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METAL-RICH GLOBULAR CLUSTERS IN THE GALAXY. III. THE "X-RAY" GLOBULAR CLUSTER NGC 6441

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ABSTRACT

From a photoelectric and photographic investigation in the *UBV* system of the very compact, low galactic latitude, southern globular cluster NGC 6441, we have found characteristics in the C-M diagram that are in accord with observations of the most metal-rich globular clusters in the Galaxy. After an extensive discussion of the problem of isolating the cluster stars from the field stars, and of the problem of determining $E(B-V)$, we adopt $E(B-V) = 0.46 \pm 0.15$ mag. If $M_{V,\mathrm{HB}} = +0.9$ mag, then $(m-M)_0 = 14.7 \pm 0.3$ mag. This makes NGC 6441, one of the intrinsically brightest globular clusters in the Galaxy, consistent with the large mass determined recently by Illingworth. However, no unusual features were detected in its C-M diagram that might account for its appearing within the error box of the 3U 1746−37 X-ray source, except possibly the anomalous position of V6 in the diagram. It is also found that NGC 6441 has a normal M/L ratio, and that, if our adopted reddening is correct, it is at perigalacticon.

Subject headings: clusters: globular — stars: abundances — stars: Population II — X-rays: sources

I. INTRODUCTION

Our studies of the metal-rich globular clusters in the Galaxy are aimed at learning more about the chemical evolution of the Galaxy in its formative stages, by further illuminating the connection between the halo of the Galaxy and the flattened disk component. As part of the long-range study results have been presented to date for NGC 6352 (Hartwick and Hesser 1972 [Paper I]), a cluster thought from *UBV* photometry to have a disklike [Fe/H] ratio, and NGC 104 or 47 Tucanae (Hartwick and Hesser 1974 [Paper II]), a cluster with [Fe/H] = −0.48 referred to the Sun. To continue our investigations of this class of objects, NGC 6441 [$\alpha(1975) = 17^{\mathrm{h}}48^{\mathrm{m}}.5$, $\delta(1975) = -37°02'$; $l = 353°$, $b = -5°$] was chosen for study, because both its late integrated spectral type of G4 (Kinman 1959) and its relatively high value of $Q = -0.11$ (van den Bergh 1967) suggest that it may be an extremely metal-rich object. Since initiation of our observations, additional reasons for study of NGC 6441 have developed: a recent study of the velocity dispersion in the cluster by Illingworth (1973) has revealed that NGC 6441 is among the most massive clusters in the Galaxy; furthermore, NGC 6441 is one of the few clusters found within the error box of an *Uhuru* X-ray source, making a good color-magnitude diagram of potential use should the source be identified eventually with a cluster member or with the cluster itself.

II. OBSERVATIONS

NGC 6441 proved to be a formidable object to study, because of both the faintness of the cluster stars and the high degree of central concentration of the cluster. (The concentration class of NGC 6441 is given as III on a scale of I to XII [Arp 1965*a*].) In this section we will describe first the calibrating photoelectric sequence and then the photographic photometry that led to the final C-M diagram.

a) *Photoelectric*

For calibration of the photographic plates, a sequence consisting of 45 photoelectrically measured stars was obtained from observations in the 1969–1973 seasons utilizing the 41-cm, 91-cm, and 1.5-m telescopes on Cerro Tololo. Measurements prior to the 1973 season were obtained with single channel, refrigerated 1P21 photometers, while in 1973 measures were obtained with the three-channel photometer used in its simultaneous two-channel, *B*, *V* mode (with an appropriate beam-splitter and two ITT FW 130 (S-20) photomultipliers). Data obtained prior to the 1972 season were registered on strip-chart paper after charge integration, while in 1972 and 1973 the pulse-counting facilities of the CTIO data system (Lasker 1971) were utilized. The photoelectrically measured

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TABLE 1

PHOTOELECTRICALLY-MEASURED *UBV* SEQUENCE STARS FOR NGC 6441

Star	V_{pe}	$(B-V)_{pe}$	$(U-B)_{pe}$	$n(V/B-V/U-B)_{pe}$	V_{pg}	$(B-V)_{pg}$
B.......	10.16	0.08	−0.10	5/5/5		
C.......	12.54	0.40	0.17	6/6/6		
E.......	10.98	0.65	0.15	5/5/4		
F.......	12.72	0.39	0.24	5/5/4		
G.......	10.96	1.88	2.27	7/7/4		
H.......	10.25	1.75	1.63	3/3/3		
I.......	11.74	0.20	0.16	3/3/3		
1.......	11.70	1.07	0.77:	5/5/3	11.68	1.06
2.......	12.91	1.89		3/3/0	13.03	1.76
3.......	12.44	0.71	0.26	9/9/8	12.39	0.66
4.......	14.76	0.79	0.29	2/2/2	14.79	0.68
5.......	13.89	2.21	2.44	6/6/1	14.05	2.26
6.......	14.04	0.70	0.64	2/2/2	14.10	0.59
7.......	15.91	2.17		3/3/0	15.91	2.04
8.......	15.69	1.65		2/2/0	15.76	1.66
9.......	14.30	0.80	0.34	2/2/2	14.40	0.68
10.......	16.23	1.73		2/2/0	16.21	1.89
11.......	15.76	0.94		1/1/0	15.82	1.00
12.......	16.28	1.97		1/1/0	15.97	2.07
14.......	16.96	1.47		1/1/0	17.08	1.42
17.......	14.27	0.58	0.38	3/3/3	14.30	0.48
18.......	15.94	1.90		3/3/0	16.00	1.91
20.......	16.74	1.09		3/3/0	16.66	1.18
21.......	16.46	1.95		3/3/0	16.49	1.95
30.......	15.77	1.74		1/1/0	15.58	1.77
31.......	15.56	0.85		2/2/0	15.36	0.95
33.......	14.95	1.05		2/2/0	14.81	1.10
35.......	16.05	2.06		1/1/0	16.05	2.11
37.......	16.17	1.79		1/1/0	16.14	1.85
38.......	16.12	1.02		2/2/0	16.02	1.07
39.......	16.90	1.63		1/1/0	17.09	1.55
40.......	16.03	2.14		2/2/0	16.22	2.31
41.......	17.50	1.77		1/1/0	17.53	1.41
42.......	16.69	1.61		1/1/0	16.73	1.59
43.......	16.07	0.92		1/1/0	16.10	0.89
44.......	15.40	1.05		2/2/0	15.47	0.93
45.......	17.59	0.95		1/1/0	17.47	1.08
49.......	15.95	1.89		2/2/0		
51.......	15.58	1.64		2/2/0	15.52	1.66
53.......	15.49	2.10		1/1/0	15.65	2.07
107.......	13.59	1.63		1/1/0	13.58	1.55
111.......	15.20	1.94		1/1/0	15.11	1.99
112.......	15.53	1.11		1/1/0	15.53	1.14
115.......	16.64	1.62		1/1/0	16.65	1.89
3501.......	14.72	1.92		1/1/0	14.75	1.88

stars were selected with care from deep plates, and sky measurements were made in two or more adjacent areas whenever possible. On each night, standards, selected as described in Hartwick *et al.* (1972) from the lists of Cousins and Stoy (1963) and Cousins *et al.* (1966), were observed. Secondary standards near NGC 6352 (Paper I), and in the 1969–1971 seasons near NGC 4372 (Hartwick and Hesser 1973), were also observed to guarantee that the measures of the different metal-rich globular clusters would be on the same system. The error in transformation of the standards to the *UBV* system is less than 0.02 mag for all measured magnitudes and colors, but we must point out that some of the NGC 6441 stars, due to interstellar reddening, are redder than the reddest standard stars, so some undetected but hopefully small systematic errors in the transformations *may* be present for them.

In Table 1 we present for each photoelectrically measured star the V, $B-V$, and $U-B$ photoelectric values, the number of nights on which the star was observed in each color, and, for those stars observed photographically, the resultant V_{pg} and $(B-V)_{pg}$ values following transformation and correction for color equations. The stars whose *UBV* values are given in Table 1 are identified in Figure 1 (Plate 1).

Of the stars in Table 1, two have discordant observations and may be variables. Star 40 was photoelectrically measured to have V and $B-V$ values, respectively, of 16.21 and 1.98 mag on 1972 June 18 and 15.85 and 2.30 mag on 1973 June 1. Furthermore, the standard errors of the photographic values for star 40 were found to be 4 times the median value in both V_{pg} and $(B-V)_{pg}$. Star 12, which was measured photoelectrically on one night only, shows a 0.3 mag residual between photoelectric and photographic V

magnitude values; the photographic values alone, however, show low scatter.

