	0.14	2E
47}	14.93	0.72	0.17	2E
47	14.92	0.72	0.21	1S
48}	14.87	0.78	0.26	2E
48	14.90	0.72	0.29	1S
49}	15.64	0.74	0.18	1E
49	15.66	0.70	0.18	1S
50	13.86	0.55	0.03	3E
56	16.41	0.82	0.26	1E
57	13.59	1.14	0.92	1E
58	16.77	0.68	(-0.05)	1E
59	13.95	1.01	0.69	1E
60	15.17	0.67	0.12	1E
61	14.10	1.10	0.86	1E
62	14.81	0.78	0.22	1E
63	15.85	0.72	0.10	1E
65	15.35	0.68	0.13	1E
66	14.97	0.88	0.42	1E
69	12.26	1.30	1.35	3E
71	15.09	0.67	0.14	1E
75	13.87	1.08	0.84	1E
76	14.94	0.68	0.15	1E
80	15.35	0.72	0.13	2E
81	15.80	0.76	0.16	2E
82}	16.72	0.82	....	2E
82	16.77	0.80	....	1S
83	16.74	0.81	(0.55)	1S
85	14.57	1.04	0.76	1E
90	15.69	0.75	0.24	1E
91	14.84	0.71	0.14	1E
92	15.39	0.69	0.13	1E
93	14.53	0.70	0.15	1E
94	16.39	0.79	0.22	1S
95	16.05	0.72	0.26	1S
96	16.56	0.86	0.33	1S
97	14.98	0.97	0.63	1E
99	14.94	0.73	0.26	1E
100	15.23	0.70	0.21	1E
101	15.00	0.68	0.07	2E
102	14.50	0.60	0.10	2E
103	15.14	0.62	0.10	2E
104	15.39	0.69	0.11	3E
105	12.30	1.17	1.07	3E
106}	11.76	0.54	-0.05	2E
106	11.81	0.53	0.01	4S
107	15.95	1.39	1.11	1E
108}	15.16	0.73	0.26	1E
108	15.15	0.72	0.25	1S
109	16.22	0.76	0.22	2E
110	16.86	0.80	(0.53)	1S
111	15.21	0.68	0.16	1E
112	14.40	0.69	0.13	2E
113}	15.97	0.78	0.29	1E
113	15.97	0.79	0.29	1S
116	13.84	0.95	0.48	1E
117	17.35	0.92	(0.80)	1S
118	16.98	1.06	0.76	1S
122	17.50	1.00	0.62	1S
124	17.13	1.02	0.60	1S
134	17.60	1.06	....	1E
135	16.97	0.93	0.45	1E
165	17.85	0.77	....	1S
166	17.96	1.26	....	1S
167	18.42	0.84	....	1S
168	17.76	0.93	0.60	1S
169	17.59	0.97	0.73	1S
170	18.95	(1.41)	. ..	2S
171	18.69	1.02	. ..	1S
172	19.03	(1.30)	.	2S
173	18.62	0.82	.	1S
174	18.70	1.27	.	1S
175	19.96	1.56	.	1S
176	18.50	0.90	. .	1S
177	18.57	1.20	.	2S
178	19.16	(1.84)		2S
179	18.27	1.12	. ..	2S
Anon	14.89	0.78	....	1S
Anon	12.25	0.62	0.06	1S
Ring II				
9	15.31	0.74	0.19	1S
12	16.23	0.72	0.24	1S
25	15.57	0.92	(0.49)	1S
27	15.30	0.68	0.22	1S
28	15.86	0.70	0.23	1S
29}	9.55	0.50	0.04	2E
29	9.55	0.50	0.02	7S
43	15.87	0.73	0.20	1S
46}	13.32	0.57	0.13	1E
46	13.34	0.54	0.15	6S
47	13.47	0.66	0.09	1S
55	15.38	0.65	0.18	1S
67	14.93	0.75	0.23	1S
73	15.03	0.69	0.18	1S
80	15.69	0.69	0.15	1S
93	14.94	0.81	0.40	1S
112	16.12	0.73	(0.28)	1S
113	16.45	0.81	(0.40)	1S
115	15.85	0.73	(0.26)	1S
116	15.97	0.70	0.21	1S
121	16.26	0.71	(0.30)	1S
131	16.35	0.76	(0.34)	1S
177	16.03	0.74	0.27	1S
185	15.41	0.70	0.18	1S
202	17.21	0.84	0.59	1S
211	17.38	0.95	0.66	1S
212	17.16	0.92	0.77	1S
223	17.52	1.08	0.70	1S
224	17.60	1.20	0.89	2S
231	17.71	1.10	0.90	1S
233	18.05	1.12	. .	1S
234	18.00	1.20	....	1S
Ring III				
1	15.52	0.69	0.21	2S
2	15.60	0.57	0.03	1S
4	11.66	1.14	1.08	7S
18	11.34	1.59	1.86	1S
22	15.28	0.69	0.22	1S
29	15.38	0.68	0.22	1S
33	15.53	0.66	0.17	1S
49	15.35	0.66	0.20	1S
57	15.76	0.71	0.14	1S
70	15.42	0.71	0.23	1S
96	15.43	0.66	0.10	1S
108	15.51	0.73	0.20	1S
117	12.46	0.70	0.17	2S
125	16.32	0.76	0.29	1S
136}	12.26	0.64	0.09	1E
136	12.28	0.63	0.06	6S
137}	12.69	0.57	0.03	2E
137	12.75	0.56	0.03	2S
138	9.78	1.52	1.73	5S
145	14.97	0.69	0.12	1S
149	15.30	0.82	0.42	1S
155	16.10	0.74	0.26	1S
159	16.94	0.91	....	1S
160	17.58	1.06	....	1S
161	16.98	0.90	...	1S
162	17.18	0.95	....	1S
163	17.41	0.75	.. .	1S
Outside				
B}	14.82	0.79	0.36	3E
B	14.90	0.77	0.37	1S
D}	13.28	0.36	0.17	1E
D	13.30	0.32	0.16	1S
E}	12.88	0.69	0.10	4E
E	12.90	0.70	0.16	1S
F}	12.10	0.54	0.05	4E
F	12.09	0.52	0.02	1S
M}	8.84	0.14	0.04	1E
M	8.91	0.11	0.17	1S
N}	10.76	0.62	0.21	2E
N	10.77	0.62	0.20	1S

standards on each night established new zero points in all three colors. The fifteen stars common to both these new observations and those of Paper I were then used for a new reduction of most of the original data tapes used for Paper I.

The new stars, taken mostly from Ring I (Paper I, Figs. 1 and 2), were picked to ensure good coverage of the magnitude range where a possible gap might occur on the evolving main sequence near $V \simeq 15.7$. Data for these stars, combined with the rereduced original data, are listed in Table 1, where the previous numbering system is used.

