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COLOR-MAGNITUDE DIAGRAMS FOR FOUR RICH CLUSTERS OF THE LARGE MAGELLANIC CLOUD

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ABSTRACT

Color-magnitude diagrams are presented for four very rich clusters of the Large Magellanic Cloud. Comparisons with theoretical color-magnitude diagrams show good agreement in the location and distribution of stars in the giant regions. All four have nearly identical ages of approximately 5×10^7 years. Each cluster has at least one anomalously luminous giant of intermediate color and $M_v \simeq -5.7$, over a magnitude brighter than both the observed and predicted giant branch.

Subject headings: globular clusters — Magellanic Clouds — stellar evolution

I. INTRODUCTION

A previous paper (hereafter called Paper I, Hodge and Flower 1973) discussed a color-magnitude diagram for the large and populous LMC cluster NGC 2164, for which observations were obtained with the 60-inch (1.5 m) telescope of the Cerro Tololo Inter-American Observatory. This paper presents similar data on the colors and magnitudes for members of three other clusters, NGC 2156, NGC 2159, and NGC 2172. These objects, sometimes called blue globular clusters, are important because, unlike most young clusters studied in our Galaxy, they are rich in giant stars, making it possible to carry out comparisons with theoretical evolutionary calculations for the giant phases of evolution. Improved photometry of NGC 2164 is also included in this paper.

II. MEASUREMENTS

The plates used are all described in Paper I, and all measures were made in a way identical to that for Paper I. Depending on their distance from the plate center, some clusters could not be measured on certain plate pairs because of field effects, and some were measurable only in the outer regions on specific plate pairs. Table 1 lists and describes the clusters and gives information on the number of plates that were usable in each case.

TABLE 1

CLUSTERS AND MEASUREMENTS

Cluster	No. of Stars Measured	No. of Plates
NGC 2156....	65	22
NGC 2159....	60	24
NGC 2164....	68	22
NGC 2172....	41	22

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Reductions of the astrophotometer measures were carried out in the same manner as in Paper I. The measures of plates with exposure times of 10 minutes or less were used if the average V magnitude was brighter than 17.0. Magnitudes fainter than 17.0 from these short-exposure plates were found to be unreliable because of background effects. Each of the long-exposure plates, with exposures of 30 minutes or more, were considered individually for the effects of background and crowding. These long exposure plates were compared with each other to check for systematic effects. We found that the measures from plate pair 5–6

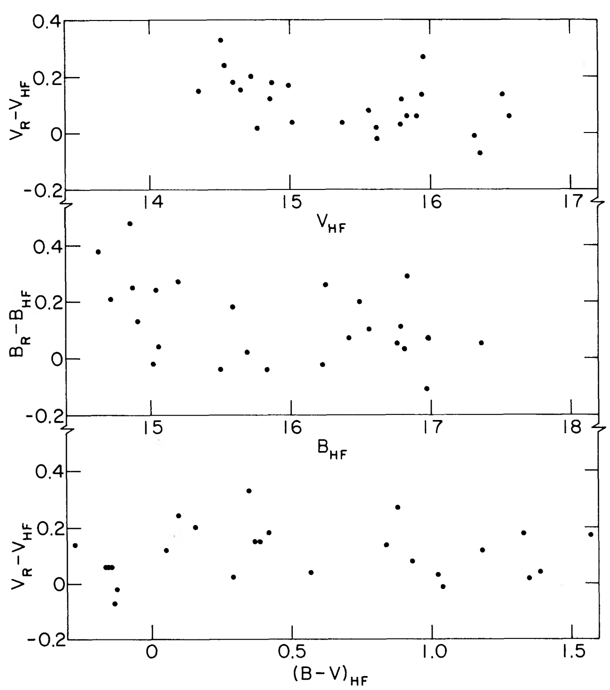

FIG. 1.—Comparison between measures of stars in common in NGC 2164 from Hodge and Flower (1973) and from Robertson (1974*b*).