We may attempt estimation of the quality of the sequence presented in Table 1 in two ways. First, for those 28 photoelectrically measured stars for which more than one measure are available, we find median values of the error of a *single* measure to be of the order of 0.025 mag in V and $B - V$ and 0.05 mag for $U - B$ for stars whose V magnitudes are brighter than 15.0; while those stars whose magnitudes lie fainter than 15.0 show median errors in V and $B - V$ of about 0.045 mag. The relatively large errors in $U - B$ of the brighter group reflect principally the errors in measurement of the secondary standards (the lettered stars and stars 1 and 3 of Table 1) that were observed primarily with the 41-cm telescopes, for which the U magnitudes were often quite faint; sufficient observations were obtained, however, to give confidence in the mean values. Next, we may compare the differences between the photoelectric values of Table 1 and the photographic values discussed below. For stars brighter than the fifteenth magnitude, the median absolute value of the residual is 0.05 mag in V and 0.10 mag in $B - V$, while for the fainter stars the median residual is 0.06 mag in both V and $B - V$. Considering the crowded nature of the field, the above mentioned errors do not seem unreasonable.

b) *Photographic*

Approximately 700 stars were measured photographically using 103a-O + GG13 and 103a-D + GG14 plate material obtained with the 1.5-m telescope. The program stars were measured with an iris diaphragm photometer on up to eight plates in V and seven in B; the exposure times ranged from 10 to 45 min. The eight V plates included four at the f/7.5 Ritchey-Chrétien focus, and four at the f/13.5 Cassegrain focus, while the division among the B plates was three at f/7.5 and four at f/13.5; it was hoped that the improved plate scale at f/13.5 ($10'' \text{ mm}^{-1}$ versus $18'' \text{ mm}^{-1}$ at f/7.5) would allow measurement of stars nearer to the center of this very compact cluster, thereby increasing the probability of finding cluster members. Allowance was made for the smaller distortion-free field of the 1.5-m telescope at f/13.5 by confining measurements to a field of radius 3′ near the center of the plate. In addition to the program stars, which are identified in Figure 2 (Plate 2), a group of 135 stars lying 8′.2 from the cluster center were measured on two f/7.5 plates in each color to serve as a sample of field stars.

The reduction of the photographic data was done in a different manner than in our recent papers. A regression was performed on the iris readings of each plate against those of an arbitrarily selected standard plate, and then all iris readings for a given star were averaged. One calibration curve was then constructed that consists of a multiple regression in which one magnitude, say V, is treated as the dependent variable, while various powers (usually up to the fourth) of the corresponding V iris readings and the B magnitude are treated as independent variables. The reason for including the B magnitude in the V regression is an attempt to build a color equation into the calibration curve. A similar procedure in which the roles of the V and B magnitudes are reversed is then carried out to obtain B magnitudes. The two equations may then be solved simultaneously for B and V separately in terms of B iris readings and V iris readings. It was found that in nearly all cases the rms error of the fit was reduced when the other magnitude was included in the regression. In spite of this procedure, residual color equations were found graphically and removed from the data for the cluster stars given in Table 2. Median standard errors for the stars in Table 2 are ± 0.03 mag in V and ± 0.04 mag in $B - V$. With the exception of stars in ring 2, where crowding effects can be expected to make all measures less certain, we have indicated by an asterisk in Table 2 stars for which the standard errors exceed 0.10 mag in V or $(B - V)$. In general stars so identified were near the plate limit and were measured on only two plate pairs. One star, 4427, was found to be variable on numerous V plates, while approximately constant on the B plates; its colors place it near the RR Lyrae star region of the cluster C-M diagram. Star 4323, which is also sufficiently blue to raise suspicions that it might be an RR Lyrae star, also has discrepant measures on two plates.

III. RESULTS

a) *The Color-Magnitude Diagram*

The C-M diagram for all program stars measured is shown in Figures 3*a*–3*d* as a function of ring number, while Figure 4 shows the field star sample measured in an area of 8.5 square arc minutes located 8′.2 from the center of the cluster. Inspection of these figures reveals several characteristics. First, from comparison of ring 4 data with those for the field stars, we find that relatively few cluster stars are contained in the fourth ring. Second, the clump of stars at $V \approx 17.1$ mag, $B - V \approx 1.47$ mag, visible in ring 3 and to a lesser extent in ring 2, is absent from Figure 4; we tentatively associate this group of stars with the red horizontal branch that is characteristic of metal-rich clusters such as 47 Tuc (Wildey 1962; Tifft 1963; Menzies 1973; Cannon 1974; Hartwick and Hesser 1974), M71 (Arp and Hartwick 1971), and NGC 6352 (Hartwick and Hesser 1972). Third, comparison of the ring 2 and 3 data suggests that crowding effects are becoming important in the former ring. Fourth, the giant branch apparently extends from $V \approx 17.1$, $B - V \approx 1.47$ to $V \approx 15.4$ and $B - V \approx 2.3$. We note from Figure 4, the field star data, that the blue plate limit in this reddened field runs along a line approximately parallel to and 1 mag below the region being associated here with the giant branch of the cluster.

To convince ourselves further that the features being associated here with the horizontal branch and the giant branch are in fact due to the cluster and not to chance superposition of field stars, the data of Figure 3*d* are plotted again in Figure 5, in which we have

TABLE 2

PHOTOGRAPHIC PHOTOMETRY FOR NGC 6441 STARS

Star	V	B−V	Star	V	B−V	Star	V	B−V	Star	V	B−V
1201	16.24	1.85	1243	17.09	1.42	1342	16.45	0.80	1432	15.76	1.58
1202	16.92	1.00	1301	16.61	1.81	1343	16.92	1.22	1451	17.48	1.40
1203	16.93	1.46	1302	15.91	2.11	1344	17.10	1.38	1452	17.68	1.20
1204	16.90	1.48	1303	16.99	1.61	1345	16.61	1.73	1453	17.64	1.22
1205	16.30	1.89	1304	17.18	1.32	1346	16.00	2.24	1454	17.49	1.37
1206	15.17	2.28	1305	17.05	1.36	1347	16.92	1.62	1455	17.48	1.39
1207	16.29	1.85	1306	16.04	1.88	1348	16.30	1.88	1456	17.43	1.34
1208	15.28	2.28	1307	17.03	1.51	1349	17.00	0.78	1457	17.84	1.18
1209	15.90	2.07	1308	16.82	1.77	1350	16.03	2.03	1458	17.43	1.38
1210	16.97	1.41	1309	17.11	1.42	1351	16.60	1.55	1459	17.80	1.28
1211	16.87	1.17	1310	17.26	1.53	1352	16.74	1.78	1460	17.93	1.10
1212	14.56	1.84	1311	16.62	1.51	1401	16.89	0.89	1461	17.94	1.11
1213	15.04	2.22	1312	16.95	1.44	1402	17.38	1.40	1462	17.78	1.15
1214	16.62	1.58	1313	16.24	1.83	1403	17.61	1.36	1463	17.48 *	1.39
1215	16.87	1.37	1314	16.13	1.51	1404	17.28	0.97	1464	17.64 *	1.33
1216	17.28	1.22	1315	16.40	1.84	1405	16.16	2.06	1465	17.93	1.13
1217	16.86	1.54	1316	16.07	1.99	1406	17.04	1.20	1470	16.18	1.84
1218	13.94	1.49	1317	14.80	1.88	1407	16.26	1.48	1471	15.72	2.17
1219	15.65	2.04	1318	15.63	2.05	1408	15.88	1.12	1472	16.34	1.74
1220	16.48	1.00	1319	17.19	1.49	1409	15.59	1.64	1473	16.02	2.25
1221	16.87	1.39	1320	16.98	1.58	1410	16.88	1.64	1474	16.36	2.05
1222	16.13	1.81	1321	17.11	1.15 *	1411	16.70	1.42	1475	15.49	1.75
1223	16.59	1.45	1322	17.06 *	1.73	1412	17.34	1.44	1501	17.00	1.54
1224	16.08	2.10	1323	16.86	1.60	1413	16.03	2.17	1502	16.59	2.07
1225	14.25	2.24	1324	16.57	1.83	1414	16.85 *	1.20 *	1503	17.01	1.71
1226	16.34	1.73	1325	17.11	1.48	1415	16.74	1.54	1504	15.76	1.18
1227	15.72	1.28	1326	15.36	2.24	1416	16.01	2.15	1505	16.09	1.12
1228	15.24	1.90	1327	17.02	1.44	1417	17.02	1.26	1570	15.65	2.03
1229	16.05	1.49	1328	16.41	1.89	1418	16.87	1.16	1571	15.39	1.78
1230	15.31	1.77	1329	16.48	1.80	1419	16.33	1.99	1601	15.99	2.29
1231	16.97	1.49	1330	17.18	1.48	1420	17.45	1.42	1602	17.43	1.61
1232	16.87	1.35	1331	16.24	2.01	1421	16.20	1.90	1603	14.62	1.57
1233	16.85	1.37	1332	16.97	1.73	1422	16.90	1.36	1604	17.23	1.12
1234	16.49	1.73	1333	17.28	1.52	1423	16.91	1.76	1605	17.16	1.71
1235	16.46	1.68	1334	16.71	1.72	1424	16.78	1.83	1670	15.25	0.83
1236	16.89	1.50	1335	17.16	1.65	1425	16.08	2.19	2201	15.37	2.01
1237	15.76	1.78	1336	16.09	1.62	1426	17.18	1.42	2202	15.89	1.82
1238	15.41	1.86	1337	17.05	1.59	1427	15.94	2.37	2203	15.85	2.07
1239	16.32	1.75	1338	16.27	1.19	1428	14.95	2.12	2204	15.68	1.53
1240	16.63	1.63	1339	16.21	1.59	1429	16.65	2.05	2205	16.45	1.85
1241	17.04	1.00	1340	16.37	1.50	1430	17.00	1.81	2206	15.52	2.23
1242	13.44	1.48	1341	17.01	1.46	1431	13.17	1.55	2207	15.40	2.31