Comparison of this table with data in Paper I shows that $\langle \Delta V \rangle$ (present minus Paper I) = -0.036 ± 0.020 (average difference), $\langle \Delta(B - V) \rangle = +0.005 \pm 0.006$, and $\langle \Delta (U - B) \rangle = 0.000 \pm 0.010$. The zero-point difference in V is moderately large and can be accounted for by the unfavorable circumstance of observing NGC 188 below the pole near lower culmination at large sec z with the 60-inch in 1958. Apparently, undue reliance was placed on these early zero points for local standards in the later 200-inch observations which make up Paper I. However, the internal accuracy of the observations of Paper I appears to be good in $U - B$ and $B - V$ as judged from the small average deviations, which ensures that our present rereduction gives the satisfactory final results listed in Table 1.

TABLE 2

V	n	ΔV	$\Delta(B-V)$	$\Delta(U-B)$
9–12 ..	5	±0.010	±0.013	±0.013
12–14	5	± .008	± .004	± .014
14–15. ..	14	± .020	± .012	± .018
15–16 ..	7	±0.025	±0.013	±0.022

Certain of the original data could not be rereduced in this way because insufficient new standards were available. The fact that stars on those records are not included in the present Table 1 explains why a few stars listed in Paper I are missing in Table 1.

Comparison of the fifteen stars common to both the new (Eggen) and the newly reduced (Sandage) photometry shows average deviations, relative to the mean, of $\langle \Delta V \rangle(\mathrm{E} - \mathrm{S}) = -0.012 \pm 0.018$(A.D.), $\langle \Delta(B - V) \rangle(\mathrm{E} - \mathrm{S}) = +0.008 \pm 0.016$, and $\langle \Delta(U - B) \rangle(\mathrm{E} - \mathrm{S}) = -0.004 \pm 0.025$, which are satisfactorily small. For those stars observed by Eggen more than once, the average deviations from the final means are again satisfactorily small, as shown by Table 2.

III. THE C-M DIAGRAM: THE PRESENCE OF A GAP

Figure 1 shows the C-M diagram for stars listed in Table 1 (*closed circles* and *open triangles*), together with a few stars (*open circles*) along the giant branch not rereduced here but taken from Paper I. Stars from Rings I, II, and III are plotted, except for stars far from the principal sequences. In the absence of radial velocities, we cannot determine how many of these are field stars. However, that most of the deviants are nonmembers of the cluster was shown in Paper I by noting that the number of stars which scatter from the sequences increases, in going from Ring I to Ring II, by a factor of 4, which is the ratio of the areas.

The elimination of field stars proved to be important for the interpretation of the $(U - B, B - V)$-diagram and the determination of the reddening. We found that when the two-color diagram was plotted by using *all* stars in Table 1, a large scatter resulted, much like Figure 7 of Paper I. However, if only stars along the principal sequences were plotted, a considerably tighter $(U - B, B - V)$-diagram emerged, much like that for M67 (Eggen and Sandage 1964, Fig. 2).

Examination of the position in the $(U - B, B - V)$-diagram of each star which is off the principal sequences showed that a group, plotted as open triangles in Figure 1, fell in a systematic pattern below the other members of the cluster. Their position in the two color diagram could be explained if they were members but had lower gravities than stars on the principal sequences (Eggen and Sandage 1964, Figs. 4 and 5; Eggen 1968, Fig. 4). These stars were kept in Figure 1 as possible blue stragglers. They are D, I-3, and II-46, which are far from the main-sequence turnoff, and I-5, 32, 33, 43, 93, 102, 103, and 112, which appear to define a brighter turnoff. These latter eight stars are candidates for cluster membership because of their location close to the cluster center in Ring I. The position in the two-color diagram for all other eliminated stars could not be explained, and we have assumed them to be field stars.

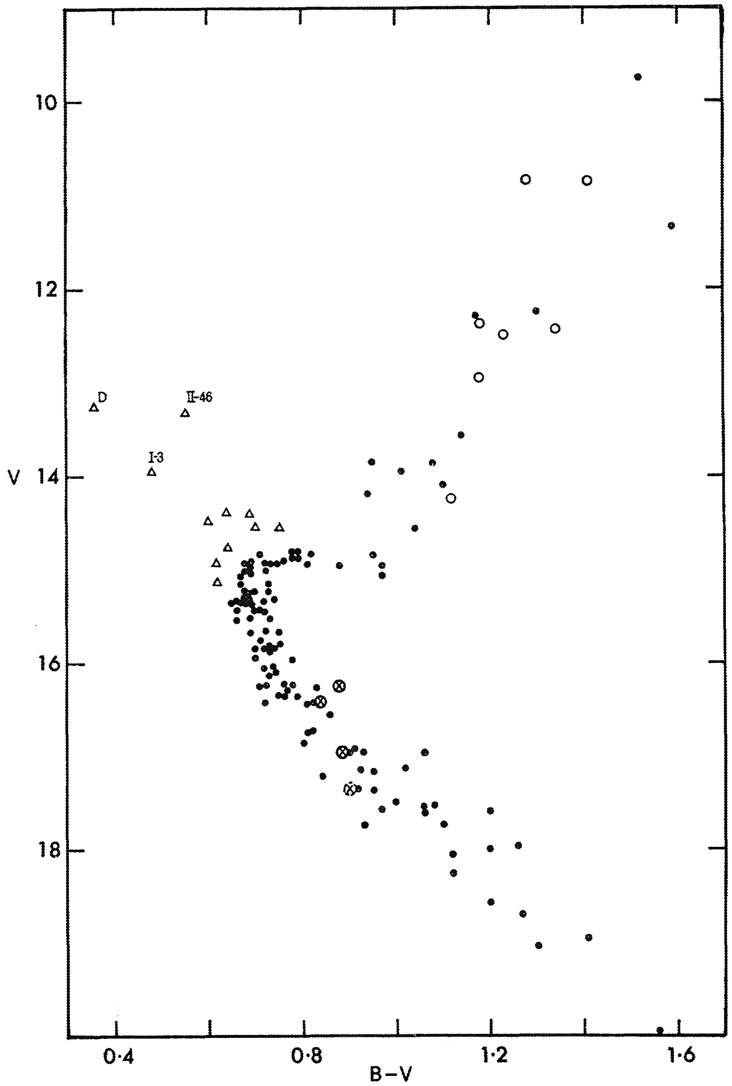

FIG. 1.—C-M diagram for stars along the principal sequences of NGC 188. *Closed circles* and *open triangles*, stars taken from Table 1. *Open circles*, additional giants from Paper I. *Open triangles*, possible blue-straggler members of the cluster chosen on the basis of a gravity anomaly in the $(U - B, B - V)$-diagram. Crossed circles represent the four known variables, which are contact binaries, plotted for a single component. No corrections for reddening, blanketing, or absorption have been applied.

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The brightest four stars along the giant branch (III-138, III-18, J, and II-75) are almost certainly cluster members. They fall on the giant sequence in the two-color diagram (Fig. 3, § IV), well below the position of the dwarfs. The probability that giant field stars exist in the foreground of such a small area is so low as to be nearly discounted.