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TABLE 2

Star	V	N	σ(v)	B-V	N	σ(B-V)	Star	V	N	σ(v)	B-V	N	σ(B-V)	Star	V	N	σ(v)	B-V	N	σ(B-V)
NGC 2156																				
1	14.71	10	0.12	0.07	10	0.12	23	17.44	2	0.06	-0.09	2	0.04	45	16.60	2	0.06	-0.16	2	0.04
2	17.29	3	0.09	-0.13	2	0.09	24	17.95	3	0.14	-0.07	3	0.13	46	16.66	3	0.12	-0.12	3	0.04
3	16.77	5	0.06	-0.03	5	0.19	25	16.79	5	0.08	-0.04	5	0.13	47	17.30	3	0.09	-0.23	3	0.24
4	16.75	5	0.06	1.24	5	0.07	26	16.69	2	0.15	-0.27	2	0.27	48	15.65	8	0.14	0.83	6	0.07
5	17.16	3	0.07	-0.16	3	0.11	27	16.61	2	0.02	-0.08	1	--	49	17.63	2	0.11	1.62	2	0.04
6	16.64	7	0.09	-0.06	7	0.09	28	17.08	3	0.12	-0.08	3	0.12	50	18.15	2	0.07	1.12	1	--
7	18.25	2	0.08	-0.26	2	0.04	29	17.34	3	0.08	-0.06	3	0.14	51	16.52	5	0.12	-0.06	4	0.10
8	17.86	3	0.13	1.27	2	0.08	30	14.76	9	0.16	0.15	7	0.10	52	16.62	3	0.07	-0.03	2	0.19
9	16.66	7	0.08	-0.02	7	0.08	31	17.28	3	0.11	-0.19	3	0.14	53	16.84	1	--	0.00	1	--
10	16.88	1	--	-0.22	1	--	32	17.98	3	0.12	-0.03	2	0.06	54	16.59	3	0.06	-0.06	3	0.11
11	16.62	3	0.11	-0.02	3	0.17	33	16.54	3	0.05	-0.03	3	0.10	55	14.93	6	0.07	0.27	3	0.05
12	16.91	3	0.15	0.03	2	0.12	34	16.76	2	0.03	-0.11	2	0.03	56	15.43	4	0.07	0.39	3	0.02
13	17.91	3	0.13	-0.08	3	0.15	35	16.84	3	0.16	-0.14	3	0.17	57*	14.92	-	--	0.21	-	--
14	17.81	3	0.08	-0.13	3	0.10	36	15.98	8	0.07	1.03	6	0.06	58	14.84	-	--	0.29	-	--
15	18.33	2	0.14	-0.24	2	0.08	37	16.80	5	0.08	-0.06	5	0.14	59	14.48	3	0.11	0.52	3	0.10
16	17.57	2	0.06	-0.21	2	0.07	38	17.96	2	0.11	-0.04	1	--	60*	13.63	-	--	0.49	-	--
17	16.07	7	0.06	0.03	6	0.03	39	17.41	2	0.10	-0.08	1	--	61	15.37	6	0.08	0.96	4	0.18
18	16.88	3	0.06	0.00	3	0.18	40	17.54	3	0.07	-0.11	2	0.05	62	15.86	5	0.11	-0.22	4	0.11
19	16.92	1	--	0.24	1	--	41	16.99	5	0.08	1.45	3	0.09	63	16.35	2	0.03	-0.40	2	0.03
20	16.53	3	0.06	-0.15	3	0.13	42	18.17	2	0.07	-0.31	1	--	64	16.58	1	--	-0.40	1	--
21	16.78	1	--	0.00	1	--	43	16.57	3	0.29	-0.26	3	0.18	65	16.47	2	0.04	-0.24	1	--
22	17.56	3	0.09	-0.12	3	0.12	44	16.72	3	0.09	-0.07	3	0.19							
NGC 2159																				
1	16.77	7	0.13	0.07	6	0.06	21	18.21	3	0.14	-0.25	3	0.26	41	16.75	5	0.10	1.65	3	0.11
2	18.50	2	0.09	0.93	1	--	22	18.66	2	0.12	-0.19	2	0.03	42	16.74	5	0.11	1.66	3	0.13
3	16.61	7	0.07	-0.07	7	0.07	23	17.69	3	0.10	-0.25	3	0.19	43	16.37	6	0.08	0.92	6	0.17
4	18.83	2	0.13	-0.19	2	0.05	24	16.96	3	0.14	-0.15	2	0.15	44	17.16	3	0.07	-0.06	3	0.13
5	17.67	3	0.08	-0.10	3	0.10	25	17.69	3	0.07	-0.13	2	0.06	45	16.82	5	0.10	-0.06	4	0.14
6	18.42	2	0.17	-0.16	2	0.09	26	17.66	3	0.08	-0.20	2	0.06	46	17.68	3	0.08	-0.18	2	0.05
7	16.74	4	0.15	-0.16	3	0.22	27	18.49	2	0.09	-0.19	1	--	47	17.87	3	0.10	-0.16	3	0.10
8	17.25	3	0.08	-0.13	3	0.13	28	17.32	2	0.19	-0.34	1	0.07	48	18.48	2	0.11	-0.25	1	--
9	15.29	10	0.09		10	0.13	29	17.48	2	0.21	-0.19	2	0.22	49	14.65	7	0.12	0.39	7	0.09
10	16.87	1	--	--	-	--	30	17.64	3	0.06	-0.04	3	0.08	50	13.31	5	0.05	0.91	5	0.12
11	18.60	1	--	--	-	--	31	18.46	2	0.07	-0.19	2	0.01	51	15.84	3	0.16	1.02	3	0.17
12	17.95	2	0.08	-0.34	1	--	32	17.50	3	0.07	-0.05	3	0.08	52*	15.62	2	--	--	2	--
13	18.82	2	0.15	-0.32	2	0.02	33	17.74	3	0.07	-0.12	3	0.06	53*	15.77	3	--	0.39	3	--
14	18.94	2	0.04	-0.03	2	0.07	34	18.49	2	0.05	-0.11	2	0.06	54*	14.76	3	--	0.94	3	--
15	18.74	2	0.05	-0.11	2	0.08	35	17.28	3	0.06	-0.12	3	0.10	55*	15.31	2	--	1.15	2	--
16	18.71	2	0.11	-0.14	2	0.06	36	17.34	3	0.05	-0.05	3	0.09	56	15.77	2	0.24	-0.11	2	0.33
