NEW PHOTOELECTRIC OBSERVATIONS OF STARS IN THE OLD GALACTIC CLUSTER M67

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ABSTRACT

New photoelectric observations are given for 190 stars in and near M67. By using the properties of the $(U - B, B - V)$ diagram it has been possible to separate the effects of interstellar reddening from those of line blanketing, and values of $E(B - V) = +0^{m}.06$, $E(U - B) = +0^{m}.04$, $\Delta(B - V) = +0^{m}.03$, $\Delta(U - B) = +0^{m}.06$ have been derived. The small value of the blanketing corrections, which indicates that the Fe/H abundance ratio is similar to that of the Sun and the Hyades cluster, shows that at least for some stars there has been very little enrichment of heavy elements in the parent interstellar medium between the time of formation of M67 and the present.

The color-magnitude diagram of the cluster shows the presence of a sharply defined gap on the rising branch of the evolved main sequence. This gap may represent a very rapid interlude on a gravitational time scale, between the depletion of the hydrogen in the stellar core and the firing of the hydrogen in a shell outside the core. Similar gaps are definitely present in NGC 2477 and NGC 752. The color-magnitude diagram of M67 also contains a horizontal branch populated by stars which are almost certainly cluster members on the basis of both the proper motions and the success with which the observed anomalies in their ultraviolet colors can be explained as a gravity effect.

A comparison of evolutionary tracks, derived from a model by Hoyle, with the observed color-magnitude diagram gives good agreement except for a slight deviation near the main sequence caused by a more vertical rise to the evolved sequence than is predicted by theory. The distance modulus of M67, corrected for absorption, is $m - M = 9^{m}.38 \pm 0^{m}.2$, obtained by using the method of the evolutionary deviation curve.

I. INTRODUCTION

Johnson and Sandage (1955) have previously found that the galactic cluster M67 ($\alpha_{1960} = 8^{h}49^{m}.0$, $\delta_{1960} = +11°58'$; $l = 216°$, $b = +32°$) differs in several respects from such prototype objects as the Hyades, Pleaides, and Perseus double cluster. The most striking differences were: (1) the main-sequence termination point was fainter and redder than that for previously well-studied galactic clusters, and (2) the giant and subgaint sequences were markedly different in shape and position from those found for globular clusters. Interpretation of these differences in terms of stellar evolution indicated that (1) the stars in M67 are extremely old, and (2) the shapes of the evolutionary tracks in the color-luminosity array for stars near 1 $\mathfrak{M}_{\odot}$ are strongly dependent on chemical composition. Although more recent studies (Eggen 1955, 1963*a;* Wilson 1959; Sandage 1962*a*) have shown that M67 probably does not contain the oldest stars in the galactic disk, the cluster will continue to be extremely important for investigations of stellar evolution.

One of the outstanding questions concerns the chemical composition of the member stars in M67. Ideas of nucleosynthesis (Burbidge, Burbidge, Fowler, and Hoyle 1957), together with models for the rate of star formation in the galactic system (Schmidt 1959; Salpeter 1959), suggest that a steady enrichment of the interstellar medium with heavy elements has occurred so that the Fe/H abundance ratio for stars in a cluster as old as M67 should be considerably smaller in than younger clusters such as the Hyades. Methods of estimating the gross chemical composition of stars, using the results of broad-band photometry, are now available (e.g., Roman 1954; Sandage and Eggen 1959; Wallerstein and Carlson 1960), and the composition of the stars in M67 can be discussed in more detail than was previously possible.

The new photoelectric observations reported here have been made to provide data

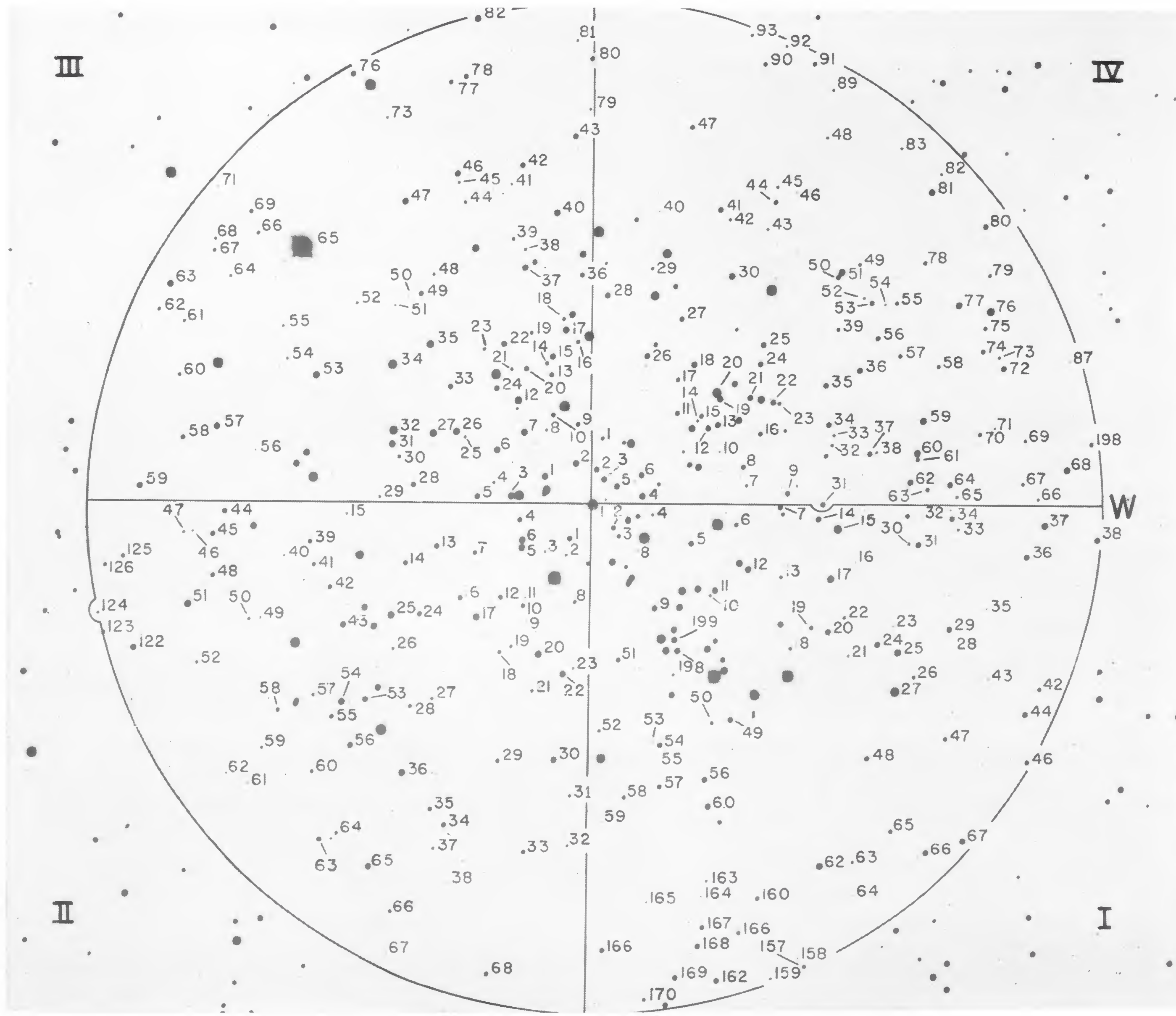

FIG. 1.—The identification chart for the program stars of Table 2 for the central zone of M67. The Fagerholm stars of Table 1 have been identified previously by Johnson and Sandage (1955) and are not repeated here. All stars measured photographically in the 1955 study are identified here so that cross-reference with Murray's proper-motion study (1964) can be made. The reproduction is from a plate taken on an Eastman 103a-D plate behind a Schott GG 11 filter with the 60-inch reflector diaphragmed

for the following purposes: (1) to separate the effects of interstellar reddening from those caused by line blanketing, (2) to confirm the presence of a gap in the rising subgiant sequence of the color-magnitude diagram, (3) to investigate the effect of differing surface gravities on the emergent flux for the evolving stars, and (4) to compare in some detail the shape of the observed evolutionary tracks with those predicted from models (e.g., Hoyle 1959).