TABLE 2—*Continued*

Star	V	B-V	Star	V	B-V	Star	V	B-V	Star	V	B-V
2208	16.72	1.40	2316	16.99	1.51	2406	17.40	1.43	2460	17.51 *	1.42
2209	16.89	1.55	2317	15.48	1.77	2407	16.08	2.49	2461	17.46 *	1.38
2210	16.54	1.49	2318	17.13	1.51	2408	17.00	1.78	2462	17.71	1.22
2211	15.81	2.01	2319	17.15	1.39	2409	16.77	1.87	2463	17.52	1.36
2212	16.31	1.47	2320	17.07	1.42	2410	16.40	1.86	2464	16.75	1.93
2213	16.53	1.43	2321	17.08	0.99	2411	16.93	1.80	2465	17.35	1.45
2214	16.12	2.18	2322	15.84	2.36	2412	17.34	1.32	2466	17.79	1.16
2215	16.84	1.45	2323	17.06	1.50	2413	17.11	1.76	2467	17.91	1.15
2216	16.75	1.64	2324	16.83	1.70	2414	15.25	1.01	2468	17.63	1.24
2217	16.90	1.01	2325	15.94	2.30	2415	16.98	1.66	2470	16.43	2.35
2218	15.44	2.21	2326	16.50	1.79	2416	16.74	1.88	2501	17.10	1.58
2219	16.18	1.89	2327	16.33	2.09	2417	15.79	2.27	2502	16.49	1.75
2220	14.92	2.45	2328	17.18	1.32	2418	16.71	1.64	2503	16.54	1.73
2221	16.08	2.01	2329	16.62	1.90	2419	16.97	1.42	2504	15.28	1.24
2222	16.53	1.61	2330	16.95	1.34	2420	15.75	2.28	2505	16.09	1.60
2223	17.10	0.89	2331	16.23	1.64	2421	16.33	2.14	2506	12.93	1.90
2224	16.88	0.96	2332	16.40	1.82	2422	15.79	2.31	2507	13.49	1.93
2225	16.34	1.77	2333	15.63	2.20	2423	16.50	1.16	2508	15.26	2.09
2226	15.36	2.23	2334	16.00	1.76	2424	16.95	1.58	2570	16.24	2.12
2227	16.10	1.86	2335	17.01	1.74	2425	17.01	1.01	2571	16.93	1.93
2228	16.45	0.73	2336	17.31	1.62	2426	15.56	2.16	2601	16.51 *	1.86
2229	15.88	2.20	2337	17.37	1.51	2427	16.25	1.60	2602	16.08	2.02
2230	16.48	1.71	2338	16.81	1.42	2428	17.25	1.42	2603	15.23	0.92
2231	15.90	1.77	2339	16.86	1.03	2429	16.59	1.96	2604	16.47	1.18
2232	15.73	1.53	2340	16.68	1.81	2430	15.59	2.21	2605	17.39	0.95
2233	16.29	1.59	2341	16.13	1.66	2431	17.15	1.51	2670	16.10	2.29
2234	16.60	1.48	2342	15.41	2.28	2432	17.34	1.50	3201	15.70	1.87
2301	16.14	1.79	2343	16.26	1.86	2433	17.31	1.52	3202	16.23	1.56
2302	17.20	1.60	2344	16.03	1.96	2434	15.21	2.02	3203	16.12	1.45
2303	16.23	2.00	2345	16.05	1.71	2435	13.43	2.14	3204	15.49	2.00
2304	15.97	2.14	2346	15.46	2.22	2436	15.44	1.36	3205	16.58	1.61
2305	17.16	1.03	2347	17.29	1.47	2437	15.67	1.38	3206	16.78	1.46
2306	17.01	1.79	2348	15.53	2.45	2438	15.56	1.00	3207	16.10	1.72
2307	16.94	1.73	2349	17.33	1.48	2451	17.47	1.49	3208	16.57	1.65
2308	17.33	1.16	2350	16.63	1.84	2452	17.84	1.16	3209	16.17	1.70
2309	16.68	1.23	2351	15.61	2.20	2453	17.91 *	1.01	3210	16.64	1.49
2310	16.52	2.07	2352	16.09	1.44 *	2454	18.04	1.01	3211	16.27	1.74
2311	17.33	1.41	2401	16.62	1.14	2455	17.93	1.04	3212	16.00	1.71
2312	16.42	1.67	2402	16.38	2.18	2456	16.98	1.80	3213	16.62	1.62
2313	16.24	1.91	2403	17.37	1.49	2457	16.89	1.72	3214	16.79	1.39
2314	17.06	1.27	2404	17.12	1.71	2458	17.57	1.41	3215	16.83	0.90
2315	16.98	1.53	2405	15.78	1.82	2459	17.81	1.21	3216	16.94	1.48