17	16.52	7	0.09	0.49	7	0.13	37	18.83	2	0.14	-0.24	1	--	57*	14.61	3	--	0.82	3	--
18	18.91	2	0.07	-0.25	1	--	38	16.59	6	0.07	0.63	6	0.11	58*	14.62	6	0.17	1.05	3	0.19
19	18.57	2	0.14	-0.38	2	0.09	39	16.24	6	0.12	1.09	6	0.15	59	16.68	2	0.05	-0.13	1	--
20	18.15	3	0.07	-0.09	3	0.11	40	16.56	7	0.05	0.87	7	0.11	60	16.38	4	0.21	-0.27	3	0.13
NGC 2164																				
1	15.02	8	0.15	1.30	6	0.28	24	15.56	8	0.20	0.16	6	0.05	47	16.60	4	0.07	-0.06	4	0.10
2	14.88	9	0.13	0.21	10	0.09	25	15.34	3	0.17	--	-	--	48	16.02	5	0.05	0.85	5	0.07
3	14.77	10	0.16	0.46	9	0.04	26*	15.52	4	0.14	0.49	2	0.05	49	16.78	4	0.04	1.63	4	0.17
4	14.68	6	0.17	0.39	4	0.17	27	15.31	3	0.13	1.24	3	0.20	50	16.53	5	0.14	0.92	4	0.08
5	15.13	6	0.12	1.53	3	0.17	28c	14.38	4	0.14	0.01	2	0.12	51	16.97	2	0.05	-0.01	1	--
6*	13.14	5	0.13	0.28	4	0.09	29*	14.56	2	0.16	0.02	2	0.08	52	14.79	6	0.14	0.43	7	0.17
7	15.48	7	0.14	1.36	5	0.08	30*	13.26	3	0.27	1.30	2	0.04	53	16.81	3	0.01	-0.03	3	0.13
8	15.72	9	0.08	1.32	7	0.06	31*	13.38	2	0.28	0.99	2	0.45	54	16.80	3	0.19	-0.28	4	0.11
9	14.70	9	0.15	0.16	9	0.16	32*	13.38	2	0.13	0.99	1	--	55	17.07	3	0.04	1.53	4	0.13
10	14.54	10	0.07	0.41	10	0.07	33*	15.40	2	0.26	0.00	2	0.18	56	16.45	2	0.01	-0.90	2	0.13
11	15.66	3	0.06	0.93	2	0.24	34	16.67	2	0.06	-0.27	2	0.12	58	16.55	2	0.01	-0.44	2	0.11
12	14.67	3	0.19	0.11	3	0.06	35	16.77	2	0.03	-0.04	2	0.07	59	17.00	4	0.09	1.30	3	0.05
13*	16.03	2	0.01	-0.32	2	0.18	36	16.75	2	0.04	-0.19	1	--	60	16.40	5	0.07	-0.05	5	0.09
14c	15.14	3	0.14	0.74	2	0.15	37	15.86	2	0.01	-0.10	1	--	61	15.98	5	0.11	-0.07	5	0.08
15*	15.12	3	0.07	0.02	2	0.03	38	16.63	2	0.02	-0.25	1.5	0.11	62	17.05	3	0.11	-0.32	4	0.16
16	14.49	3	0.12	0.07	3	0.14	39	16.20	4	0.22	-0.23	4	0.03	63	16.69	3	0.08	-0.10	3	0.22
17*	15.72	3	0.09	-0.04	3	0.22	40	17.11	3	0.07	-0.09	4	0.10	64	16.37	5	0.17	1.03	5	0.18
18*	14.83	3	0.17	0.66	3	0.10	41	17.41	3	0.07	0.99	4	0.06	65	17.39	3	0.06	-0.18	4	0.12
19	14.58	3	0.14	0.34	3	0.05	42	18.00	3	0.14	-0.06	4	0.16	66	16.43	4	0.33	-0.22	3	0.12
20*	14.39	3	0.15	0.57	3	0.02	43	16.55	6	0.15	-0.18	6	0.17	67	17.52	3	0.07	-0.14	4	0.12
21	15.87	5	0.09	1.01	4	0.10	44	17.40	3	0.08	-0.14	4	0.11	68	15.91	6	0.09	-0.06	6	0.05
22	16.02	5	0.19	0.88	4	0.07	45	17.44	3	0.08	-0.12	4	0.10							
23	15.01	6	0.08	0.11	6	0.06	46	15.88	6	0.13	1.16	5	0.05							
NGC 2172																				
1	16.45	6	0.09	0.31	5	0.06	15	17.84	3	0.04	-0.18	4	0.04	29	17.52	2	0.05	-0.34	1	0.02
2	17.27	2	0.04	-0.01	1	--	16	17.52	2	0.03	-0.05	2	0.06	30	16.52	4	0.30	-0.23	4	0.25
3	16.87	3	0.11	0.03	2	0.01	17	13.52	6	0.04	0.39	4	0.06	31	17.42	1	--	-0.05	1	--
4	16.67	3	0.05	-0.12	2	0.02	18	15.47	10	0.09	1.07	7	0.04	32	17.44	1	--	-0.16	1	--
5	17.79	2	0.05	-0.19	2	0.08	19	15.68	3	0.11	0.51	2	0.12	33	15.66	4	0.12	1.19	4	0.05
6	17.41	1	--	-0.19	1	--	20	15.79	5	0.03	1.06	4	0.05	34	16.67	1	--	0.90	1	--
7	17.79	1	--	-0.21	1	--	21	15.52	1	--	1.11	1	--	35	16.80	1	--	0.32	1	--
8	17.11	2	0.00	-0.15	1	--	22	15.19	10	0.07	0.42	10	0.10	36	14.54	6	0.09	0.22	4	0.05
9	17.25	1	--	-0.21	1	--	23	17.50	1	--	-0.17	1	--	37	15.69	2	0.03	-0.41	2	0.24
10	16.66	2	0.17	--	-	--	24	17.53	1	--	-0.31	2	0.01	38	16.04	2	0.04	-0.12	2	0.04
11	16.83	2	0.03	-0.16	2	0.25	25	17.24	1	--	--	-	--	39	16.18	2	0.14	0.56	2	0.14
12	17.78	1	--	0.39	1	--	26	16.27	2	0.20	--	-	--	40	15.71	1	--	--	-	--
13	16.23	6	0.20	-0.19	5	0.11	27	16.66	3	0.19	-0.19	3	0.20	41	16.04	1	--	--	-	--
14	16.19	6	0.15	-0.12	5	0.05	28	17.45	2	0.05	0.05	1	0.13							