II. THE DATA

Over 300 new photoelectric observations in three colors of 190 stars in the region of M67 were obtained with the 100- and 200-inch reflectors in 1963. The stars observed include most of those used as photoelectric standards by Johnson and Sandage (1955, Table 2) and the majority of those brighter than visual magnitude 14 in a 9′.5 radius zone in the center of the cluster. Because one of our purposes was to attempt confirmation of the apparent break in the color-magnitude diagram near the main-sequence termination point at visual magnitude 13 (Johnson and Sandage 1955, Fig. 3), we concentrated on the stars brighter than visual magnitude 14; a few fainter objects were observed with the 200-inch reflector.

Our new results, combined with the Johnson-Sandage (JS) results for the standard stars, are listed in Table 1. Independent observations were made by both authors using

TABLE 1

COMBINED DATA FOR THE PHOTOELECTRIC STANDARDS USED BY JOHNSON AND SANDAGE†

Star	V	$B-V$	$U-B$	n	Star	V	$B-V$	$U-B$	n
81......	10.03	−0.073	−0.385	Std	162......	12.84	+0.58	+0.08	2
83......	13.24	+0.605	+0.065	2	164......	10.55	+1.125	+1.015	2
84......	10.59	+1.115	+0.955	2	170......	9.69	+1.355	+1.48	4
94......	12.83	+0.56	+0.07	3	175......	13.72	+0.595	+0.08	2
95*.....	12.67	+0.51	+0.01	3	190......	10.98	+0.245	+0.15	2
105......	10.30	+1.260	+1.320	Std	193......	12.26	+1.015	+0.80	2
108......	9.72	+1.38	+1.545	3	223......	10.58	+1.10	+0.975	2
111......	12.74	+0.56	+0.045	2	224......	10.76	+1.13	+1.09	2
115......	12.65	+0.63	+0.12	2	225......	13.08	+0.55	+0.04	2
117......	12.61	+0.77	+0.28	3	226......	12.77	+0.755	+0.255	2
119......	12.57	+0.59	+0.07	3	227......	12.97	+0.915	+0.57	2
124......	12.14	+0.45	+0.03	4	231......	11.50	+1.05	+0.88	2
125......	13.86	+0.58	+0.04	1	241......	12.68	+0.595	+0.09	2
127......	12.77	+0.56	+0.06	7	243......	12.61	+0.61	+0.075	2
130*.....	12.88	+0.47	+0.005	6	244......	10.78	+0.94	+0.67	2
131......	11.22	+0.415	+0.06	2	255......	12.72	+0.56	+0.04	1
132......	13.12	+0.61	+0.08	4	266......	10.55	+1.105	+0.945	2
134......	12.27	+0.58	+0.06	3	280......	10.70	+0.11	+0.09	2
135......	11.45	+1.06	+0.92	3	a........	14.89	+0.725	+0.215	2
136......	11.31	+0.63	+0.14	3	149a.....	14.91	+0.78	+0.26	1
141......	10.48	+1.11	+0.98	2	i........	15.23	+0.84	+0.30	1
142......	14.17	+0.62	+0.11	1	m*......	14.83	+0.69	+0.16	1
143......	11.52	+0.86	+0.50	3	s........	16.19	+0.66	+0.17	1
145......	12.82	+0.585	+0.055	2	t........	14.05	+0.64	+0.16	1
147......	13.28	+0.59	+0.065	2	v........	15.75	+0.85	+0.51	2
149......	12.56	+0.605	+0.085	2	w........	15.64	+0.89	+0.53	1
151......	10.49	+1.10	+0.096	3	aa.......	16.05	+1.07	+0.83	2
153......	11.31	+0.13	+0.11	3	132a.....	15.83	+1.08	+0.76	1
156......	10.99	+0.11	+0.09	3	149b*....	14.76	+0.48	−0.02	1
157......	12.78	+0.58	+0.075	2					

† The star numbers are those of Fagerholm (1906). The identification chart for all stars in this table appears as Figure 1 in *Ap. J.*, **121**, 616, 1955.

(UBV) standards around the sky, and the agreement between these current sets of observations and those published by Johnson and Sandage (1955) is satisfactory, as can be seen from the following comparisons:

	No.	ΔV	$\Delta(B-V)$	$\Delta(U-B)$
E−JS........	28	$-0^{\mathrm{m}}.030 \pm 0^{\mathrm{m}}.034$	$+0^{\mathrm{m}}.010 \pm 0^{\mathrm{m}}.010$	$-0^{\mathrm{m}}.005 \pm 0^{\mathrm{m}}.017$
S−JS.........	21	-0.017 ± 0.027	0.000 ± 0.010	0.000 ± 0.012

The stars in Table 1, which are labeled according to the numbering system used by Fagerholm (1906), are identified by Johnson and Sandage (1955, Fig. 1).

Table 2 lists the new photoelectric data for 130 stars (identified in Fig .1) in the central region of M67. The number of independent observations are given in the last column where E and S identify the observer. The systematic differences between the two observers, in the sense E − S, from thirty-seven stars in common, are $+0^{\mathrm{m}}.006 \pm 0^{\mathrm{m}}.02$, $-0^{\mathrm{m}}.002 \pm 0^{\mathrm{m}}.01$ and $+0^{\mathrm{m}}.025 \pm 0^{\mathrm{m}}.02$ for V, $B - V$, and $U - B$, respectively; these values are so small that no systematic corrections were considered necessary in combining the data. Stars labeled with an asterisk in Tables 1 and 2 are considered to be nonmembers of the cluster on the basis of the new proper-motion study by Murray (1954); four stars, I-22, I-23, III-32, and IV-25, are arbitrarily excluded from membership on the basis of their position in the color-magnitude diagram.

All stars previously studied photographically (Johnson and Sandage 1955) in the central region of the cluster are identified in Figure 1, regardless of whether they appear in Table 1, in order to facilitate the identification of the objects in Murray's proper-motion study where the older, photographic magnitudes and colors are now tabulated for the first time.