TABLE 2—*Continued*

Star	V	B-V	Star	V	B-V	Star	V	B-V	Star	V	B-V
3217	16.02	1.85	3324	15.62	1.99	3366	16.97	1.50	3441	16.60	1.25
3218	16.04	1.62	3325	15.96	1.79	3367	16.93	1.50	3442	14.90	2.02
3219	16.48	1.47	3326	16.57	1.55	3401	16.05	1.86	3451	17.54	1.38
3220	15.54	2.09	3327	17.01	1.41	3402	15.56	2.09	3452	17.54	1.18
3221	16.10	1.77	3328	17.00	1.49	3403	17.16	1.57	3453	17.41	1.40
3222	16.11	1.84	3329	16.67	1.67	3404	17.03	1.64	3454	17.77	1.20
3223	15.23	0.97	3330	16.03	2.01	3405	15.74	2.25	3455	17.31	1.50
3224	15.91	1.95	3331	17.12 *	1.53	3406	15.66	2.14	3456	17.19	1.58
3225	16.61	1.42	3332	15.54	2.12	3407	16.49	1.88	3457	17.47	1.26
3226	15.58	2.12	3333	15.58	2.13	3408	17.12	1.42	3470	16.52	1.88
3227	14.69	0.89	3334	16.36	1.80	3409	14.93	1.74	3501	14.75	1.88 *
3228	15.35	1.94	3335	16.13	1.91	3410	17.26	1.39	3502	16.53	1.73
3229	16.42	1.60	3336	15.77	1.98	3411	16.52	1.36	3503	16.35	1.74
3230	15.79	1.76	3337	16.71	1.43	3412	16.56	1.64	4201	16.26	1.55
3231	15.97	1.90	3338	15.91	1.68	3413	17.30	1.29	4202	16.74	1.51
3232	16.27	1.14	3339	16.81	1.42	3414	16.47	1.88	4203	14.83	1.06
3233	15.39	2.00	3340	16.21 *	2.05	3415	16.26	2.03	4204	16.96	1.52
3234	15.29	2.07	3341	16.69 *	1.58	3416	16.48	1.85	4205	15.88	1.67
3235	15.42	2.12	3342	15.63	1.90	3417	16.56	1.46	4206	15.64	1.93
3301	15.85	1.98	3343	16.71	1.43 *	3418	17.14	1.09	4207	15.79	1.88
3302	16.58	1.69	3344	17.00	1.45	3419	15.65	2.06	4208	16.53	1.72
3303	15.48	1.27	3345	15.24	2.15	3420	16.10	1.25	4209	16.52	1.00
3304	16.99	1.43	3346	16.84	1.39	3421	17.09	1.49	4210	15.89	1.82
3305	16.81	1.63	3347	16.49	1.66	3422	16.34	1.86	4211	15.41	2.10
3306	16.63	1.72	3348	16.27	1.56	3423	17.02	1.64	4212	15.30	2.17
3307	16.52	1.41	3349	16.69	1.38	3424	16.15	0.57	4213	16.51	1.61
3308	16.58	1.58	3350	16.53	1.47	3425	17.08	1.40	4214	15.60	2.12
3309	16.93	1.43	3351	17.13	1.47	3426	16.50	1.74	4215	15.82	1.62
3310	17.11	1.45	3352	17.00	1.48	3427	17.09	1.57	4216	15.92	1.33
3311	17.03	1.15	3353	15.40	2.23	3428	17.06	1.58	4217	16.48	1.73
3312	15.69	2.12	3354	16.56	1.55	3429	17.01	1.18	4218	16.75	1.52
3313	16.79	1.67	3355	16.90	1.11	3430	16.85	1.68	4219	16.50	1.61
3314	16.18 *	1.48	3356	17.11	1.44	3431	15.76	2.27	4220	16.02	1.22
3315	15.80	1.89	3357	15.36	2.21	3432	15.89	1.97	4221	15.51	2.02
3316	16.86	1.59	3358	17.19	1.46	3433	16.11	1.32	4222	15.64	1.71
3317	15.36	1.61	3359	17.33	1.20	3434	16.02	1.26	4223	16.70	1.53
3318	16.66	1.72	3360	16.65	1.51	3435	15.70	2.04	4224	16.28	1.43
3319	15.31	2.16	3361	16.51	1.69	3436	15.76	2.20	4225	16.27	1.66
3320	15.28	2.32	3362	16.76	1.32	3437	16.03	2.05	4226	15.89	1.88
3321	17.15	1.52	3363	15.07	1.38	3438	16.77	1.74	4227	16.50	1.59
3322	16.24	1.88	3364	16.31	1.92	3439	17.24	1.54	4228	16.51	1.58
3323	16.58	1.40 *	3365	17.21	1.64	3440	15.52 *	1.57	4229	15.56	2.18

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TABLE 2—*Continued*

Star	V	B-V	Star	V	B-V
4230	15.54	2.09	4337	16.97	1.36
4231	16.98	1.39	4338	15.96	1.77
4232	17.22	1.45	4339	17.07	1.43
4233	16.76	1.47	4340	16.98	1.41
4234	16.53	1.59	4341	16.71	0.95
4235	16.60	1.54	4342	16.96	1.42
4301	16.58	1.35	4343	17.48 *	1.27
4302	16.53	1.73	4344	16.00	1.86
4303	16.66	0.96	4345	17.27	1.52
4304	16.85	1.49	4346	17.18	1.38
4305	16.80	1.20	4347	16.65	1.57
4306	16.87	0.89	4348	17.07	1.37
4307	16.73 *	1.31 *	4349	16.01	1.85
4308	16.12	1.30	4401	16.43	1.80
4309	17.02	1.48	4402	16.58	1.59
4310	17.21	1.44	4403	16.77	1.35
4311	16.76	1.33	4404	16.85	1.44
4312	16.74	1.52	4405	16.72	0.91
4313	16.95	1.57	4406	17.27	1.52
4314	17.07	1.48	4407	17.35	1.52
4315	17.00	1.56	4408	16.59	1.77
4316	17.16	1.50	4409	17.19	1.51
4317	15.78	1.84	4410	17.15	1.17*
4318	16.07	1.65	4411	16.48	1.93
4319	16.63	1.69	4412	17.07	1.58
4320	17.26	1.46	4413	17.07	1.48
4321	16.49	1.71	4414	16.88	1.74
4322	17.24	1.54	4415	17.10	1.51
4323	16.89	0.85	4416	16.48	1.91
4324	17.10	1.52	4417	17.13	1.42
4325	16.95	1.57	4418	16.04	1.22
4326	17.21	1.66	4419	17.01	1.65
4327	17.09	1.44	4420	16.22	1.81
4328	16.84	1.45	4421	17.28	1.49
4329	16.92	1.67	4422	15.54	2.23
4330	15.63	2.12	4423	16.49	1.30
4331	17.28	1.56	4424	15.50	2.20
4332	15.58	2.09	4425	17.20	1.45
4333	17.23	1.49	4426	16.04	1.99
4334	16.81	0.79	4427	17.25 *	0.92
4335	16.60	1.70	4428	16.60	1.58
4336	15.63	1.52	4429	15.94	2.05

Star	V	B-V	Star	V	B-V
4430	16.02	1.85	4455	17.41	1.46
4431	15.85	1.73	4456	17.41	1.42
4432	17.45	1.20	4457	17.39	1.45
4433	16.95 *	1.63	4458	17.55	1.33
4434	15.56	1.89	4459	16.96	1.65
4435	15.23	1.53	4460	17.92	1.00
4436	12.53	0.46	4461	17.29	1.40
4437	15.54	1.28 *	4462	17.00	1.66
4438	15.02	1.94	4470	16.47	1.76
4439	16.05	1.46	4501	17.27	1.56
4451	16.87	1.70	4502	17.37 *	0.99
4452	17.32	1.59	4503	16.68	1.75
4453	16.63	1.66	4504	15.97	2.12
4454	17.12	1.57	4505	13.80	0.94