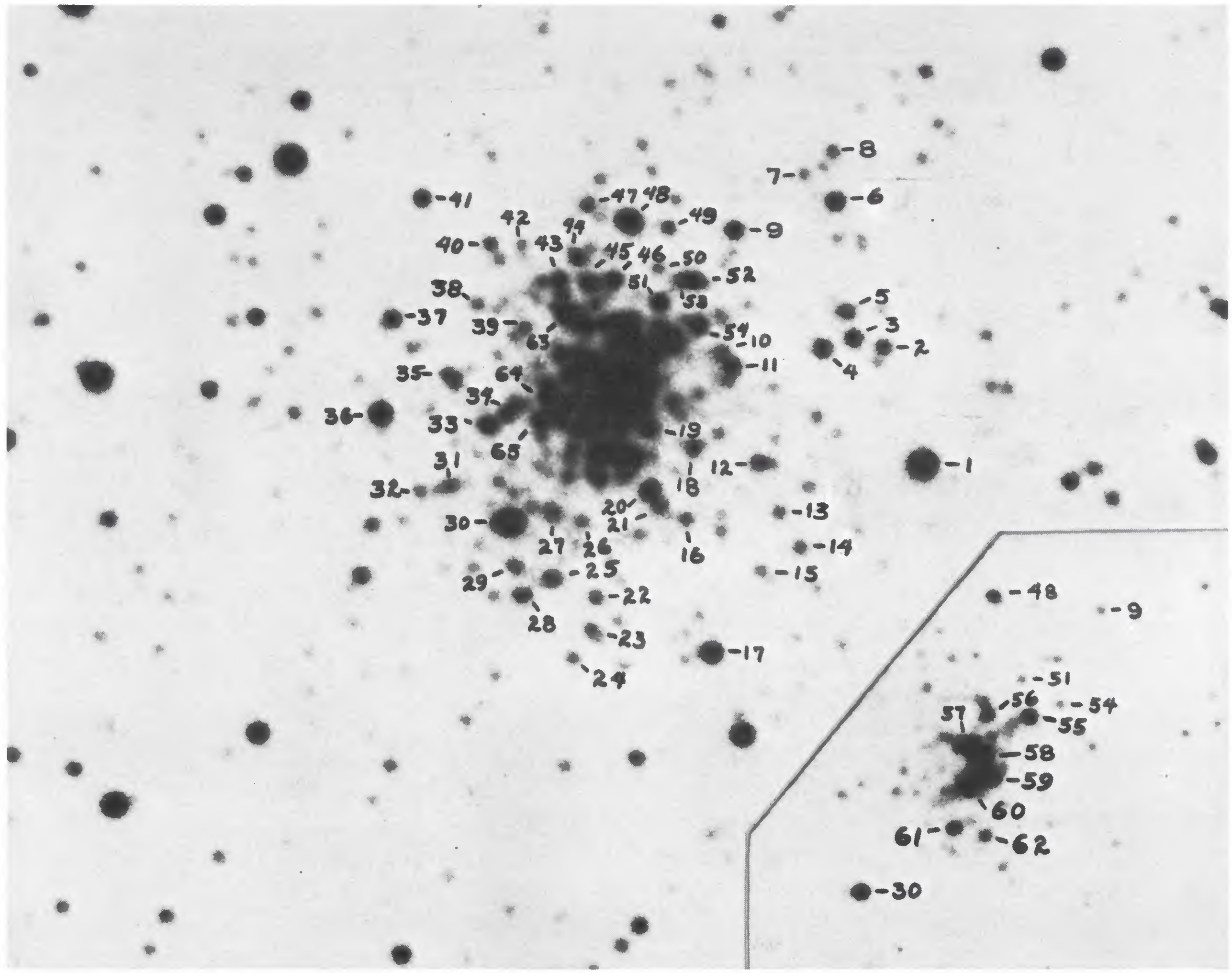

FIG. 2.—NGC 2156 from a V plate taken with the Cerro Tololo 60-inch telescope