III. SEPARATION OF THE REDDENING AND BLANKETING EFFECTS

It is difficult to separate the effects of line blanketing and of interstellar reddening on the observed colors except under unusual circumstances. However, when, as in M67, the cluster stars are spread over a wide range of $B - V$ colors, the differences in the slopes of the reddening and blanketing lines in the ($U - B$, $B - V$) diagram can be used for this purpose. Figure 2 shows the stars in Tables 1 and 2 for which two or more independent photoelectric observations are available; different symbols indicate stars in different parts of the color-magnitude diagram. The two objects near $B - V = +0.4$, which are shown as crosses, have been corrected for the effect of surface gravity on the $U - B$ colors by application of Figure 5, as discussed in Section V.

All stars plotted in Figure 2 fall above the standard ($U - B$, $B - V$) relation for Hyades main-sequence stars (Sandage and Eggen 1959, Table III), shown as a continuous curve. Merely shifting the standard relation along a reddening trajectory [$E(U - B)/E(B - V) = 0.72$] will not force agreement with the mean relation derived for the stars in M67. Agreement between the relation for Hyades and M67 stars can be obtained by shifting the former parallel to itself, giving differences of $+0^{\mathrm{m}}.03$ in $B - V$ and -0.02 in $U - B$ in the sense M67 − Hyades; these values presumably represent the compounded effects of line blanketing and interstellar reddening.

Because values of the ultraviolet excess $\delta(U - B)$, defined in the standard way (Sandage and Eggen 1959, Fig. 4), are very nearly independent of $B - V$ for a given chemical composition (Eggen 1963*a*) and are the same for giants and dwarfs (Appendix to this paper) over the range from about 0.6 to 1.0 in $B - V$, the shape of the standard relation in Figure 2 will not be distorted by line-blanketing effects over this range of $B - V$. In the range of $B - V$ between $+0^{\mathrm{m}}.4$ and $+0^{\mathrm{m}}.6$ the shape of this relation will

TABLE 2

PHOTOELECTRIC DATA FOR STARS IN THE CENTRAL REGION OF M67 IDENTIFIED IN FIGURE 1

Star	V	B−V	U−B	n	Star	V	B−V	U−B	n	Star	V	B−V	U−B	n
I-1.....	10.51	0.59	+0.035	2S	I-168.....	13.70	0.55	+0.09	1S	III-43.....	13.33	0.63	+0.03	1E
4.....	15.71	0.93	+0.58	2E	197.....	13.92	0.59	+0.07	1S	46.....	13.22	0.60	+0.06	1E
5.....	13.68	0.58	0.00	3ES	198.....	13.16	0.58	+0.05	2S	47.....	12.79	0.60	+0.09	1E
6*....	14.34	0.54	−0.05	4ES	199.....	13.19	0.58	+0.06	1S	49.....	13.80	0.61	+0.06	1E
7.....	13.90	0.59	+0.065	2S	....	.....	....	.....	...	53.....	12.54	0.675	+0.15	2ES
9.....	13.20	0.565	+0.06	2ES	II-1.....	13.83	0.635	+0.12	2E	57.....	12.94	1.01	+0.73	1E
11.....	13.09	0.565	+0.03	2S	13.....	13.74	0.655	+0.14	2E	59.....	13.38	0.59	+0.08	1E
13.....	15.20	0.79	+0.27	2E	17.....	12.70	0.695	+0.205	3ES	63.....	12.83	0.595	+0.095	2ES
14.....	13.36	0.58	+0.02	1S	20.....	12.64	0.575	+0.045	2E	65*....	7.85	1.12	+0.99	1S
15*....	11.55	0.41	−0.035	2S	22.....	12.93	0.93	+0.59	2E	82.....	12.81	0.77	+0.28	1S
16.....	16.38	1.00	+0.70	2E	24.....	13.78	0.59	+0.09	2E	86*....	10.98	0.80	+0.36	2S
17.....	12.40	0.985	+0.725	2ES	25*....	12.37	0.575	−0.035	2E	187.....	10.57	0.27	+0.11	1S
18.....	15.08	0.92	+0.54	2E	30.....	13.15	0.59	+0.065	2E	....	.....	....	.....	...
19.....	14.55	0.70	+0.22	2E	36.....	12.73	0.57	+0.08	2E	....	.....	....	.....	...
20.....	13.41	0.585	+0.02	3ES	43.....	13.41	0.58	+0.04	2E	....	.....	....	.....	...
21*....	15.87	0.78	+0.29	2E	44.....	13.92	0.695	+0.185	2E	IV- 2.....	13.51	0.57	+0.065	2ES
23*....	16.19	0.80	+0.30	2E	45.....	14.00	0.605	+0.11	2E	3.....	13.26	0.585	+0.05	2ES
24.....	13.46	0.585	+0.03	2ES	51*....	12.50	0.60	+0.04	2E	4.....	12.72	0.58	+0.01	3ES
25.....	12.65	0.63	+0.10	1S	53.....	13.40	0.54	+0.06	1E	6.....	13.30	0.47	−0.015	2ES
26.....	14.96	0.76	+0.33	4ES	54.....	12.91	0.48	−0.05	1E	8.....	14.18	0.61	+0.09	1S
27.....	11.32	0.295	+0.125	2S	56.....	13.42	0.55	+0.06	1E	9.....	13.86	0.59	+0.065	2ES
28.....	16.64	1.00	+0.70	1E	57.....	12.94	0.99	+0.68	1S	11.....	13.98	0.585	+0.06	2ES
29.....	13.44	0.635	+0.06	2S	65.....	13.24	0.57	+0.07	1E	12.....	13.54	0.58	+0.04	2ES
31.....	13.52	0.60	+0.07	2S	....	.....	....	.....	...	13.....	13.20	0.55	+0.065	2ES
34.....	13.79	0.57	+0.05	1S	....	.....	....	.....	...	18.....	13.07	0.855	+0.47	2ES
35.....	16.25	1.09	+0.92	1E	III-1....	12.68	0.60	+0.09	1E	19.....	13.20	0.56	+0.10	1E
36.....	13.31	0.58	+0.07	1S	2....	12.89	0.46	0.00	1E	20.....	11.21	1.07	+0.89	1E
37*....	12.66	0.54	−0.01	1S	5....	13.60	0.59	+0.06	1E	21.....	13.41	0.575	+0.055	2ES
38.....	13.61	0.55	+0.04	1S	6....	12.87	0.52	+0.06	1E	24.....	13.66	0.545	+0.025	2ES
42.....	14.60	0.72	+0.18	1S	7....	12.64	0.59	+0.11	1E	25*....	13.70	1.02	+0.68	2ES
43.....	16.33	1.19	+0.70:	1E	12....	12.27	0.27	+0.10	2E	26.....	13.34	0.57	+0.06	2ES
44.....	13.59	0.67	+0.10	1S	15....	13.31	0.49	+0.03	1E	27.....	13.95	0.61	+0.05	1S
46.....	14.41	0.74	+0.17	1S	17....	12.67	0.68	+0.19	1E	28.....	13.32	0.575	+0.085	2ES
48.....	14.05	0.70	+0.17	1S	22....	13.23	0.62	+0.11	1E	30.....	12.85	0.58	+0.065	2ES
49.....	13.44	0.60	+0.04	1S	24....	13.70	0.55	+0.06	1E	34.....	13.62	0.575	+0.08	2ES
56.....	13.44	0.57	+0.06	1S	26....	12.60	0.60	+0.10	1E	35.....	13.84	0.565	+0.065	2ES
60.....	13.28	0.58	+0.09	1S	27....	12.26	0.59	+0.075	4ES	36*....	13.38	0.55	+0.04	2ES
61.....	14.54	0.73	+0.16	1S	28....	13.83	0.59	+0.07	1E	37.....	13.79	0.58	+0.01	1S
62.....	12.80	0.79	+0.27	1S	31....	13.54	0.59	+0.11	1E	41.....	13.60	0.61	+0.16	1E
63.....	15.70	0.82	+0.63	1S	32*...	13.68	1.055	+0.85	2ES	59.....	12.77	0.745	+0.26	2ES
64.....	16.43	1.35	.....	1S	34....	11.32	1.085	+0.91	2ES	60.....	12.69	0.62	+0.09	1S
65*....	14.55	0.57	−0.06	1S	35....	12.16	1.02	+0.81	2ES	64.....	13.51	0.61	+0.06	1S
67*....	13.57	0.49	−0.01	1S	37....	13.08	0.58	+0.08	1E	68.....	12.95	0.87	+0.475	2ES
160.....	14.46	0.67	+0.10	1S	40....	12.86	0.60	+0.11	1E	76.....	12.04	0.60	+0.08	1E
162.....	13.61	0.52	+0.07	1S	42....	13.67	0.65	+0.10	1E	77.....	12.89	0.98	+0.65	2ES
										81.....	12.79	0.815	+0.38	2ES