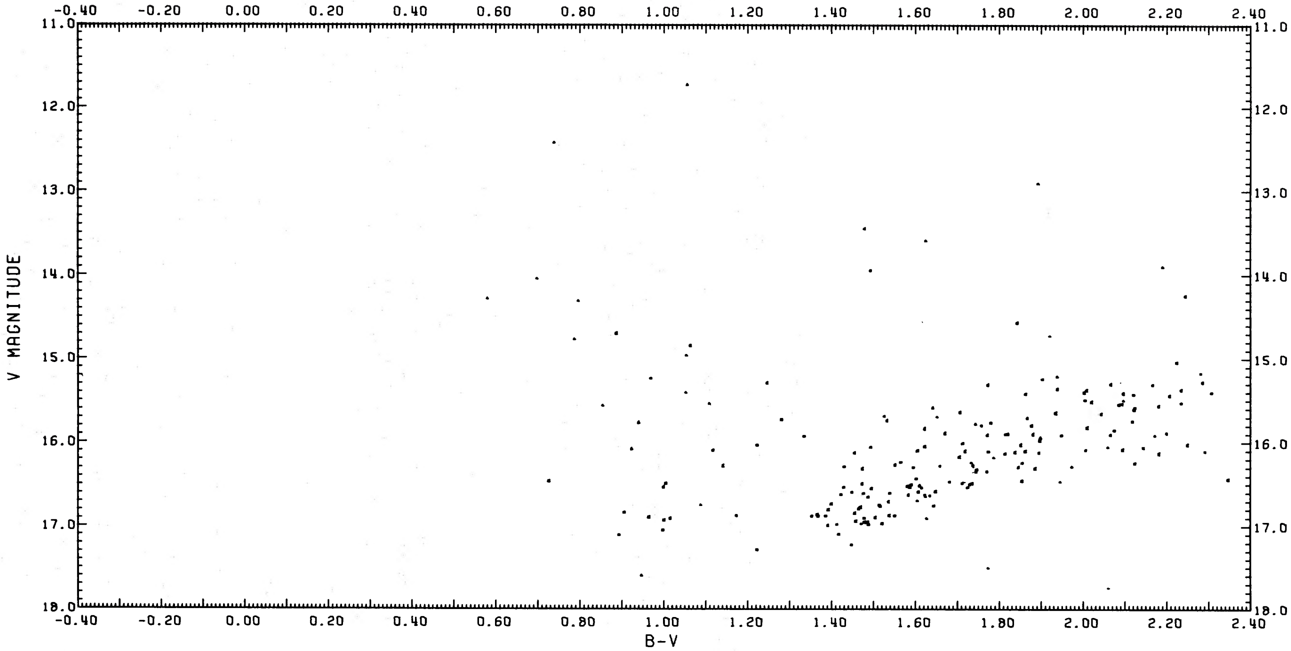

FIG. 3a

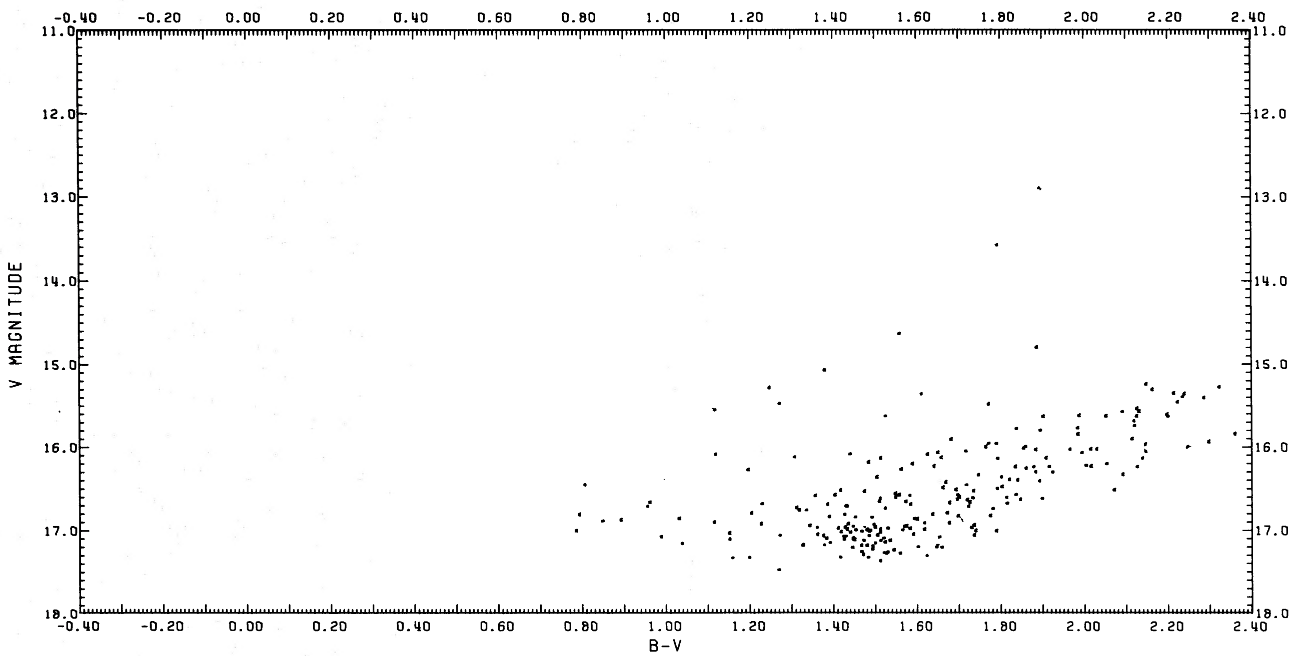

FIG. 3b

FIG. 3.—(*a*) The photoelectrically calibrated C-M diagram for stars identified in ring 2 of Fig. 2. (*b*) The photoelectrically calibrated C-M diagram for stars identified in ring 3 of Fig. 2. (*c*) The photoelectrically calibrated C-M diagram for stars identified in ring 4 of Fig. 2. (*d*) The photoelectrically calibrated C-M diagram for the stars of Figs. 3*a*–3*e* combined; stars denoted by crosses are the photoelectrically measured ones of Table 1.