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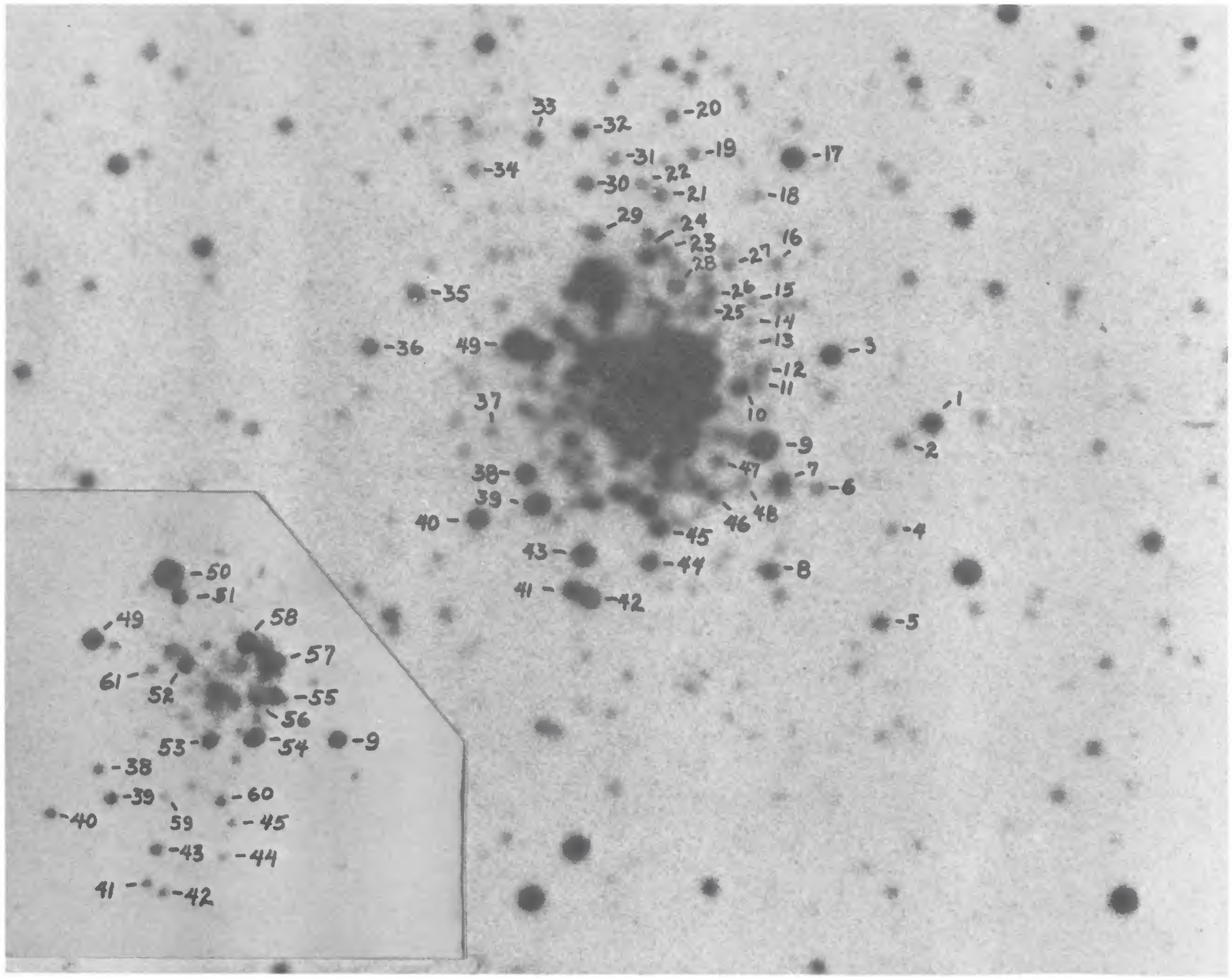