not be independent of luminosity but, as already mentioned, the stars in Figure 2 within this range have been corrected for the effect of varying surface gravity by the precepts developed in Section V.

If we assume that the standard $(B - V, U - B)$ relation is also undistorted by reddening over the same range of $B - V$, which will be true for small values of the reddening, the total displacement between the continuous and broken curves in Figure 2 is composed of the terms $E(B - V)$ and $E(U - B)$ caused by the reddening and $\Delta(B - V)$ and $\Delta(U - B)$ caused by line blanketing, in the following way:

$$(B - V)_{67} - (B - V)_H = E(B - V) - \Delta(B - V) = +0\overset{m}{.}03$$
$$(U - B)_{67} - (U - B)_H = E(U - B) - \Delta(U - B) = -0\overset{m}{.}02\,, \quad (1)$$

whose simultaneous solutions give the reddening and blanketing values separately. The ratio $E(U - B)/E(B - V)$ is taken as $0\overset{m}{.}72$ for all values of $B - V$ considered here,

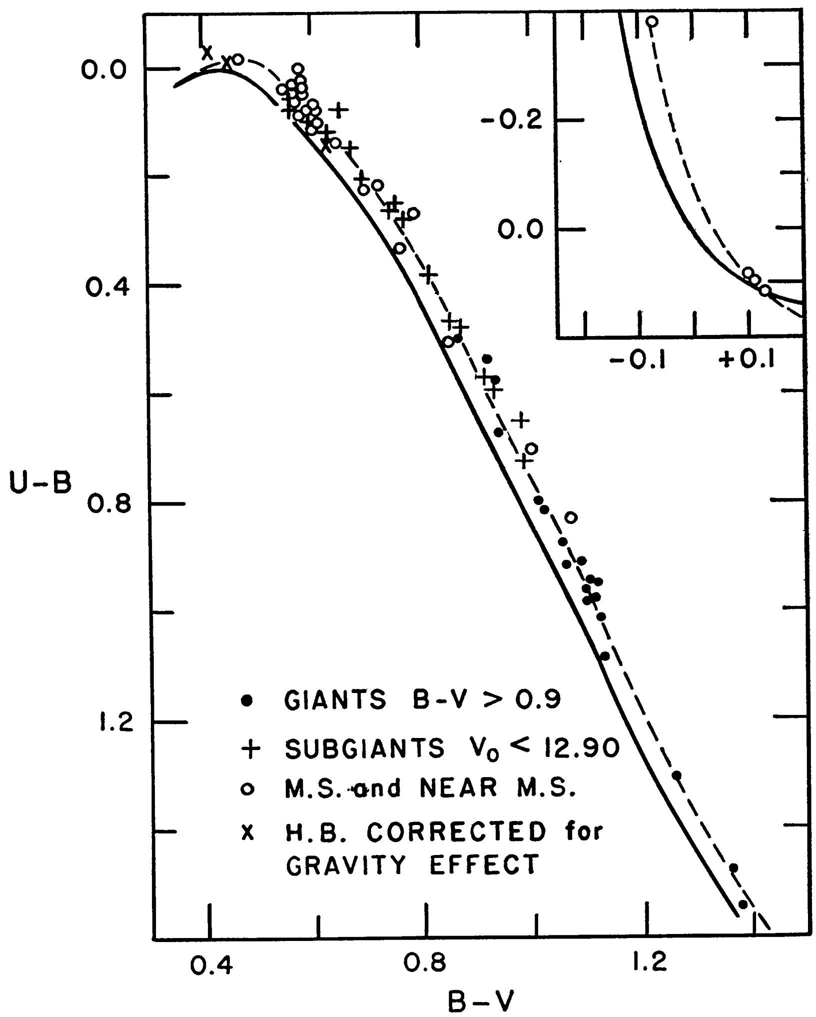

FIG. 2.—The two-color diagram for M67 stars redder than $B - V = 0\overset{m}{.}4$ which have two or more photoelectric measurements. The solid line is the fiducial Hyades relation. The dotted line is this relation shifted parallel to itself by $0\overset{m}{.}03$ redward in $B - V$ and $0\overset{m}{.}02$ blueward in $U - B$. The inset shows the bluest four stars in the cluster which are unaffected by line blanketing. The dotted line is obtained from the intrinsic line by the reddening tranformation $E(B - V) = 0\overset{m}{.}06$, $E(U - B) = 0\overset{m}{.}04$.

but the ratio $R = \Delta(U - B)/\Delta(B - V)$ must be regarded as a function of $B - V$ (Wildey, Burbidge, Sandage, and Burbidge 1962, eq. [9]). Considering six values of $(B - V)$ and their resulting values of the ratio $\Delta(U - B)/\Delta(B - V) = R$, we obtain the following:

$B-V$	R	$E(B-V)$	$\Delta(B-V)$	$\delta(U-B)$
$+0^{m}5$..........	2.07	$+0^{m}060$	$+0^{m}030$	$+0^{m}03$
+0.6..........	2.24	+ .057	+ .027	+ .035
+0.7..........	2.50	+ .053	+ .023	+ .025
+0.8..........	2.78	+ .050	+ .020	+0.02
+0.9..........	3.05	+ .047	+ .017	....
+1.0..........	3.32	+0.046	+0.016	....

The values of $\delta(U - B)$ have been taken from Table 4 of Wildey *et al.* (1962). We have adopted values of $E(B - V) = +0^{m}06$ and $\Delta(B - V) = +0^{m}03$, which result from giving the highest weight to the solutions of equation (1) above for values of $B - V$ near $+0^{m}6$. The main reason for this weighting is that the slightly smaller values obtained for $B - V$ near $+1^{m}0$ result from the increased values of R, and the available evidence from clusters and wide binaries is that although the values of $\delta(U - B)$ are guillotined near $B - V = +0^{m}8$ in the dwarfs—presumably because R approaches the slope of the intrinsic $(U - B, B - V)$ relation—they are apparently unaffected in the giants. The surmise that the values of R for giants do not vary as much as they do for dwarfs, as we go from $B - V = +0^{m}6$ to $+1^{m}0$, can only be tested when a blanketing theory for giants is available.