The presence of a gap on the evolving main sequence, as suggested by the photographic data for Rings I and II (Figs. 5 and 6 of Paper I), appears to be confirmed in Figure 2. Here the photoelectric data (*closed circles*) from Rings I and II are plotted, together with all remaining stars in Ring I (*open triangles*) which were not observed photoelectrically, but which have photographic data listed in Paper I. Stars in Ring III have not been plotted because of the greater probability of contamination by field stars. Large contamination in Ring III is shown not only by the number of stars which fall off the principal sequences but also by the increased scatter in the $(U - B, B - V)$-diagram. But even if Ring III had been plotted, only three stars (III-1, III-33, and III-108) fall in the gap at $15.65 \geq V \geq 15.45$, and two of the three deviate from the mean $(U - B, B - V)$-relation defined by Ring I stars, most of which are certainly cluster members.

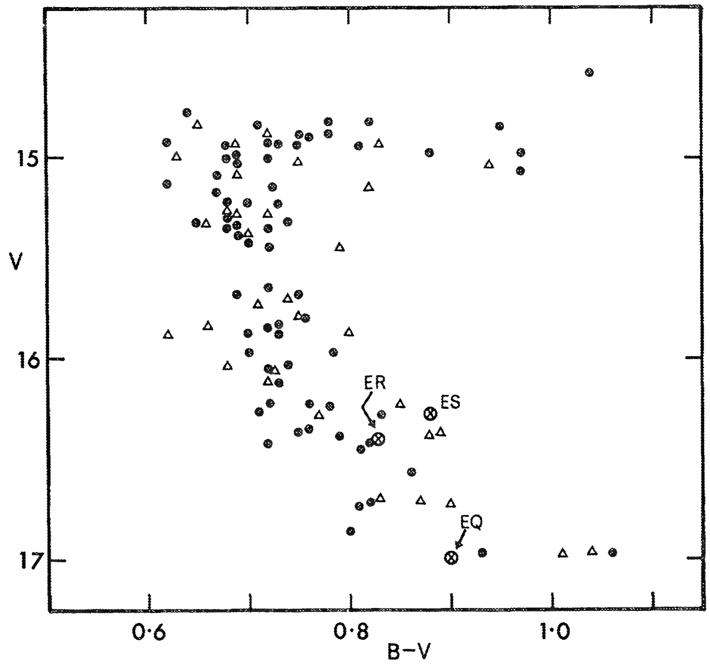

FIG. 2.—Enlarged portion of the C-M diagram for stars near the evolving main sequence showing the presence of a gap near $V = 15.55$. *Closed circles*, photoelectric observations for stars in Rings I and II. *Open triangles*, remaining stars in Ring I for which only photographic observations exist from Paper I. The three contact binaries ER Cep, ES Cep, and EQ Cep are plotted as crossed circles at the magnitude of a single component under the assumption of equal components.

Independent analysis of these data by Aizenman, Demarque, and Miller (1969), who used a new statistical method, confirms our conclusion that the gap is real. The question is of some importance because the gap position at $4.33 \geq M_V{}^0 \geq 4.53$ (obtained later) is so faint that, until recently, no theory of evolving models could produce a gap at this luminosity. The reason is that convective cores were absent in model stars of such low mass, and the hydrogen exhaustion of the core did not occur at this evolutionary stage. The detection of a gap in such an old cluster gives information on the core opacity and/or the point of changeover from energy production by the proton-proton reaction to that by the CNO cycle.

Models computed by Aizenman *et al.* (1969), who used opacities due to Cox (1965) and the energy rates of Reeves (1965), appear now to require a gap for stars as faint as in NGC 188, although earlier models by Iben (1967), Demarque (1968), and Demarque and Schlesinger (1969) did not permit it. This led Iben (1967) to the implied conclusion, illustrated by his modulus-fitting procedure, that if the gap in NGC 188 were real, the cluster must have a brighter point of turnoff from the main sequence than that given by the direct determination of photometric parallax—a conclusion which now appears to be unnecessary.

In any case, we believe that the gap in NGC 188 is real and that it is similar to those found in M67 (Tammann 1963; Eggen and Sandage 1964), NGC 3680 (Eggen 1969), NGC 752 (Eggen 1963), NGC 2477 (Eggen and Stoy 1961), the Hyades extended cluster (Eggen 1970), the Pleiades (Eggen 1964*a*), the α Per cluster (Mitchell 1960), and many other adequately studied clusters. The existence of these gaps appears to provide the strongest possible observational confirmation of the predicted phase of hydrogen exhaustion of evolving models just prior to the phase of main-sequence termination.

IV. THE TWO-COLOR DIAGRAM: REDDENING, BLANKETING, CHEMICAL COMPOSITION, AND GRAVITY

All cluster stars adopted from Ring I, together with additional giants from Figure 1 (I-57, I-59, I-69, I-85, I-105, II-51, II-75, III-18, III-138, J, and L) and the suspected blue stragglers, are plotted in the two-color diagram shown in Figure 3. Main-sequence stars, stars near the main sequence, and the bluer subgiant stars in the observed interval $0.66 \geq (B - V) \geq 0.76$ show an ultraviolet *excess* of $\langle \delta(U - B) \rangle \simeq 0.05$ mag, read relative to the dashed line which has been shifted from the Hyades intrinsic relation by $E(B - V) = 0.09$, $E(U - B) = 0.06$, as derived below.

No shift along a reddening line of slope $E(U - B)/E(B - V) = 0.72$ of *any size* can remove this excess, and we conclude that stars in NGC 188 near $B - V = 0.70$ show a slight line *weakening* relative to the Hyades. Similar stars in M67 (Eggen and Sandage 1964, Fig. 2) and NGC 3680 (Eggen 1969) show the same effect by about the same amount. The errors in the photometry are small enough ($\epsilon(B - V) \simeq \epsilon(U - B) \simeq \pm 0.015$ for an individual star, or $\epsilon(\text{color}) \simeq \pm 0.003$ for the mean of twenty such stars) to ensure that the effect is real in all three clusters, and not a result of observational error.

Our present results for an ultraviolet excess in the dwarfs differ from the data of Spinrad and Taylor (1967, 1969), who show that an ultraviolet *deficiency* exists for a special group of M67 *giants* relative to the Hyades. However, the two sets of data are not necessarily in contradiction. We cannot test Spinrad and Taylor's conclusion for giants from our *UBV* data alone because the slope of the blanketing vector shown in Figure 3 (taken from Wildey *et al.* 1962) is nearly the same as that for the intrinsic Hyades line. This means that *small* blanketing differences will not be detected in the *UBV* system for stars such as the M67 giants, which are redder than $B - V \simeq 0.9$.

However, if both our results and those of Spinrad and Taylor are correct, then evidence exists for *different* line blanketing (relative to the Hyades) for giants and dwarfs in the *same cluster*. Such an effect is known in M92 and M3 (Sandage and Walker 1966, Figs. 5, 6, 8, and 9) and in ω Cen (Geyer 1967), where stars on the asymptotic branch have redder $(U - B)$-values than subgiant stars of the same $B - V$. That the effect may be similar in M67 is suggested by the fact that many of the stronger-lined giants in M67 appear to be in a clump at $V_0 \simeq 10.4$, $(B - V)_0 = 1.04$, which may form the vestige of an asymptotic giant branch where the color anomaly is known to occur in M92. If future observations substantiate the blanketing difference between giants and dwarfs in M67 as they do in M92, then, no matter what its cause (metal abundance, or a second parameter such as microturbulence [Conti and Deutsch 1966]), the effect cannot be primeval but must result from the evolutionary process.