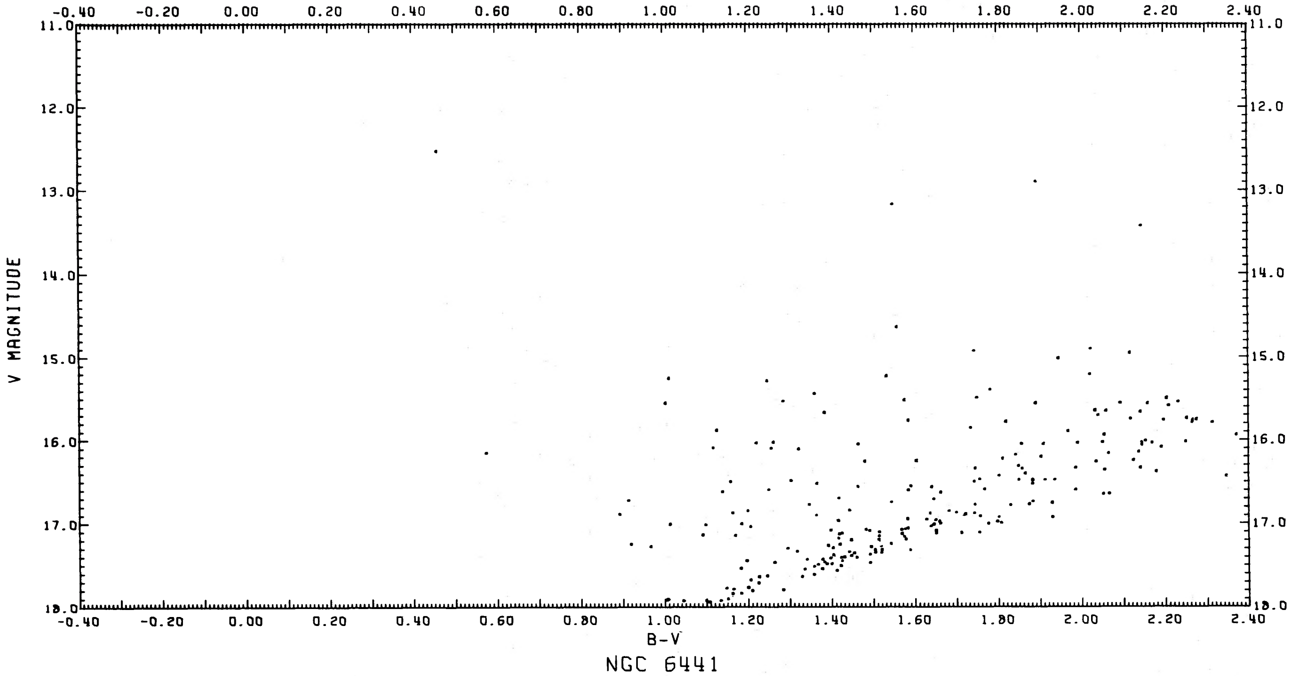

FIG. 3*c*

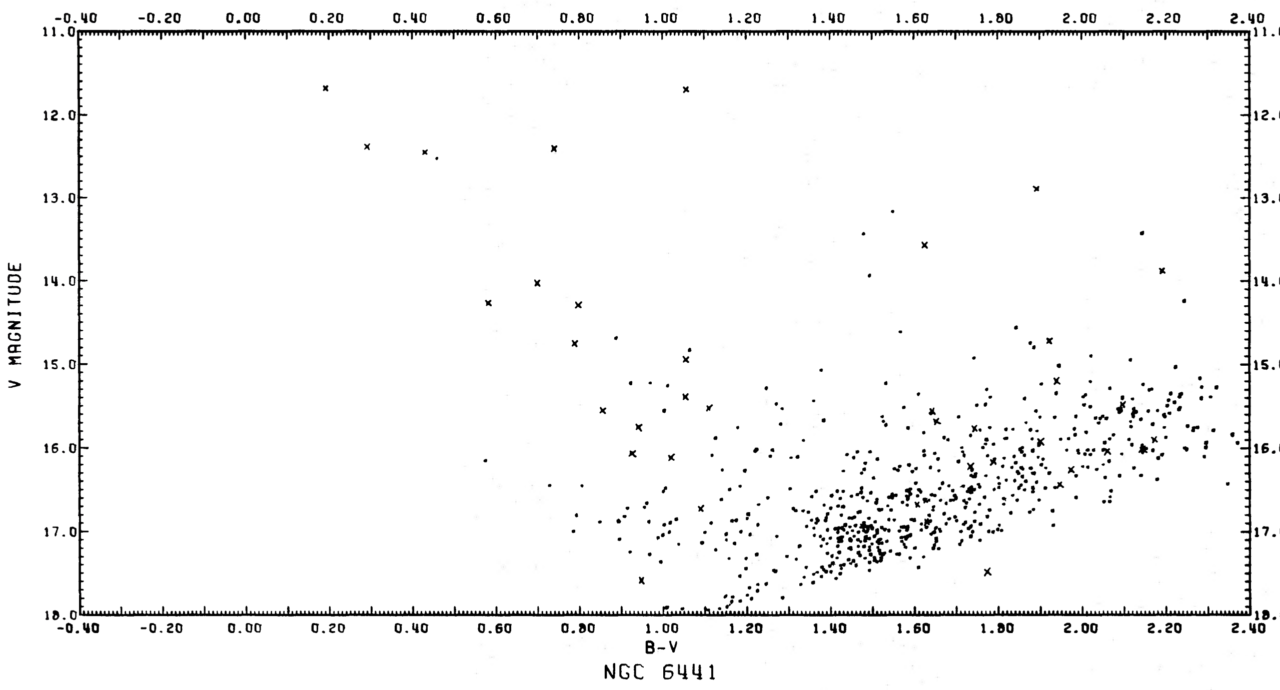

FIG. 3*d*

FIG. 3.—*Continued*

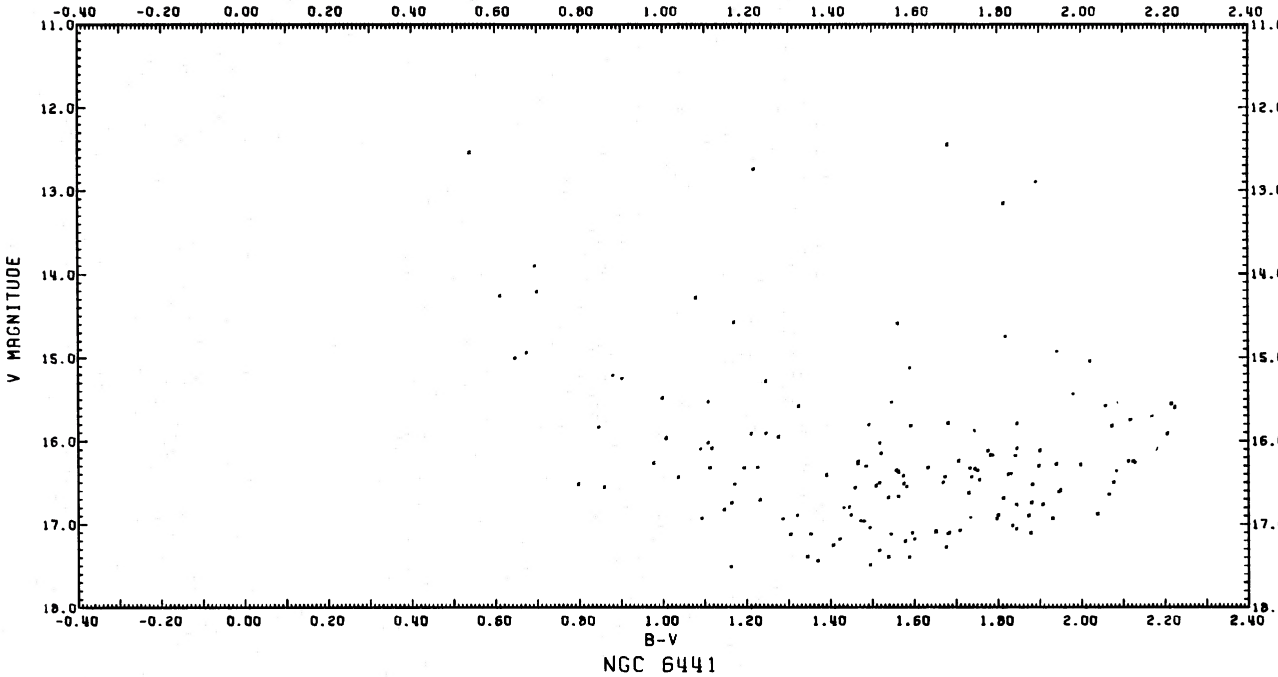

FIG. 4.—The C-M diagram for the field stars measured near the cluster, as explained in the text

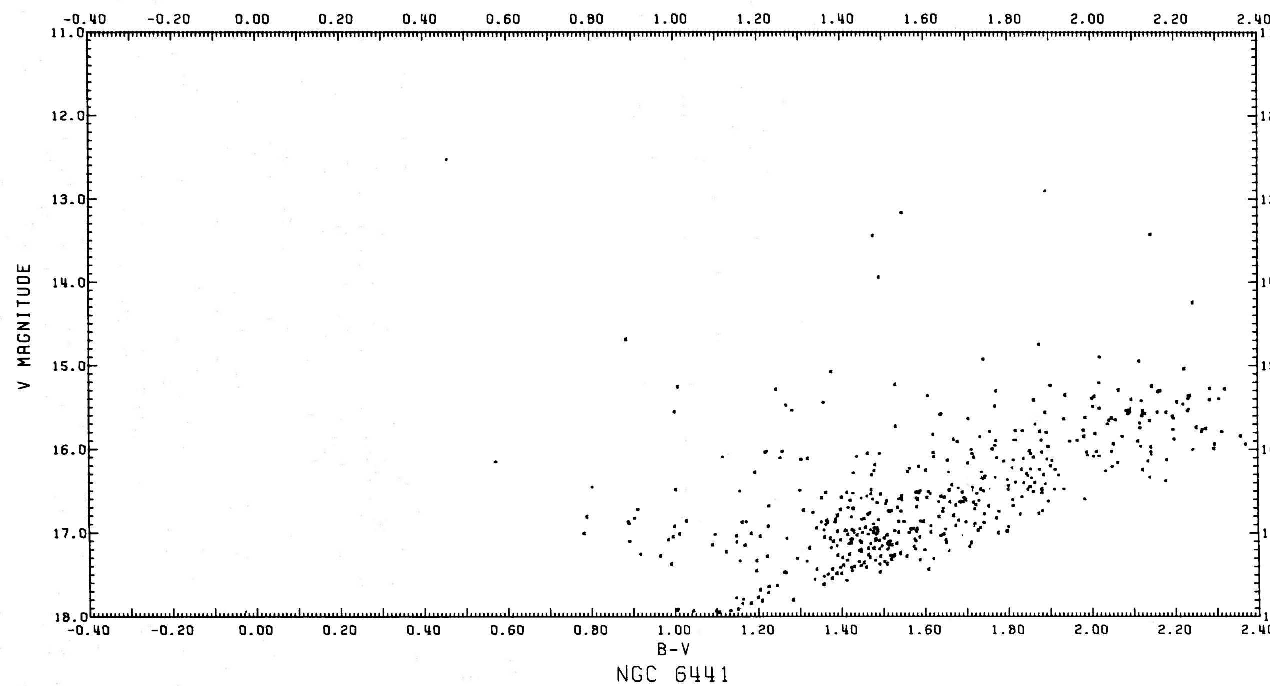

FIG. 5.—A C-M diagram (initially Fig. 3*d*), after correcting in a statistical sense for the effects of field stars, as explained in the text.

attempted to eliminate the effect of field stars in the following manner. The C-M diagram was divided up into areas of dimensions 1.0 mag in V and 0.2 mag in $(B - V)$. The number of field stars in each area (after normalizing these numbers for the area sampled for field stars to the area measured in the cluster) was then determined. This number determined how many stars chosen at random were removed from each area of the cluster measurements; the features identifiable with the horizontal and giant branches in the original figure persist after statistical correction for the effects of field stars. As a final aid in segregating cluster stars from field stars, V- and I-band photographs were obtained with the CTIO vidicon system on the 91-cm telescope in 1973 June. On the I-band photograph recorded from the video monitor the red giants stand out very clearly; among those stars that could be so identified are 1228, 1326, 1408, 2206, 2207, 3319, 3320, 3345, and 3357, whose characteristic magnitudes and colors lie at $V \approx 15.4$ and $B - V \approx 2.25$, confirming this position effectively to be the tip of the giant branch in NGC 6441.