The four stars, Fagerholm Nos. 81, 153, 156, and 280, which are bluer than $B - V = +0^{m}15$ and, by the proper-motion criterion, are known cluster members, provide a test of the reddening corrections. The continuous curve in the insert to Figure 2 represents an intrinsic $(U - B, B - V)$ relation for early-type stars previously derived from the observed colors of the nearest objects (Eggen 1963*d*). The broken line represents this relation shifted by our values of $E(B - V) = +0^{m}06$ and $E(U - B) = +0^{m}04$; blanketing effects should be negligible for such blue stars. The position of the bluest star, No. 81, in the insert to Figure 2 is excellent confirmation of our reddening values; the other three objects, because of their position in a relatively insensitive part of the $(U - B, B - V)$ relation, can only be said to not contradict our result.

Although the derived values of $\delta(U - B)$ indicate a small excess with respect to the Hyades stars, it is similar to that found for such young clusters as Coma Berenices and Ursa Majoris, notwithstanding the very large age differences. Support for this result is given by the following distribution of the values of the blanketing correction, $\Delta(B - V)$, for 67 stars, from a sample of 1000 in the solar neighborhood (Eggen 1964), which reliable trigonometric parallaxes place more than $0^{m}5$ above the main sequence, such that they lie between the subgiant sequences of M67 and NGC 188 (Sandage 1962*b*):

	No.
$-0^{m}03 > \Delta(B - V) < +0^{m}03$	21
$+ .03 \leq \quad < + .06$	18
$+ .06 \leq \quad < + .10$	22
$+ .10 \leq \quad < +0.15$	5
$+0.15 \leq$	1

Apparently stars with ages between those of M67 and NGC 188 are uniformly distributed among values of $\Delta(B - V)$ from $-0^{m}03$ to $+0^{m}10$, which indicates that only a small abundance anomaly exists relative to the Hyades. This result is at variance with theories that predict a heavy-element production and redistribution within the interstellar medium that is uniform with time.

IV. THE COLOR-MAGNITUDE DIAGRAM

Figure 3, *a*, shows the color-magnitude diagram for the stars in Tables 1 and 2 for which at least two independent photoelectric observations are available. Reddening, $E(B - V) = +0^{m}.06$, and absorption, $A_V = +0^{m}.18$, corrections have been applied. Blanketing corrections have not been applied but their effect is discussed in Sections V and VI.

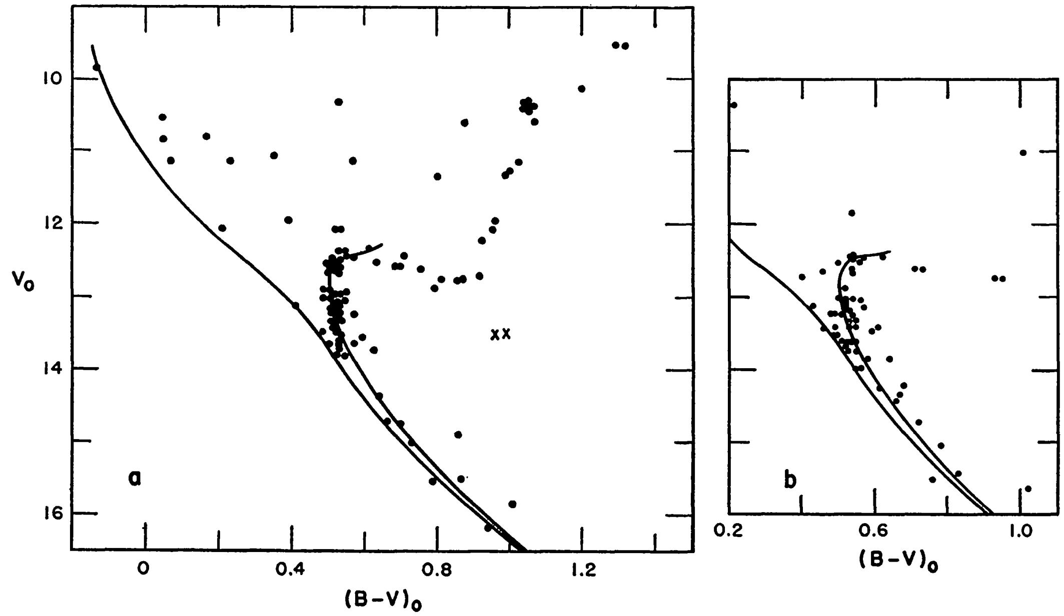

FIG. 3.—(*a*) The C-M diagram for stars with two or more photoelectric measurements. The data are from Tables 1 and 2 corrected for reddening by $E(B - V) = 0^{m}.06$, $A_V = 0^{m}.18$. An age-zero main sequence is shown as if the blanketing were zero. (*b*) Same as *a* but for stars which have only one photoelectric observation.

Perhaps the most striking feature of Figure 3, *a*, is the gap on the evolving branch, just above the main sequence between $V_0 = 12^{m}.90$ and $12^{m}.70$. Because of the completeness of our coverage in the central zone of the cluster, we believe this phenomenon to be established beyond reasonable doubt; Figure 3, *b*, which includes the less accurate data for stars in Tables 1 and 2 having only one photoelectric observation available, confirms the presence of this gap.

A natural explanation of this gap is that it results from an increase in the rate of evolution in this region of the color-magnitude diagram. The first theoretical prediction of this phenomenon appears to have been obtained by Henyey, LeLevier, and Levée (1955) in their computation of the evolutionary track for Sirius, mass = 2.3⊙, where a discontinuity appeared in an otherwise smooth track when the central convective core depleted its hydrogen. The cessation of thermonuclear energy production caused a gravitational collapse of the core, with a subsequent heating of the interior that in turn caused the nuclear reactions to recommence in a shell surrounding the core. After the core hydrogen was depleted, the star rapidly moved upward and to the left along a Kelvin contraction path in the $(M_V, B - V)$-plane until the hydrogen burning in the shell began and the evolution proceeded as before. The time scale, during this discontinuity, is a gravitational one which is short compared to that of the hydrogen burning, accounting for the lack of stars in this stage of the evolution. Subsequent model computations by Hazelgrove and Hoyle (1956) for stars of solar mass with a convective core, by Kushwaha (1957) for stars of 10 $\mathfrak{M}_\odot$, and by Hoyle (1960) for stars of 4 $\mathfrak{M}_\odot$, have confirmed this result.

The first convincing evidence that such a discontinuity exists in the evolving sequence of a cluster was in NGC 2477 (Eggen and Stoy 1960) and NGC 752 (Eggen 1963*c*). The evidence is less definite in such clusters as NGC 188 (Sandage 1962*a*, Fig. 5) and NGC 6940 (Larrson-Leander 1960), but the available data suggest that such a discontinuity may exist. Although more extensive and accurate data are required to establish if this gap is a universal feature of high metal-abundance clusters, it appears likely that the presence of this discontinuity will provide a useful criterion for dating these clusters when the necessary model computations are available.