Our results on the $(U - B)$-excess suggest that main-sequence stars in M67, NGC 3680, and NGC 188 have a slightly lower metal abundance than stars in the Hyades. This conclusion is also consistent with direct spectrographic analyses of M67 (Sargent 1968) and NGC 752 (Gunn and Kraft 1963), and also of old subgiants similar in age to M67 and NGC 188, such as β Hyi (Rodgers and Bell 1963), δ Eri (Hazelhurst 1963; Pagel 1963), ζ Her (Helfer, Wallerstein, and Greenstein 1963), ι Per, λ Aur, β Vir (Wallerstein 1962), γ Ser (Kegel 1962), and δ Pav (Rodgers 1969). These stars give no evidence for abundances in excess of those of Hyades stars by factors larger than 2.5 in the extreme. Furthermore, there is no *systematic* trend in the *mean* value of [Fe/H], as discussed in § VI. These conclusions are not the same as those of Spinrad and Taylor (1967).

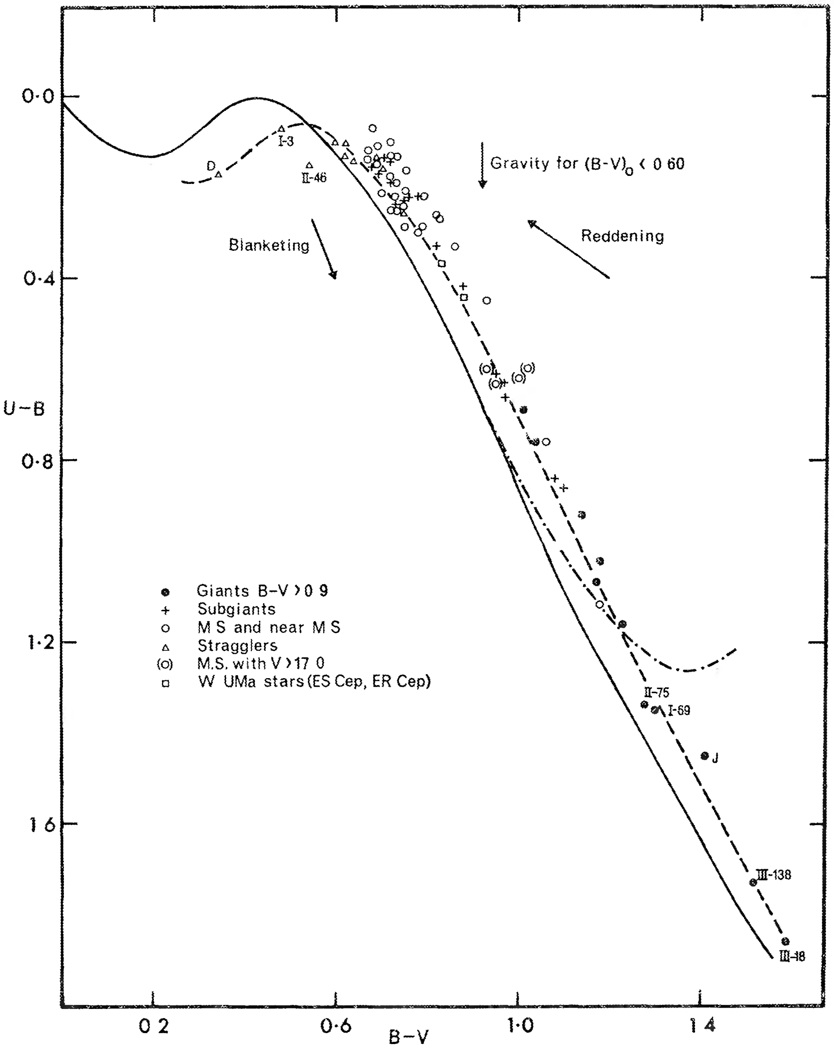

FIG. 3.—The two-color diagram for stars in Ring I of NGC 188. The Hyades intrinsic relation (*solid*) is shown as a dashed line shifted by $E(B - V) = 0.09$ and $E(U - B) = 0.06$ for reddening. The $(U - B)$-excess for stars near the main sequence near $B - V \simeq 0.7$ is evident. The intrinsic relation for dwarfs is plotted as the dot-dash line. Vectors for the reddening, blanketing, and gravity effects are shown.

The separation of the reddening effects from the blanketing effects in NGC 188 has been made by using the procedure described elsewhere (Eggen and Sandage 1964, § III).

The method depends on the difference in slope between the reddening and the blanketing vectors, as shown in Figure 3. Our best fit of the Hyades intrinsic line to the NGC 188 data is obtained if shifts in Figure 3 of $\Delta(B - V) = 0.06$ mag redward and $\Delta(U - B) = 0.02$ blueward are made. Solution of the two relevant equations gives the results shown in Table 3, where R is the adopted slope $[\Delta(U - B)/\Delta(B - V)]$ of the blanketing vector, $E(B - V)$ is the reddening, and $\Delta(B - V)_{\mathrm{bl}}$ is the correction to $B - V$ for line weakening relative to the Hyades. From these solutions we adopt $E(B - V) = 0.09$ mag for reddening, and $\Delta(B - V)_{\mathrm{bl}} = 0.03$. The reddening value is closer to those obtained by Abt and Golson (1962) for stars in this region of the sky than is the value of $E(B - V) = 0.05$, which was derived from the less complete analysis of the cluster in Paper I.

Figure 3 shows two other interesting features. (1) The dot-dash line is the intrinsic relation for Hyades-like dwarfs. There was an implicit question in Paper I of whether the brightest star III-138 was a cluster member. Figure 3 shows that III-138, III-18, J, I-69, and II-75 are undoubtedly giants and are therefore likely to be members, and that the giant branch in NGC 188 extends at least to $V \simeq 9.8$ ($M_V{}^0 \simeq -1.3$), which is brighter than indicated in Paper I. (2) All the stars which are marked as open triangles in both Figures 1 and 3 and which have $0.34 \leq (B - V) \leq 0.64$ (or $0.25 \leq (B - V)_0 \leq 0.55$ after correcting for reddening), lie below the dashed curve in Figure 3 if blanketing corrections of $\Delta(B - V)_{\mathrm{bl}} = 0.03$ and $\Delta(U - B)_{\mathrm{bl}} = 0.07$ are applied. These stars are the blue stragglers in Figure 1. Their anomalous position (after blanketing corrections) is expected if they have lower gravities than other cluster stars with similar $(B - V)$-values (Eggen and Sandage 1964, Figs. 4 and 5 and § V; Eggen 1968, Fig. 4). The three stragglers with observed colors redder than $B - V = 0.69$ (I-12, I-33, I-93) show no gravity anomaly, which is consistent with the observed limit of the effect at $(B - V)_0 \simeq 0.60$ (Eggen and Sandage 1964, Eggen 1968). The curious "second main-sequence turnoff" defined by the eight stragglers with $0.76 \geq (B - V) \geq 0.60$ at $15.2 \geq V \geq 14.4$ is presently unexplained. Among other possibilities, it may be due to (*a*) two epochs of star formation or (*b*) the various effects of secondary parameters such as rotation.