FIG. 3.—NGC 2159 from a *V* plate taken with the Cerro Tololo 60-inch telescope

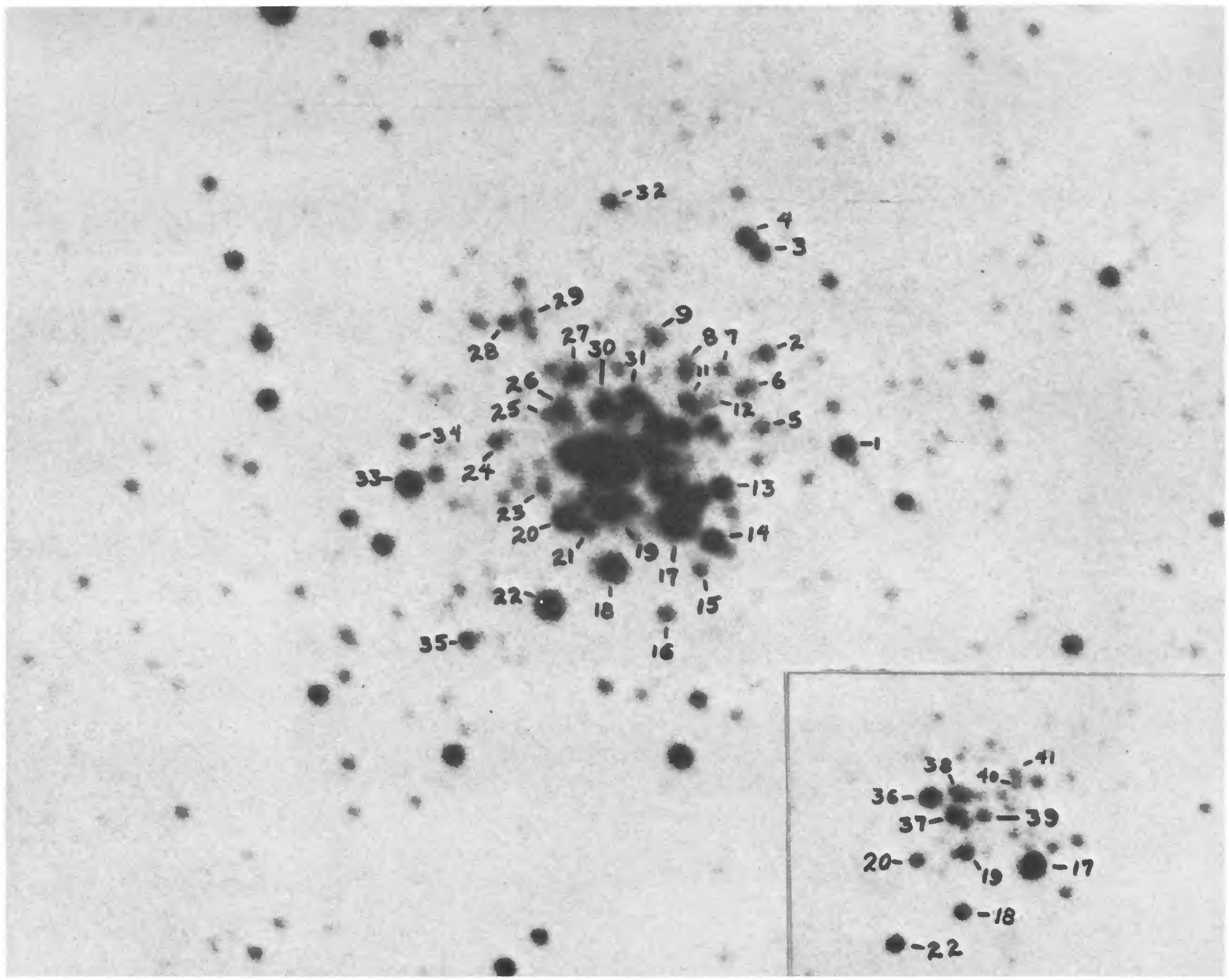

FIG. 4.—NGC 2172 from a *V* plate taken with the Cerro Tololo 60-inch telescope

were not reliable for NGC 2172, and for the inner portion of NGC 2156.

The data for NGC 2164, given in Paper I, are rediscussed here after being adjusted for color and magnitude equations. Least-squares solutions for the second set of plates, taken with the field corrector, give

$$B_{pe} = B_{pg} - 0.07(B - V)_{pg} + 0.06$$

and

$$V_{pe} = V_{pg} = 0.06(B - V)_{pg} - 0.03\,,$$

for color equations. This least-squares solution excluded plates with exposure times of 2 minutes or less, since on these plates there were too few standards brighter than the plate limit usable for a good determination. Application of these corrections to the data of Paper I for NGC 2164 improves agreement with the theoretical models and largely resolves the discrepancy of the main-sequence colors. With these corrections, we have compared our data with that of Robertson (1974*b*), kindly sent to us in advance of publication. His C-M diagram of NGC 2164 has 25 stars that are common to both programs, compared in figure 1. The comparison shows that there are systematic differences between the two sets of magnitudes and that they are not correlated with color. These differences are greatest at brighter magnitudes and nearly zero at the magnitude limit. To bring the data into better agreement, we have included his magnitudes for NGC 2164 stars in our final analysis of the data for the clusters of this paper. The resulting final magnitude equations are:

$$V' = V + 0.07(17.0 - V)\,,$$

$$B' = B + 0.07(18.0 - B)\,,$$

approximately valid over the interval $14 < V < 17$; $15 < B < 18$.

For all clusters the average V and $B - V$ and their standard deviation were calculated for each star. If a magnitude or color was found to be greater than 3 times the standard deviation, it was not included in the averages. Table 2 gives the magnitudes and colors, and figures 2 to 4 identify the measured stars in NGC 2156, 2159, and 2172.

Tests have shown that vignetting effects on plates taken with this telescope are less than 0.1 mag at the edges (Graham 1972). Field effects, however, due to uneven emulsion sensitivity or to the uneven unresolved LMC background can amount to as much as 0.1 mag. Therefore, the astrophotometer measures for these clusters are expected to be mutually consistent within a given cluster, but may be systematically off by perhaps 0.1 mag.

III. RESULTS

Figures 5 to 8 give the color-magnitude diagrams for the clusters, which are all four remarkably similar. Comparisons with theoretical models using Schlesinger's (1969) theoretical cluster color-magnitude diagrams give essentially identical estimates of turnoff masses and ages for the clusters, 7 $M_\odot$ and 5×10^7 years, respectively. The solid lines in the figures are based on Iben's (1967) calculations, after interpolation to 7 $M_\odot$, as in Paper I. Discussions of the individual clusters follow.

a) *NGC 2156* (Fig. 5)

This diagram is quite similar to that for NGC 2164, although it has fewer giants (~25 for NGC 2164, ~10 for NGC 2156). It has a concentration at the blue end of the helium-burning track, consisting of six stars with colors that agree well with the theoretical tracks, which also show a concentration at this location (Schlesinger 1969). At the red turnaround point there is, however, no conspicuous concentration. Three of the faint red stars are at some distance from the cluster center, and are possibly field stars. The open box at the top of the diagram represents a star at absolute magnitude of approximately −5.6, a magnitude brighter than any other of the giants. It was measurable on only one plate pair, so uncertainties in its magnitude and color are unknown, probably large, on the order of 0.3 mag or so. It is located right at the center of the cluster. It might be considered a field star, but the presence of similarly anomalous giants, occurring at the centers of the other clusters (table 3), makes it much more reasonable to accept that these stars are members and that they are in some superluminous stage of evolution, not yet reached in the theoretical calculations. Alternatively, they may be stragglers, which formed more recently than the cluster as a whole.