Another interesting feature of Figure 3, *a*, is the strong concentration of bright stars along what may be a horizontal branch near $V_0 = 11^{m}0$. The proper-motion data indicate that most of these stars are cluster members. The analogy with color-magnitude diagrams for globular clusters suggests that these stars may be moving back to the main sequence from the tip of the giant branch; in this case it is interesting that their luminosity is near $M_V = +1^{m}5$ instead of near $+0^{m}5$, as in the halo globular clusters. Three stars of special interest in this connection are Nos. III-12, IV-6, and Fagerholm 81, which all lie close to the age-zero main sequence but are considerably brighter than those near the termination point of the bulk of the main-sequence stars in the cluster. The proper-motion data for all three stars and the spectroscopic results for Fagerholm 81 by Wallerstein (1959) indicate that these objects are cluster members. No completely satisfactory explanation is available for the presence of these objects. A similar situation exists in M3 where recent observations (Sandage 1964) of several stars on the main sequence, brighter than the main-sequence termination point, have established cluster membership by the presence of a large ultraviolet excess. The likely alternative explanations of the presence of these objects seem to be that (1) they do not share the pattern of evolutionary tracks followed by the majority of cluster stars or (2) they are considerably younger than the other cluster stars. The first alternative may require a mixing of the manufactured helium throughout the stellar interior so as to prevent the formation of a discontinuity in chemical composition, whereas the second requires a rather large spread in the formation time of cluster stars. Unfortunately there is little hope of determining the mass of these objects and thereby making a choice between these alternatives.

V. THE EFFECT OF SURFACE GRAVITY ON THE COLORS

The position of a star in the ($U - B$, $B - V$)-plane is dependent upon its surface gravity because of the sensitivity of the electron pressure and, therefore, the Balmer discontinuity to g. This "gravity effect" is easily computed but, because of the presence of the Hertzsprung gap, it is difficult to calibrate observationally for stars with spectral types from A5 to G0. Recent photometry (Eggen 1963*a* and unpublished) of a large number of wide binaries and multiple systems which contain a main-sequence secondary and a giant or subgiant primary has provided empirical ($U - B$, $B - V$) relations for stars in the range $+0^{m}2 > B - V < +0^{m}6$ that lie $1^{m}0$ and $2^{m}0$ above the Hyades main sequence. Only systems in which the main-sequence component shows little or no ultraviolet excess were used to avoid confusion with blanketing effects.

The composite ($U - B$, $B - V$) diagram in Figure 4 has been compiled from the following sources. The relation for Luminosity Class V stars is defined by the Hyades main sequence in the range $+1^{m}10 > B - V > +0^{m}2$ (Sandage and Eggen 1959, Table III) and is extended to the bluer objects by a study of the nearby stars (Eggen 1963*b*, 1963*d*). The relation for objects of Luminosity Class II is taken from a tabulation by Johnson (1963, Table 3). Individual stars of Luminosity Classes I*a*, I*b*, and II, shown by various symbols, are taken from studies by Kron (1958) for the earlier types and by

Kraft and Hiltner (1961) for the later types; the values of $E(U - B)$ for these stars have been computed from the values of $E(B - V)$ tabulated by these authors and the ratio $E(U - B)/E(B - V)$ given by Fernie (1963). Evolved A-type stars in the cluster M11, based on the data given by Johnson, Sandage, and Wahlquist (1956), are shown in Figure 4 by crosses; the two extreme values for M11 shown in the figure are for stars $2^{m}.6$ and $2^{m}.0$ above the unevolved main sequence.

The intersection of the relations for Luminosity Classes I*a*, *b*, and Class V, near $B - V = +0^{m}.2$, is predicted from theoretical considerations (e.g., Hack 1956). For stars of a given temperature bluer than $B - V = +0^{m}.2$ the Balmer discontinuity increases with

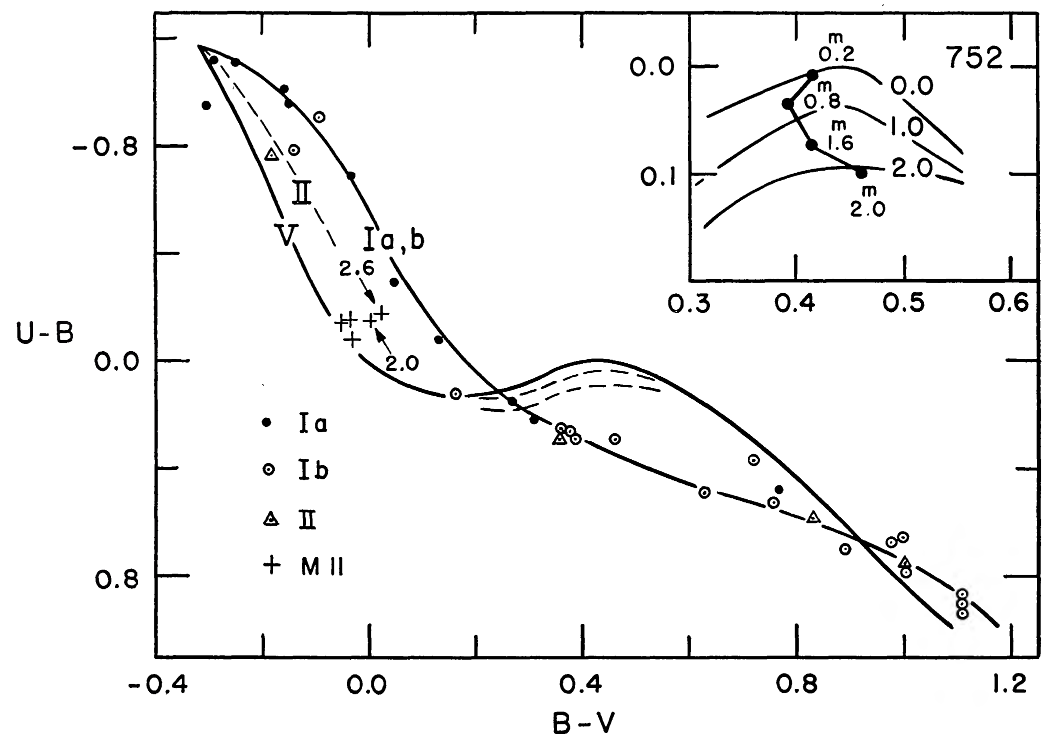

FIG. 4.—The $U - B$, $B - V$ diagram showing the effect of surface gravity on the colors. Individual supergiant and giant stars are shown together with the intrinsic lines for Luminosity Classes V, II, and I*a*, *b* stars. The calibration of the surface gravity effect for A and F stars is shown as two dotted lines and in more detail in the insert diagram which gives the data for four normal points along the evolving main sequence of NGC 752.

increasing surface gravity, thereby causing a larger hydrogen dip in the two-color curve. For cooler stars the discontinuity decreases with increasing gravity, which explains why the main-sequence stars lie above the I*a*, *b* relation for $B - V > 0^{m}.2$.