TABLE 3

$B-V$	R	$E(B-V)$	$\Delta(B-V)_{\mathrm{bl}}$
0 5	2.07	0.107	0.047
0.6	2.24	.101	.041
0.7	2.50	.096	.036
0.8	2.78	.091	.031
0.9	3.05	.087	.027
1.0	3.32	0.084	0.024

V. DISTANCE MODULUS AND A COMPARISON OF NGC 188 WITH M67

Knowledge of the chemical composition of main-sequence stars in NGC 188 is required to obtain a proper photometric modulus. As a first approximation we have corrected for the observed line weakening by adding 0.03 mag to the reddening-free colors for all normal points on the main sequence for NGC 188 listed in the following paper (Sandage and Eggen 1969, Table 3). The resulting C-M diagram was then fitted to the zero-age main sequence (Sandage 1957, 1962*b*; Johnson and Iriarte 1958; Eggen 1965*a*) by using the method of an evolutionary-deviation curve (Johnson 1960; Sandage 1962*b*). This procedure assumes that the main sequence of NGC 188 agrees with that of the Hyades in the M_V, $(B - V)_{0,c}$ diagram despite *small* differences in Fe/H. The errors made by using this assumption will not be large if one judges (1) by the smallness of the main-sequence displacement given by theory for this change of Fe/H or (2) from an empirical standpoint from the observational results of Eggen and Sandage (1962) for main-sequence positions for various $\delta(U - B)$-values, after blanketing corrections. The question is discussed more fully in the following paper (Sandage and Eggen 1969).

New curves of evolutionary deviation were calculated from the models of Iben (1967) and of Aizenman *et al.* (1969) as described in the following paper (Sandage and Eggen 1969). Figure 4 shows the comparison of the Aizenman *et al.* models with the observed normal points for NGC 188, corrected by $E(B - V) = 0.09$, $A_V = 0.27$, and $\Delta(B - V)_{\text{bl}} = 0.03$, i.e., a total correction of 0.06 mag to the observed $(B - V)$-colors for main-sequence stars and stars near the main sequence.

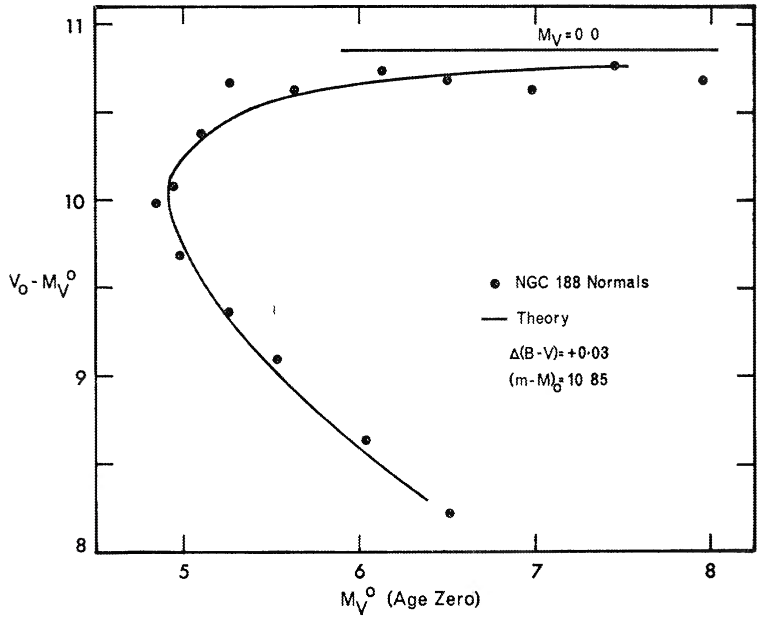

FIG. 4.—Curve of evolutionary deviation for NGC 188 showing the effect of initial evolution from the zero-age main sequence. The normal points have been corrected for $E(B - V) = 0.09$, $\Delta(B - V)_{\text{bl}} = 0.03$ (a net correction of 0.06 mag has been subtracted from the observed colors), and $A_V = 0.27$ mag. Theoretical curve is from models by Aizenman *et al.* (1969).

That the agreement of the observations with the shape of the curve is good shows that the calculated isochrones predict the deviation of the evolving main sequence from the zero-age sequence very well. An equally good fit of theory and observation can be achieved using deviation curves calculated from either Hoyle's (1959) type I model or the models of Iben (1967).

The true modulus for NGC 188 determined in this way is $(m - M)_0 = 10.85 \pm 0.15$, which may be compared with $(m - M)_0 = 10.95$ obtained in Paper I. With this new modulus, and the value of $(m - M)_0 = 9.38$ for M67 (Eggen and Sandage 1964), the blanketing-corrected and reddening-free normal points for the two clusters can be changed to M_V^0 and $(B - V)_{0,c}$ values, and the C-M diagrams can be compared as in Figure 5. The differences between this plot and a similar diagram from Paper I (Sandage 1962*a*, Fig. 8) are (*a*) NGC 188 has been moved brighter by ~0.1 mag, (*b*) M67 has been moved fainter by 0.2 mag, (*c*) the giant branches are not parallel owing to the acceptance of stars III-138, II-75, and J as members of NGC 188 (in Paper I, star III-18 was taken to be the terminus of the giant branch), and (*d*) the greater extent of the M67 giant branch, which reaches $M_V \simeq -0.8$, a value resulting from Murray and Clements's (1968) discovery of brighter giant members from a new proper-motion study, with photometry reported by Eggen and Sandage (1969).

The coalescence of the giant branches of M67 and NGC 188 near $(B - V)_{0,c} \gtrsim 1.3$ appears to be real and is part of a more general funnel effect toward the Hayashi limit for clusters of all ages older than the Hyades. This point is discussed in the following paper (Sandage and Eggen 1969).