b) *NGC 2159* (Fig. 6)

This cluster's C-M diagram is also similar to that of NGC 2164. There are four stars near the red tip of the branch (and two somewhat beyond the theoretical tip), two stars at the blue tip, and four that lie near the end of the theoretical tracks as plotted.

c) *NGC 2164* (Fig. 7)

The newly plotted diagram is nearly identical to that given in Paper I, except that the color and magnitude equations have led to better detailed agreement with the theoretical curves, especially on the main sequence and at the blue turnaround on the giant branch.

TABLE 3

SUPERLUMINOUS GIANTS

Cluster	Star No.	M_v*	$B - V$
2156..........	60	−5.4	+1.0
2159..........	50	−5.7	+0.9
2164..........	6	−5.9	+0.2
	30	−5.9	+1.4
	31	−5.7	+1.0
	32	−5.7	+1.0
2172..........	17	−5.5	+0.4

* An apparent modulus of 19.05 was assumed.

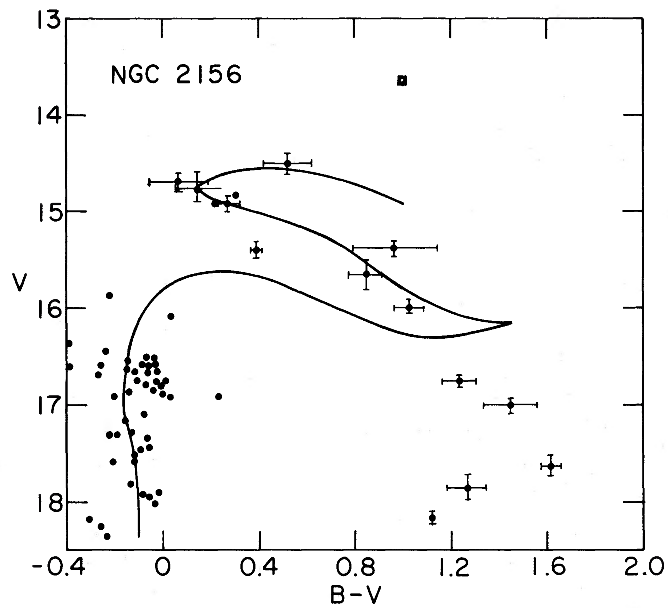

FIG. 5.—C-M diagram for NGC 2156. Error bars of main-sequence stars were omitted due to crowding of the diagram. Three of the faint red stars and two of the stars at the second turnoff are distant from the cluster and thus are possibly field stars. The line is a 5 × 10^7 yr isochrone from Schlesinger's (1969) curves, based on Iben's (1967) model calculations, adjusted as in Paper I.

d) *NGC 2172* (Fig. 8)

This cluster's C-M diagram is similar to the above, though the data show more scatter and larger measured errors for the main-sequence stars, apparently because of crowding of the fainter stars. There are fewer giants than in NGC 2164, probably nine among the plotted stars. Four are near the red tip, making up an accumulation there, as predicted by the theoretical models. The blue turnaround area of the giant branch has only two stars. There is a superluminous star above the giant branch, as found in the other clusters (table 3).

The theoretical evolutionary C-M diagrams used

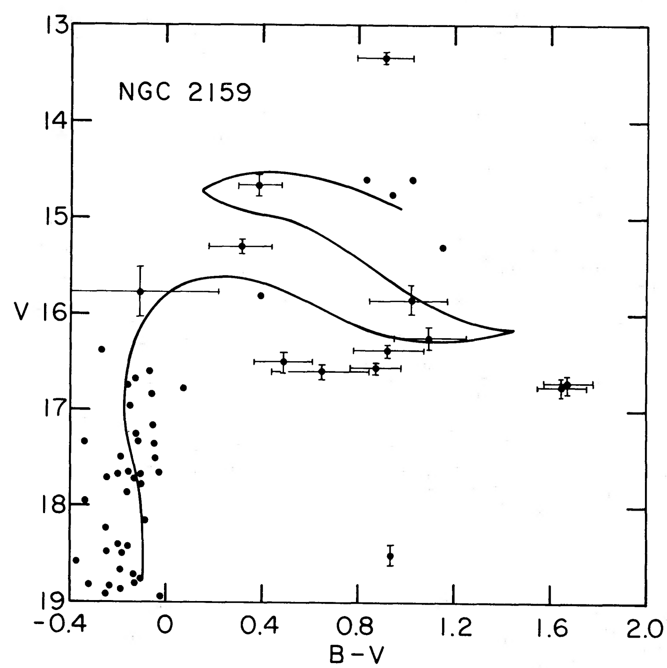

FIG. 6.—C-M diagram for NGC 2159. Isochrone is same as in fig. 5.