The region of Figure 4 between $B - V = +0^{m}.2$ and $+0^{m}.6$ is of special importance in connection with M67, because the cluster members falling on the horizontal branch of the color-magnitude diagram are in this range. The empirical $(U - B, B - V)$ relations for stars $1^{m}.0$ and $2^{m}.0$ above the Hyades main sequence, derived from the wide double and multiple systems, are shown as broken curves in Figure 4 and in more detail in the inset to the figure. The inset to Figure 4 also contains normal points taken from the rising branch of the evolved main sequence of NGC 752 which confirm the empirical relations. The main-sequence termination point in NGC 752 is in the early F-type stars with $B - V = +0^{m}.4$ where the Balmer discontinuity is very sensitive to variations in surface gravity and the evolved cluster stars show this sensitivity (e.g., Arp 1962; Gunn and

Kraft 1963, Fig. 1). The NGC 752 data used here were obtained from a new solution for the reddening and blanketing values by the method described in Section III, which gives $E(B-V) = +0^{m}.04$, $E(U-B) = +0^{m}.03$, $\delta(U-B) = +0^{m}.06$ and a corrected modulus of $m-M = 7^{m}.80$ (e.g., Arp 1962; Eggen 1963*c*).

The empirical $(U-B, B-V)$ relations for stars $1^{m}.0$ and $2^{m}.0$ above the Hyades main sequence are repeated in Figure 5 where individual stars on the horizontal branch of M67 are also shown as open circles after correction for reddening only; the filled circles represent the colors corrected for both reddening and blanketing effects. The data for the individual stars on the horizontal branch are listed in Table 3 where the second column gives the departure from the age-zero main sequence (Sandage 1957, Table 1), the third and fourth columns given the colors corrected for reddening, and the last two contain the colors corrected for both blanketing and reddening effects. Figure 5 shows that the data for the M67 stars agree with the previously calibrated surface-gravity relations.

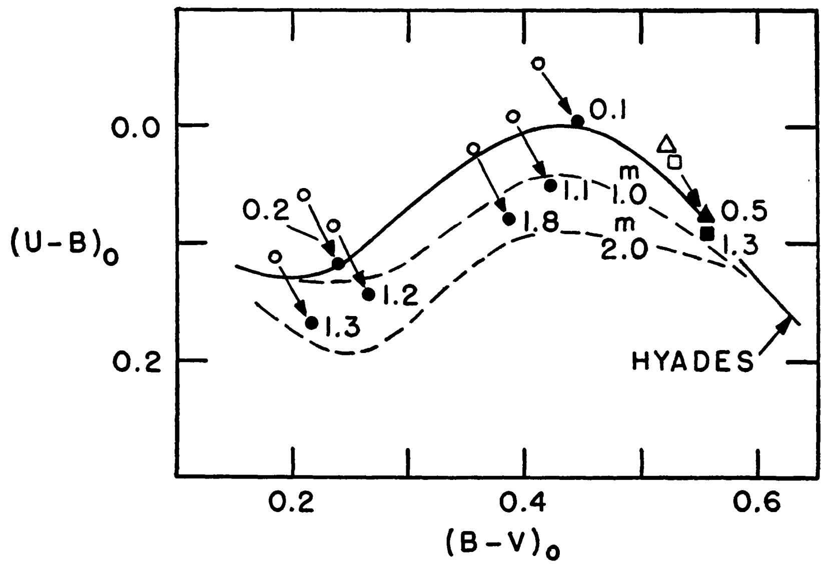

FIG. 5.—Detail of the calibrated lines for the surface-gravity effect. Open circles are for six stars on the "horizontal branch" of M67 corrected for reddening but not for blanketing. The filled circles show their positions after applying blanketing corrections of $\Delta(B-V) = 0.03$, $\Delta(U-B) = 0.06$, which is probably an overcorrection for the three bluest stars. The open square and open triangle are normal points along the evolving main sequence before blanketing corrections. The corresponding filled symbols are after applying blanketing corrections.

TABLE 3

DATA FOR STARS SHOWING THE SURFACE-GRAVITY EFFECT IN FIGURE 5

Star	ΔV	$(B-V)_0$	$(U-B)_0$	$(B-V)_{0,c}$	$(U-B)_{0,c}$
190	1.25	0.185	+0.11	0.215	0.17
III-12	0.16	.21	+ .06	.24	.12
I-27	1.21	.235	+ .085	.265	.145
131	1.82	.355	+ .02	.385	.08
124	1.10	.39	− .01	.42	.05
IV-6	0.00	.41	− .055	.44	.005
Normal pt	0.53	.521	+ .018	.551	.078
Normal pt	1.35	0.525	+0.030	0.555	0.09

It is worth emphasizing that the rising branch of the evolved main sequence in M67 is just enough redder than that of NGC 752 to avoid the sensitivity of the Balmer discontinuity in this region of the diagram to variations in the surface gravity. This is demonstrated in Figure 5 by two normal points formed from stars on the rising branch of the evolved main sequence in M67, one at $V_0 = 12^{m}55$, which is just above the break in the sequence seen in Figure 3, and the other at $V_0 = 13^{m}3$, which is below this break. These normal points are listed in Table 3 and plotted as an open triangle and an open square, respectively, before correction, and as a filled triangle and a filled square after

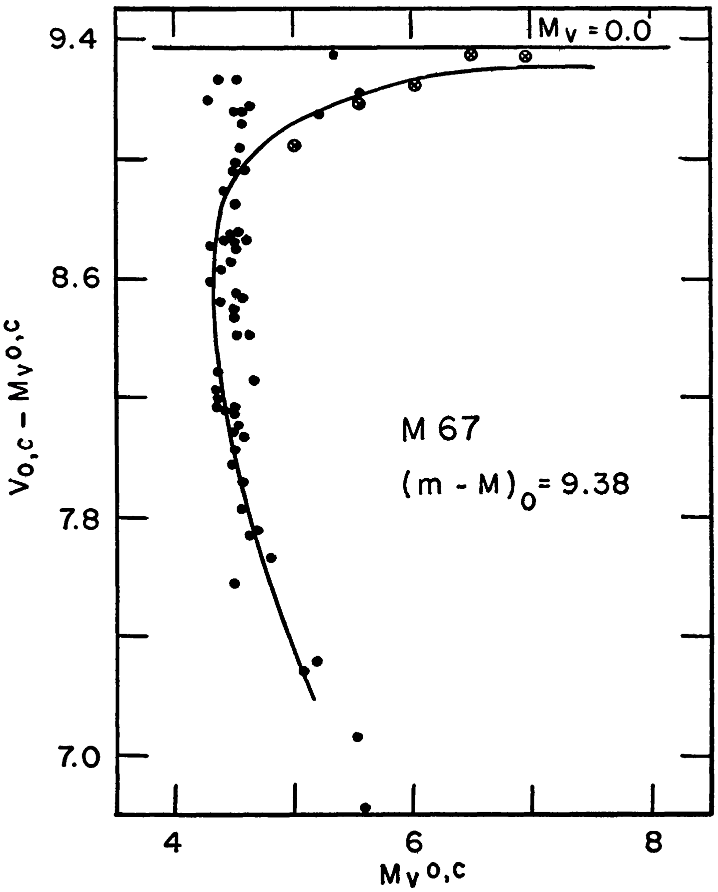

FIG. 6.—The theoretical evolutionary deviation curve compared with observed stars. The true modulus from this fit is $(m - M)_0 = 9.38$.

correction for blanketing effects. The cluster data appear to confirm that obtained from the wide binaries in the collapse of the gravity effect near $B - V = +0^{m}6$ for stars less than $2^{m}0$ brighter than the main sequence.