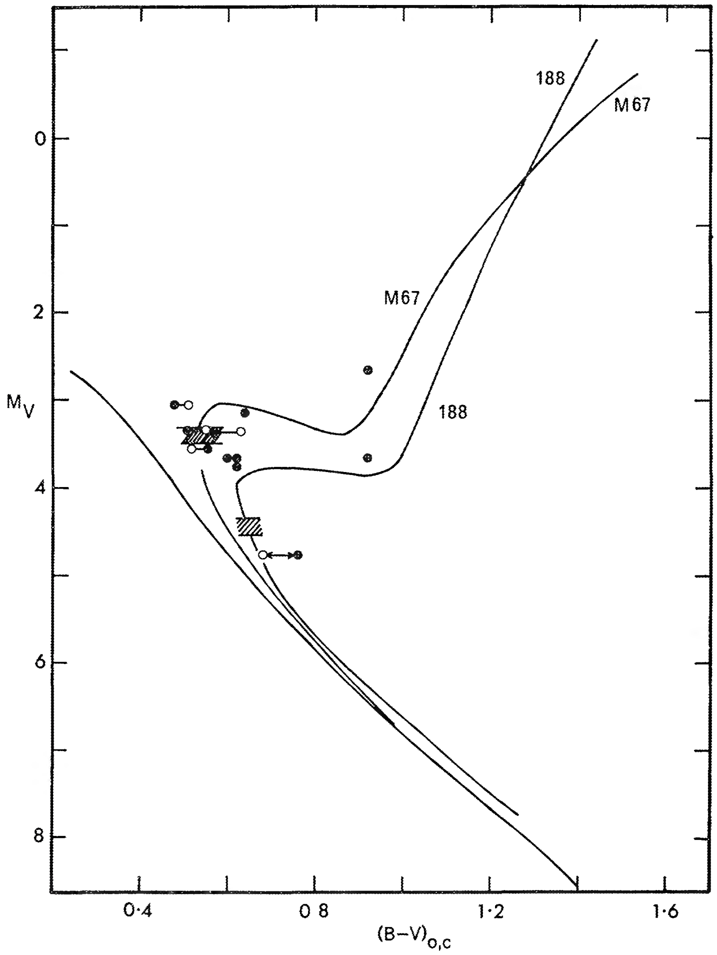

FIG. 5.—Comparison of the C-M diagrams of M67 and NGC 188 The gap along the evolving main sequence is hatched in both clusters Eleven subgiants of large parallax and with known metal abundances are plotted from data in Table 4. *Closed circles*, positions determined by using observed colors except for ζ Her which has been corrected for a visual companion. *Open circles*, positions determined by using blanketing-corrected colors as estimated from the $(U - B)$-excess or deficiency given in Fig. 6. Stars δ Pav and β Vir are moved blueward due to apparently stronger lines compared with the Hyades. Stars χ Her, γ Ser, and ι Psc are moved redward.

VI. COMPARISON WITH FIELD SUBGIANTS: THE CHEMICAL HISTORY OF THE EARLY GALACTIC DISK

Our result that stars near the main sequence in M67 and NGC 188 show slight line weakening and presumably, therefore, have slightly lower metal abundances than the Hyades can be discussed further. Shown in Figures 5 and 6 are eleven subgiants of large parallax ($\pi \geq 0''.056$) whose ages are similar to those of M67 and NGC 188 and which have direct spectrographic abundance determinations. The data, listed in Table 4, are taken from Eggen (1964*b*) and Johnson *et al.* (1966) as regards photometry, while the abundances, expressed as [Fe/H] ≡ log Fe/H relative to the Sun, are taken from the summary by Cayrel and Cayrel de Strobel (1966), where references to the original work of the authors quoted in § IV are given.

The directly determined abundances are consistent with the photometric blanketing evidence given by the two-color diagram shown in Figure 6 in all cases except ι Per, which has an *overabundance* of [Fe/H] = +0.20 but which shows a small $(U - B)$-*excess*. However, the overabundance is consistent with the Strömgren m_1 index (Herbig 1965) which gives $[Fe/H]_{m_1} = 0.19$. The difference between the $\delta(U - B)$ and m_1 indices should be investigated. In both Figure 6 and Table 4 the colors of ζ Her have been corrected for the visual companion (Eggen 1965*b*), and again the photometric and spectrographic indications for [Fe/H] are consistent to within the errors of $\epsilon[Fe/H] \simeq \pm 0.15$. The fiducial line in both panels of Figure 6 is the Hyades relation, taken from

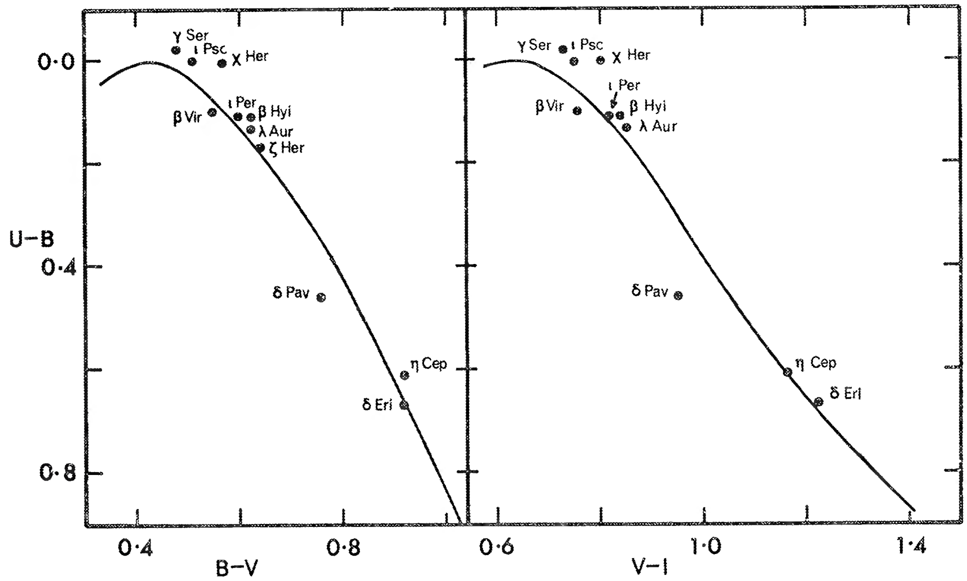

FIG. 6.—Two-color diagrams in $U - B, B - V$, and $V - I$ for the subgiants listed in Table 4. The Hyades intrinsic relation has been used as the fiducial line.

TABLE 4

SUBGIANTS WHICH HAVE ABUNDANCE ANALYSES

Name	HR/BS	π	M_V	$U-B$	$B-V$	$V-I$	[Fe/H]
β Hyi. .	98	0″153	3.67	+0.11	0 62	0.84	−0.30
ι Per. . .	937	084	3.66	+ .11	.60	0 82	+ .20
δ Eri......	1136	.109	3.67	+ .67	.92	1.22	− .04
λ Aur. .	1729	.066	3.78	+ .13	62	0.85	+ .18
β Vir. . . .	4540	.098	3 57	+ 10	.55	0.76	+ .33
χ Her.. .	5914	056	3 36	00	57	0.80	− .44
γ Ser ..	5933	069	3.03	− .02	.48	0.73	− 38
ζ Her* .	6212	.110	3.11	+ .17	.64	..	+ .07
δ Pav. ..	7665	.170	4 71	+ .46	.76	0.95	− .02
η Cep. ...	7957	.071	2.68	+ 61	.92	1.16	.00
ι Psc. . .	8969	0.064	3 32	0 00	0.51	0.75	−0.04

* M_V, $U-B$, and $B-V$ have been corrected for the visual companion

Sandage and Eggen (1959), Eggen (1965*a*), and Johnson, MacArthur, and Mitchell (1968).

The two stars which show the largest $(U - B)$-excess (γ Ser and χ Her) also show the largest metal deficiency ([Fe/H] = −0.38 and −0.44). In the opposite direction, β Vir shows *excess* blanketing and has an overabundance of [Fe/H] = +0.33.