The crowded nature of the field surrounding NGC 6441 makes the attainment of a "clean" C-M diagram impossible, and we feel that the best compromise is to use the data from rings 2 and 3 (Figs. 3*a* and 3*b*) as re-plotted in Figure 6, to which we shall hereafter refer as the C-M diagram. Shown also in Figure 6 are the average V and $B - V$ positions of several variable stars (Hogg 1973) as measured on our plates. It will be of interest to determine if any of these variables are of the Mira type, in view of a possible correlation between Mira period and cluster metallicity (cf. Andrews *et al.* 1974).

b) *Reddening*

From the galactic coordinates of NGC 6441 ($l = 353°$, $b = -5°$), we expect the cluster to be heavily reddened, an expectation borne out by our detailed investigation. Inspection of long exposure photographs, such as the *National Geographic Society–Mount Palomar Sky Survey prints*, shows that the obscuration in the immediate vicinity of NGC 6441 is approximately uniform and considerably less than in regions only a degree or so away. The patchy nature of the obscuration makes the derivation of an accurate value of $E(B - V)$ extremely difficult; in this subsection we shall describe various attempts we have made to establish such a value.

i) *Photoelectric Photometry of Foreground Stars*

Four different approaches falling under this general category have been examined: *UBV* reddening determinations using bright stars selected from the *Smithsonian Astrophysical Observatory Catalog* (SAO); *UBV* reddening determinations using the fainter photoelectric sequence stars of Table 1; *uvby*–Hβ reddening determinations using HD and fainter stars selected by objective prism spectroscopy (Hesser 1975); and, finally, relatively nearby Cepheid variables.

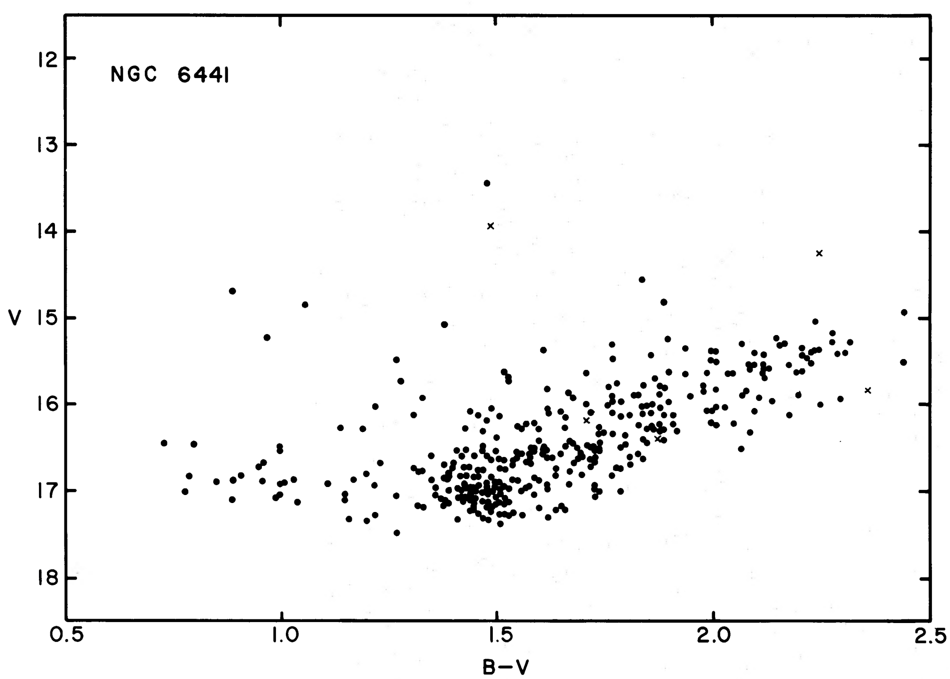

FIG. 6.—The combined data for rings 2 and 3 (Figs. 3*a* and 3*b*) which we adopt as the best representation to the C-M diagram of NGC 6441 obtainable from the available data.

TABLE 3

UBV PHOTOMETRY FOR FOREGROUND EARLY-TYPE STARS

SAO Number	V	$B-V$	$U-B$	Spectral Type	E_{B-V}	Distance (pc)
209297.......	8.40	−0.03	−0.51	B8	0.16	360
209300.......	9.84	0.07	−0.12	A0	0.17	790
209304.......	7.00	−0.07	−0.93	B2	0.22:	570
209309.......	7.30	0.01	−0.10	A0	0.08	180
209323.......	8.73	.08	−0.58	B3	0.31	770
209333.......	9.19	.08	−0.45	B9	0.27	400
209334.......	9.75	.19	−0.28	B9	0.36	460
209336.......	8.00	.08	−0.59	B8	0.31	230
209337.......	7.79	.02	−0.28	B9	0.15	250
209345.......	7.59	.01	−0.06	B9	0.06	260
209346.......	7.04	− .01	−0.10	B9	0.06	200
209371.......	7.28	+ .03	−0.09	B9	0.10	200

On 1969 June 17/18 we observed 12 bright early-type stars selected from the SAO catalog to lie in a rectangle about 4° long in declination and 0ᵐ2 wide in right ascension centered on NGC 6441. Table 3 gives the observations made with the number 1 41-cm telescope and a refrigerated 1P21 photometer. By assuming that each star was on the main sequence, we derived reddening and distance modulus estimates for it; should the star be evolved, our procedure will overestimate the reddening and underestimate $(m - M)_0$. The resultant points are plotted in Figure 7 as dots, and show a very steep increase in $E(B - V)$ out to a distance of about 400 pc, where the growth of reddening as a function of distance appears to slow dramatically. However, assuming that the absorption takes place in the classical 100 pc thick layer discussed by Arp (1965*b*), which would be intersected by the line of sight to NGC 6441 at $r = 1150$ pc, any apparent leveling based on stars with $r \lesssim 1150$ pc must be treated with caution. An average value of $E(B - V) = 0.27 \pm 0.07$ mag is obtained from the 5 SAO stars in Figure 7 whose distances are estimated to lie in the range 400–800 pc.

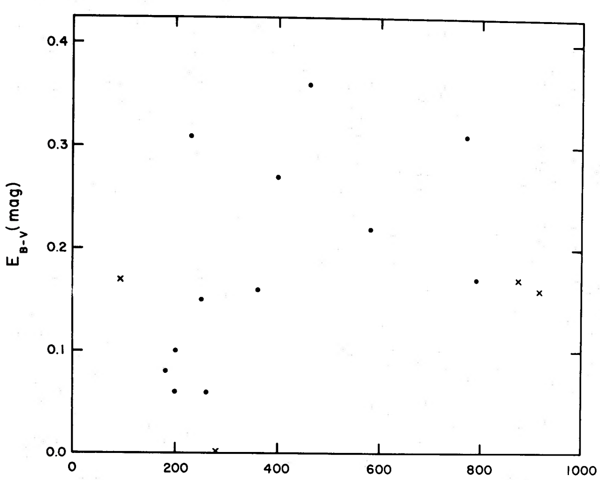

FIG. 7.—Values of reddening determined as a function of distance from photoelectric *UBV* photometry of field stars in the areal vicinity of NGC 6441; stars selected from the SAO Catalog are denoted by dots, while those from Table 1 are denoted by crosses.

To extend the *UBV* method of reddening determination to larger distances we de-reddened the bluer stars whose photoelectric colors are listed in Table 1. Of the 11 stars with appropriate colors, one (No. 6) looks photometrically peculiar, while only one (star B) of the remaining 10 gives, without knowledge of the spectra, an unambiguous result for $E(B - V)$. From objective prism spectra taken with the Curtis Schmidt on Cerro Tololo, star F can be classified as an A star, thus also yielding a uniquely determined $E(B - V)$ value. In Table 4 we list the possible solutions for each star, with their corresponding distances; as before, we assumed each star was of luminosity class V. The value we adopt as most likely being the correct one is denoted by an asterisk. Formally recalculating the previously determined $E(B - V)$ for the increased sample of eight *UBV* stars with unique values of reddening and having $400 \leq r \leq 1130$ pc yields $E(B - V) = 0.23 \pm 0.08$ mag. However, the data of Table 4 clearly show the possibility of considerably higher values of the reddening,[1] such that the average calculated here is considered to represent only a lower limit to the actual $E(B - V)$ for NGC 6441.

Additional evidence that the growth of reddening slows greatly beyond 400 pc comes from *uvby*–Hβ measures of 36 stars within 1° of NGC 6441 on the sky and extending to 1.6 kpc from the Sun (Hesser 1975). These stars, selected both from the HD catalog and from objective prism spectra, show the same leveling of the reddening beyond 400 pc as do the *UBV* stars of Figure 7, and the nine stars more distant than 790 pc yield $E(B - V) = 0.30 \pm 0.04$ mag.

[1] For instance, a consistent solution for $E(B - V)$ from stars C, 4, 9, and 17 of Table 4 is 0.41 ± 0.06 mag. The solution yielding E of ~ 0.9 mag can be rejected from the superposition of color-magnitude diagrams, as discussed in § III*b* (iv) below.