VI. THE DISTANCE MODULUS AND COMPARISON WITH THEORETICAL EVOLUTIONARY TRACKS

The distance modulus of M67 has previously been estimated by Johnson and Sandage to be $(m - M) = 9^{m}70 \pm 0^{m}10$ by making a fit to the age-zero main sequence after correction for a reddening of $E(B - V) = +0^{m}06$. Another determination was made by Sandage (1962*b*) who obtained $9^{m}58$ by using the method of an evolutionary deviation curve (Johnson 1960) with a curve computed for low-mass stars using an evolutionary track for 1.09 $\mathfrak{M}_{\odot}$ (Hoyle 1959) and with no blanketing corrections. Eggen (1959) found

$m - M = 9^{m}.6 \pm 0^{m}.3$ for $E(B - V) = +0^{m}.06$ and no blanketing corrections, or $9^{m}.0 \pm 0^{m}.3$ for $\delta(U - B) = +0^{m}.06$ and no reddening. Our new results permit a more accurate solution to be made using $E(B - V) = +0^{m}.06$, $\Delta(B - V) = +0^{m}.03$ and the procedure given elsewhere (Sandage 1962*b*, Table 9). The individual stars are plotted as filled circles in Figure 6 and the asymptotic approach of the evolved sequence to the age-zero main sequence is represented by five normal points obtained from the data in Figure 3, *a;* the resulting value of the corrected modulus is $9^{m}.38$. The notation $V_{0,c}$ and $M_V{}^{0,c}$ follows that used previously (Sandage 1962*b*) with the addition of *c* to indicate that the data are corrected for blanketing effects.

The shape of the continuous curve in Figure 6 is governed by the shape of the theoretical evolutionary track based on the model by Hoyle. The close agreement with the ob-

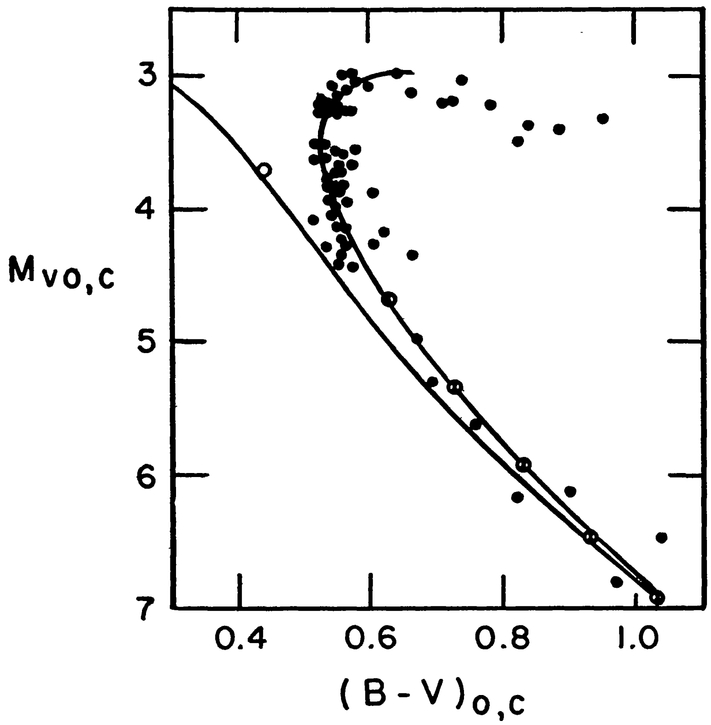

FIG. 7.—The fit of M67 to the age-zero main sequence as transformed from Fig. 6. Blanketing and reddening corrections have been applied to the data. The shape of the solid line through the points is computed from Hoyle's theory of an evolutionary track for a star of 1.09 $\mathfrak{M}_{\odot}$.

servations is evident, except for the stars between $9^{m}.3 > V_{0,c} - M_V{}^{0,c} > 9^{m}.0$, which are closer to the line $M_V = 0$ than predicted by theory. The deviating stars do not rise above the main sequence as rapidly as theory predicts, as can be seen in Figure 7 where the age-zero main sequence, the observations, and the theoretical curve of Figure 6 are shown together in a more familiar form. However, aside from this small deviation, which may be connected with differences in the chemical composition of the model and the cluster stars, the over-all representation of the observations by the evolutionary track in Figure 7 is quite good. Another possibility for the lack of complete agreement involves the accuracy of the transformation of T_e to $B - V$, but discussion of this point is beyond the scope of this paper. Suffice it to say that the M67 stars on the evolving subgiant branch near the main sequence are just cool enough to be beyond the multivalued function $T_e = f(B - V)$ predicted for a range of surface gravities (Sandage 1956, Figs. 1 and 2).

APPENDIX

Table 4 lists data for 13 binary systems which satisfy the condition $+1^{m}.2 > B - V > +0^{m}.35$ and for which one component is a main-sequence star and one an evolved subgiant or giant. The data are taken from a previous study (Eggen 1963*a*) and some unpublished results; the second and third columns list the observed colors, the fourth gives the values of $\delta(U - B)$ relative to the Hyades main-sequence stars, and the last column gives the absolute magnitudes of the components derived from the photometric parallax of the main-sequence component.

TABLE 4

DATA SHOWING EQUALITY OF $\delta(U-B)$ FOR GIANTS AND DWARFS IN BINARIES

Name	$B-V$	$U-B$	$\delta(U-B)$	M_V
ADS 237	0.665	0.18	+0.035	4.1
	0.635	.14	+ .03	5.1
ADS 439	0.885	.43	+ .17	2.9
	0.695	.055	+ .19	6.2
ADS 475 AB	0.73	.30	.00	3.0
C	0.57	.07	+ .03	4.4
ADS 7311 A	0.91	.68	− .02	0.9
B	0.35	.03	.00	3.1
ADS 7961	0.94	.61	+ .11	2.5
	0.58	.01	+ .10	5.1
BDS 6632 A	1.08	.84	+ .14	1.6
B	0.58	.01	+ .10	5.1
HR 5649 A	0.91	.68	− .02	0.7
B	0.48	.02	.00	4.0
ADS 9559	0.96	.67	+ .09	0.8
	0.59	.00	+ .12	5.1
ADS 9799	0.65	.19	.00	3.9
	0.81	.46	− .01	5.9
HR 7908	0.98	.60	+ .20	3.0
	0.63	.00	+ .17	5.7
ADS 15431	0.97	.68	+ .10	2.3
	0.52	.00	+ .05	4.4
HD 196755	0.69	.235	+ .005	3.0
	0.91	.645	+ .015	6.4
ADS 16407	0.92	.56	+ .12	3.0
	0.575	0.03	+0.075	5.0

Because both components of a binary are expected to have the same chemical composition, it follows that the data in Table 4 should provide the relation $\delta(\text{dwarf}) = f[\delta(\text{giant})]$ for stars of the same composition. The result is that $\delta(\text{dwarf}) = \delta(\text{giant})$ for $+0^{m}.20 > \delta(U - B) > -0^{m}.02$ when $B = V$ of the dwarf is between about $+0^{m}.35$ and $+0^{m}.8$. This relation is the one used in the solution of Section III which separates the effects of blanketing and reddening.

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