The most interesting case is δ Pav, which has a large $(U - B)$-deficiency but has the solar abundance (Rodgers 1969). Evidently a second parameter is involved (Conti and Deutsch 1966) for this star at least. Rodgers identifies the parameter with microturbulence from his direct measurements. The star δ Pav, plotted as a closed circle in Figure 5 at its observed color of $B - V = 0.76$, falls far below NGC 188. Correction for the stronger blanketing, made by subtraction of $\Delta(B - V) = 0.08$ mag as measured by Rodgers, puts δ Pav on the NGC 188 sequence, as shown by the open circle. The question of whether all stars which lie appreciably below NGC 188 (Eggen 1964*b*, Fig. 2) can be explained in this way remains to be investigated. In this connection we must also account for the fact that the dispersion in the W-components of the space motion for these stars is twice that of stars which lie *between* the M67 and NGC 188 subgiant sequences (Eggen 1964*b*, table on p. 599). These points are crucial in deciding if disk stars exist which are appreciably older than NGC 188.

Table 4 shows that none of the eleven stars gives evidence for abundance variations larger than $-0.44 \geq [\mathrm{Fe/H}] \geq +0.33$ relative to the Sun. The mean of the group gives $[\mathrm{Fe/H}] = -0.04 \pm 0.17$(A.D.), i.e., the solar abundance to within a factor of 1.5(A.D.). We have found nearly the same result for NGC 188 and M67 themselves by using the observed $(U - B)$-excess, which by § IV leads to $\Delta(B - V)_{\mathrm{bl}} = 0.03$. This blanketing correction implies that $[\mathrm{Fe/H}] \simeq +0.07$ for these clusters as obtained from a rediscussion (Eggen 1964*b*, Fig. 19) of the Wallerstein (1962) correlation betw een color exces and abundance.

The conclusion to be drawn from these results is the same as previously reached (cf. Sandage 1962*a;* Rodgers and Bell 1963; Hazelhurst 1963; Pagel 1963; Eggen and Sandage 1964; Eggen 1964*b;* Cayrel and Cayrel de Strobel 1966), namely, that the oldest disk stars so far isolated have nearly the solar abundance in the mean. Because NGC 188 is nearly as old as the globular clusters in the halo, it follows that the metal content of the disk has been nearly fixed since the time of its formation shortly after the start of halo collapse about 10^{10} years ago. Table 4 shows that *variations* in the metal content do occur, reaching factors of 2 either way from the solar value, but there is no *systematic* trend in the data with age for age values ranging from that for NGC 188 ($T \simeq 10^{10}$ years), through M67 ($T \simeq 5 \times 10^9$ years), to the Hyades ($T \simeq 2 \times 10^8$ years), and on into the modern era (h and χ Per with $T \simeq 10^6$ years). In particular, there is no evidence from our present cluster data and from the stars in Table 4 for a systematic overabundance by a *mean* factor of 2–3 in Fe/H.

The same result was obtained previously (Eggen 1964*b*, Figs. 1, 2, and 24, and the Table on p. 608) from a study of the distribution of $(B - V)$-differences from the Hyades for a large sample of 255 stars in the relevant age range. Only 3 percent of the G dwarfs and subgiants had stronger lines ($B - V$ deficiencies) than the Hyades, while 86 percent had blanketing differences (which translate into abundances) in the small range of $-0.20 \leq [\mathrm{Fe/H}] \leq +0.30$ relative to the Sun. The distribution has a peak at $\Delta(B - V) = 0.03$ or $[\mathrm{Fe/H}] \simeq +0.07$, which is the same as our present value for main-sequence stars in NGC 188 and M67.

Similar conclusions have been reached by Strömgren (1963) from his $(m_1, b - y)$-diagram for late F and early G stars. Few stars exceed the Hyades in the m_1 index in the range $0.40 \geq b - y \geq 0.30$, while many have smaller m_1 values.

The total material can be represented schematically by the diagram of age versus [Fe/H] shown in Figure 7, which is modified from a previous discussion (Arp 1961; Sandage 1968, Fig. 7). The lower envelope at [Fe/H] = −0.40 is based on (1) stars in Table 4,

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(2) the more extended study of a larger sample (Eggen 1964*b*), and (3) Strömgren's results. This envelope can be extended schematically toward shorter ages than NGC 752, as shown by the dashed line, by noting the decrease in the scatter in the (m_1, $b - y$)-diagram for $b - y$ bluer than 0.30. Strömgren (1963) interprets the result to mean that stars in this younger age range from a more homogeneous group with regard to chemical composition.

In summary, the conclusion from Figure 7 is the same as before. Nearly complete enrichment of the galactic disk took place at its formation, although variations up to factors of ±2 from the solar metal abundance occurred. The question of whether these variations are systematic functions of place of star formation (Arp 1962; Eggen 1964*b*) still awaits complete solution.

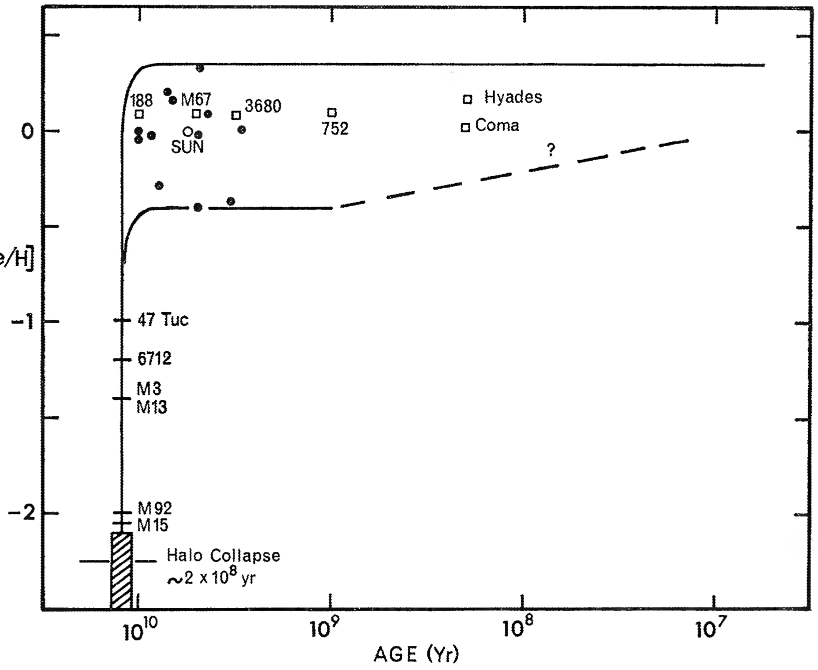

FIG. 7.—Variation of [Fe/H], relative to the Sun, with age. *Closed circles*, stars from Table 4. The lower envelope extending from the oldest ages to NGC 752 is from data by Eggen (1964*b*). The extension to shorter ages is from data by Strömgren (1963).

APPENDIX A

THE FOUR CONTACT BINARIES

Four short-period variables were discovered in NGC 188 by Hoffmeister (1964*a*, *b*). These are designated S8278 (EQ Cep), S8279 (ER Cep), S8280 (ES Cep), and S8474 (EP Cep) in the Sonneberg system, and in the standard constellation notation. Stars ER Cep and ES Cep were independently discovered by N. Richter, as reported by Hoffmeister (1964*b*). Although they were first considered RR Lyrae stars, Efremov *et al.* (1964) concluded that the variables were contact binaries (W UMa stars) whose periods were double those given by Hoffmeister.