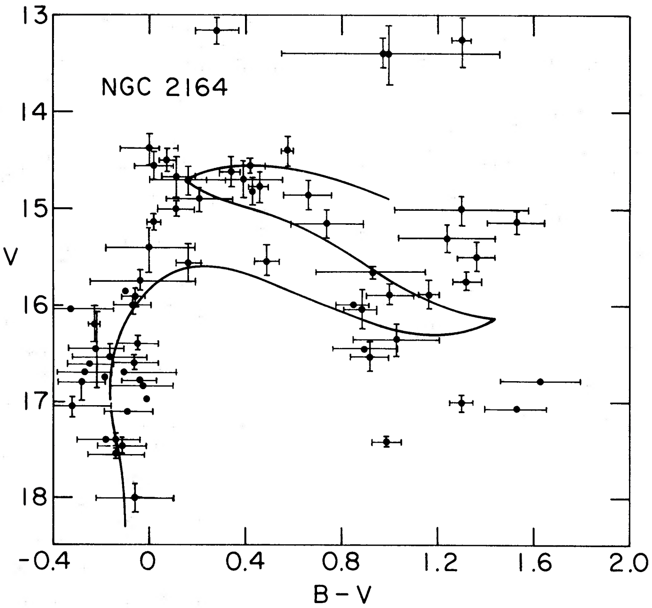

FIG. 7.—C-M diagram for NGC 2164. Isochrone is same as in fig. 5.

here (Schlesinger 1969) show accumulations of giants at the red end of the giant branch and at the blue, helium-burning turnaround. Schlesinger's cluster model B, for example, has six stars grouped between $B - V = +1.0$ and $+1.4$ at the red end and eight stars grouped between $B - V = +0.1$ and $+0.5$ at the blue turnaround. In general the observed clusters also show this tendency, with some interesting deviations in detail. NGC 2164 and NGC 2172 seem to agree with the model, but NGC 2156 and NGC 2159 seem to have significant differences from the model, in opposite sense. The giant branch of NGC 2156 is relatively depleted at the red turnaround, while that of NGC 2159 is depleted at the blue.

Robertson (1974*a*) has discussed the ratio, t_{br}, of the number of blue giants to the number of red giants for the clusters in his study. Having pointed out (Robertson 1972) the sensitivity of this ratio to abundances, he makes tentative conclusions about Y and Z for some of the clusters. The average for his clusters is $t_{br} = 0.7$.

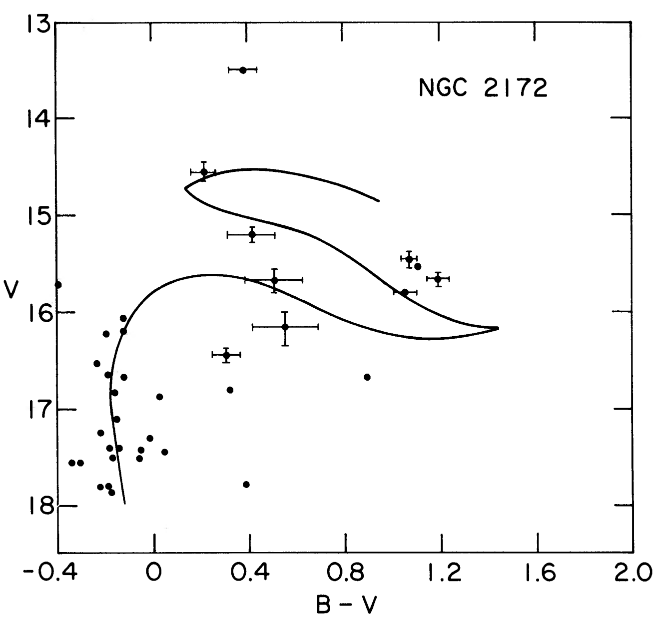

FIG. 8.—C-M diagram for NGC 2172. Isochrone is same as in fig. 5.

This shows better agreement with Cox-Stewart opacities than with Keller-Meyerott opacities, although the dependency of t_{br} on both abundances and opacities makes interpretation uncertain. We derive values for t_{br} of 2.0 ± 0.3 for NGC 2156, 0.3 ± 0.2 for NGC 2159, 1.0 ± 0.4 for NGC 2164, and 0.5 ± 0.4 for NGC 2172. Those for NGC 2164 and NGC 2172 are not significantly different from Robertson's average value, but those for NGC 2156 and NGC 2159 seem to show real differences. If these differences are ascribed to different Z values for the clusters, the qualitative conclusion is that NGC 2156 has unusually high Z while for NGC 2159, Z is unusually low. These conclusions must remain tentative until a more complete array of models is available (we are calculating these with Paczynski's program), and until more accurate photometry is possible, using the larger telescopes soon to be available in the southern hemisphere.

In summary, we have obtained color-magnitude diagrams for four "blue globular" clusters of the LMC. Comparisons with Iben's models indicate good agreement, both in shape and in distribution of stars on the giant branch. There are, however, superluminous, intermediate-color giants lying considerably above the giant branch in all of the clusters. All four clusters are of very nearly the same age (5×10^7 yr). This is significant in light of the results presented in another paper (Baird *et al.* 1974), which shows that many of the smaller, "open" clusters in this area of the Cloud also have this age.

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Note added in proof.—Since writing this paper, one of us has computed new models from Paczynski's programs and has derived a series of isochrones intermediate in age between those of Schlesinger (1969). Comparison with the C-M diagrams indicates: (1) the main sequence fits better if Robertson's (1974*b*) magnitudes are *not* included with ours in the photometric reductions, and (2) the ages are probably somewhat smaller than derived above, more nearly 3×10^7 years.

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