The stars can be identified on the finding charts in Paper I as follows. S8278 (EQ Cep) is the unmarked star 3.6 mm south and 2.0 mm west of star I-27 in Ring I of Figure 2 of Paper I. S8279 (ER Cep) is the unmarked star 2.2 mm north and 3.2 mm east of star II-26 in Ring II of Figure 3 of Paper I. S8280 (ES Cep) is star II-114. S8474 is the unmarked star 6.0 mm north and 2.1 mm west of star III-117, Ring III (Fig. 3, Paper I). We are indebted to N. Richter for supplying a finding chart on which these stars were marked.

Preliminary periods of the variables, together with their position in the C-M diagram of NGC 188, were given by Kholopov and Sharov (1966). Improved periods, also by Kholopov and Sharov (1967*a*, *b*, *c*), have been published.

Photoelectric observations of ER Cep (S8279) and ES Cep (S8280) were obtained by Eggen on two nights (1965 December 1 and 2) with the 200-inch reflector, with the results shown in Figure A1. The observations on December 1 are plotted as triangles; those on December 2, as circles. To phase the observations it was necessary to change slightly the periods from $0\overset{\mathrm{d}}{.}342452$ for ES Cep and $0\overset{\mathrm{d}}{.}285736$ for ER Cep (Kholopov and Sharov 1967*a*, *b*) to $0\overset{\mathrm{d}}{.}347$ and $0\overset{\mathrm{d}}{.}288$, respectively. In view of the paucity of the observations and the well-known variation in period of other contact binaries, we consider this apparent change to be insignificant for the present purpose.

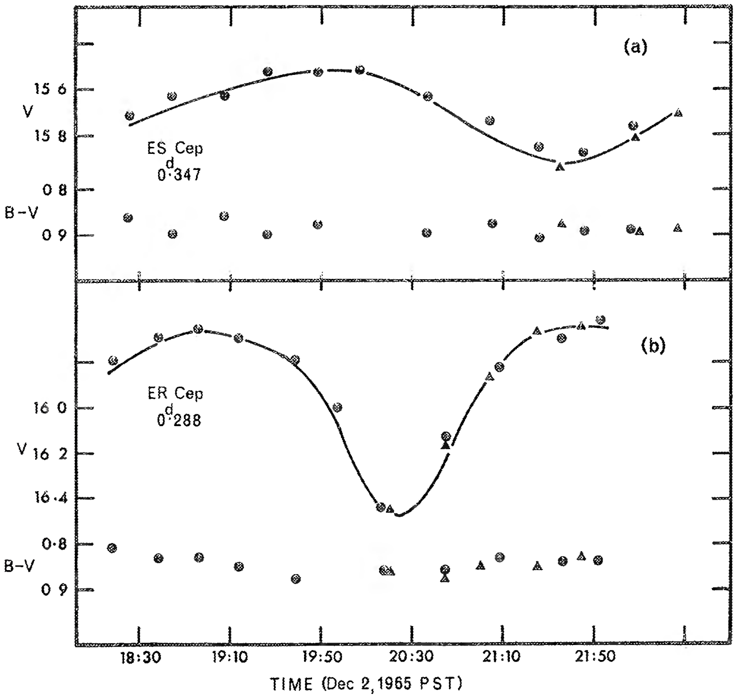

FIG. A1.—Observations of (*a*) ES Cep and (*b*) ER Cep on 1965 December 1 (*triangles*) and December 2 (*circles*) with the 200-inch reflector. Continuous curves represent mean light curves for V 700 Cyg ($P = 0\overset{\mathrm{d}}{.}34$) in (*a*), and SW Lac ($P = 0\overset{\mathrm{d}}{.}32$) in (*b*).

The light and color curves of ES Cep and ER Cep shown in Figure A1 are typical of contact binaries with similar periods (Eggen 1967). The continuous curves shown in this diagram are for V 700 Cyg ($P = 0\overset{\mathrm{d}}{.}34$) published elsewhere (Eggen 1967), and SW Lac ($P = 0\overset{\mathrm{d}}{.}32$) from unpublished observations. The mean values of the magnitude and colors at maximum are given in Table A1.

No complete photoelectric data were obtained for EQ Cep ($P = 0\overset{\mathrm{d}}{.}362$). Two photoelectric observations of EQ Cep (S8278) give $B - V = 0.90$, $U - B = 0.54$. Four photographic observations from the work in Paper I give $V = 16.2$–17.0, a value which agrees moderately well with 16.3–17.2 obtained by Kholopov and Sharov (1966, 1967*c*). We adopt $V = 16.25 + 0.75 = 17.00$ and $B - V = 0.90$ for the parameters of a single star in EQ Cep, under the assumption of equal components.

No photographic or photoelectric data were obtained for EP Cep ($P = 0\overset{\mathrm{d}}{.}289$), but Kholopov and Sharov (1967*b*) give a maximum of $V \simeq 16.6$ and $B - V \simeq 0.9$, or $V + 0.75 \simeq 17.35$ for a single equal component.

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The four stars are plotted in Figure 1 as crossed circles at their single-component luminosities. The uncertainty of the data for EP Cep is indicated by the dotted circle at $V = 17.35$, $B - V = 0.9$. The three stars with the most reliable data are also plotted in Figure 2.

ES Cep and ER Cep are plotted as open squares in the two-color diagram of Figure 3 at $B - V = 0.88$, $U - B = 0.44$, and $B - V = 0.83$, $U - B = 0.37$, respectively. The fact that these systems do not deviate from the $(U - B, B - V)$-relation for other cluster stars confirms a previous conclusion (Eggen 1967, p. 117) that no intrinsic ultraviolet excess is caused by their contact nature.

All four variables are on the evolving main sequence of NGC 188 and have therefore increased their radii from the initial values of the zero-age main sequence. But the fact that the four variables have followed the same evolutionary tracks as single stars in NGC 188 (i.e., they fall among the other main-sequence stars in Fig. 1) shows that the normal evolution has not yet been stopped by reaching the inner Lagrangian surface. In this respect the stars differ from the contact binary III-33 in M67 (Eggen 1967, Fig. 5), which has not followed the evolution of single dwarfs of the same $B - V$ but has remained on the unevolved main sequence. M67 III-33 may therefore be in complete contact (both components fill the inner contact surface). The variables in NGC 188 have apparently not yet reached that stage.

In this regard, it is interesting that ES, EQ, and ER Cep lie appreciably below the upper boundary line of the period-color relation for other W UMa stars (Eggen 1967, Fig. 6), as does AH Vir (*ibid.*, Fig. 5) which has also evolved from the main sequence, whereas M67 III-33 lies nearly along the upper boundary. As the evolution of NGC 188 stars proceeds in future time, the four variables will undoubtedly reach their respective inner contact surfaces and will cease to evolve in the same manner as single cluster stars of similar luminosity and color. They should then deviate from the C-M diagram defined by such stars and might be expected to lie close to the upper boundary of the period-color relation.

TABLE 1A

Star	V	$B-V$	$U-B$	$V+0.75$
ES Cep. . .	15.52	0.88	0.44	16.27
ER Cep...	15.65	0.83	0.37	15.40

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