TABLE 4

REDDENING VALUES FOR STARS OF TABLE 1*

Star	Solution 1 E_{B-V}(mag)	Solution 1 Distance (pc)	Solution 2 E_{B-V}(mag)	Solution 2 Distance (pc)	Solution 3 E_{B-V}(mag)	Solution 3 Distance (pc)
B.........	0.17	875*				
C.........	0.11	555	0.48	1560		
E.........	0.12	195	0.20	215	0.79	675
F.........	0.16	915*	0.43	1600		
I.........	0.10:	965	0.18:	1130		
1.........	0.17:	95*	0.91:	230		
3.........	0.00	280*	0.33	430	0.83	1115
4.........	0.14	800	0.39	1100	0.92	3040
9.........	0.08	575	0.43	990	0.92	2300
17.........	0.35	1410	0.62	2475		

* Values denoted by asterisks are believed to be the correct ones.

Finally, three Cepheids (V1004 Sgr, R4 Sco, V717 Sco, with E_{B-V} values of 1.1, 0.73, and 1.5 mag, respectively [Fernie and Hube 1968]) lie in the range $356° \leq l \leq 359°$ and $-3° \geq b \geq -5°$ and have values of $E(B-V)$ that must represent upper limits to the reddening near NGC 6441, as the stars lie 3° closer in longitude to the galactic center than does NGC 6441.

ii) *Integrated Colors of NGC 6441*

From a rediscussion of van den Bergh's (1967) *Q*-method applied to his integrated colors of NGC 6441, Racine (1973) and Burnstein and McDonald (1974) have found that on the average $E(B-V)$ may be accurately predicted from the observed integrated *UBV* colors for the halo globular clusters. Using van den Bergh's (1967) photometry, Racine predicts $E(B-V) = 0.46$ mag while Burnstein and McDonald (1974) find 0.49 mag, in agreement with the value obtained using Koehler's (1965) predicted $(B-V)$ and the observed colors of van den Bergh. The accuracy of the (integrated color)–(spectral type)-technique is difficult to assess for the late G-type clusters, however, as they nearly all lack truly independent and accurate reddening determinations. Until such time as it is understood why clusters exhibiting disparate C-M diagrams should all appear to obey the intrinsic color–spectral type relation upon which the integrated-color method of reddening determination is based, we cannot rule out the possibility that the close agreement between the finally adopted reddening for NGC 6441 and the value derived from the intrinsic color relation may be only fortuitous.

iii) *Neutral Hydrogen in the Direction of NGC 6441*

Knapp and Kerr (1974) have provided an extensive list of neutral-hydrogen column densities in the direction of galactic globular clusters, from the analysis of which they have derived a correlation between color excess and H I. Applying their relation to NGC 6441, a value of $E(B-V) = 0.50$ mag is obtained; however, as their relation to a large extent depends upon van den Bergh's $[Q, E(B-V)]$-relation, it is not a reddening determination entirely independent from that of Racine.

iv) *Superposition of Color-Magnitude Diagrams*

Within observational uncertainties, the general characteristics of the C-M diagram of NGC 6441 superpose well with those in the diagrams for NGC 6352 (Paper I), NGC 6356 (Sandage and Wallerstein 1960) and NGC 6553 (Hartwick 1975); while they superpose slightly less well with those of NGC 104, a cluster thought to have lower [Fe/H]. Superposition with NGC 104 at the level of the horizontal branch and lower giant branch, and assuming that $E(B-V)_{47\,\mathrm{Tuc}} = 0.04$ mag (Paper II), leads to an estimate of $E(B-V)_{6441} \leq 0.65$ mag, where the $\leq$ accounts for potential systematic deviations due to differences in chemical composition, etc., between the two clusters. Hesser and Hartwick (1975) have found that the tip of the giant branch in 47 Tuc terminates at $(B-V)_0 = 1.66$ mag. From the stars at the tip of the giant branch of NGC 6441, identified with the aid of the vidicon photograph, we find $(B-V) \approx 2.25$ mag, so $E(B-V)_{6441} \approx 0.59$ mag, a result consistent with the superposition of the horizontal and giant branches of the two clusters.

v) *Summary of Reddening Estimates*

A summary of the various $E(B-V)$ estimates for NGC 6441 is made in Table 5. For the purposes of the subsequent discussion we shall adopt the average of the field star reddening from *uvby*–Hβ photometry and of the C-M superposition reddening: $E(B-V) = 0.46 \pm 0.15$ mag. The large probable error will prevent an accurate age determination of this object should main-sequence photometry be achieved in the future.

c) *Distance Modulus and Integrated Magnitude*

In order to estimate the distance modulus of NGC 6441, we must make a further assumption regarding the absolute magnitude of the horizontal branch. This feature in 47 Tuc was found in Paper II to have $M_V = +0.9 \pm 0.2$ mag on the basis of main-sequence

TABLE 5

$E(B-V)$ Estimates for NGC 6441

Method	$E(B-V)$	Reference
UBV: SAO and Table 1 foreground stars ($400 \leq r \leq 1130$ pc)......	$\geq 0.23 \pm 0.08$	This paper
uvby–Hβ: foreground stars ($790 \leq r \leq 1535$ pc)..................	$\geq 0.30 \pm 0.04$	Hesser 1975
Cepheids..	≤ 0.7	Fernie and Hube 1968
Integrated colors..	0.46	Racine 1973
Neutral hydrogen..	0.50	Knapp and Kerr 1974
C-M superposition: NGC 104.................................	≤ 0.65	This paper

fitting. With $V_{HB} = 17.1 \pm 0.1$ from Figure 6 we find $(m-M)_{app, V} = 16.2 \pm 0.2$. If $E(B-V) = 0.46$ mag as adopted above, and the ratio of total to selective absorption is 3.3, then $(m-M)_0 = 14.7 \pm 0.3$ mag, yielding a distance of 8.7 kpc from the Sun, 760 pc below the galactic plane. [On the other hand, if $E(B-V)$ were 0.65 mag, then $(m-M)_0 = 14.1$, resulting in a distance from the Sun of 6.5 kpc at 565 pc below the plane.] Based on the integrated V magnitude of 7.1 for NGC 6441 (Peterson and King 1973), we find $M_V = -9.1$ mag, making NGC 6441 among then 10 intrinsically brightest galactic globular clusters known (cf. Harris 1974). It is interesting to note that if the correct value of $E(B-V)$ is eventually found to be nearer the upper limit derived from superposition of C-M diagrams, then the integrated color of NGC 6441 (whose C-M diagram and integrated spectrum show all characteristics of it being a very metal-rich cluster) will turn out to be quite blue: $(B-V)_{0, \text{integ}} = 0.61$ mag for $E(B-V) = 0.65$ mag instead of $(B-V)_{0, \text{integ}} = 0.81$ mag as found using $E(B-V) = 0.46$ mag. (Unlikely as it is that this is the case, it serves to emphasize the need for an improved reddening estimate.)

d) NGC 6441 as an X-ray Source

The third *Uhuru* catalog of X-ray sources (Giacconi *et al.* 1974) shows that NGC 6441 lies approximately centered within the 0.0184 square degree error box of the low flux source 3U 1746−37. As mentioned in the above discussion, the C-M diagram of NGC 6441 appears similar to those of other metal-rich globular clusters, such as 47 Tuc or NGC 6352, that do not have 3U X-ray sources superposed. Even though NGC 1851 has recently been linked to a transient X-ray source (Markert and Clark 1975), Vidal and Freeman (1975) have proposed that a B6 III star 0'.5 from the cluster center that possibly exhibits a variable radial velocity may be responsible for the X-ray emission, thereby continuing the association of galactic X-ray sources with mass-exchange binaries.

However, since the central densities of some clusters are as high as or higher than $10^5 M_\odot$ pc^{-3}, it is of interest to reconsider the question of stellar collisions in clusters in connection with the fact that some clusters lie within the error boxes of *Uhuru* X-ray sources. Table 6 gives the relevant data taken from the work of Illingworth (1973) and Peterson and King (1973), along with the collision rate calculated from the expression $n^2\sigma v V$, where n is the number of stars per pc^3 (for convenience assumed to be 1 $M_\odot$ stars), σ is the collision cross section [in this case taken to be $\pi(2 R_\odot)^2$], v is the average stellar velocity (taken to be the square root of 1.6 times the derived central velocity dispersion), and V is the volume calculated using the core radius as the size of the relevant region. As seen from the table, the calculated collision rates are relatively low—only about 30 collisions are expected in NGC 6441 over the lifetime of the Galaxy[2]—and it seems unlikely that the sources of X-rays in globular clusters are due to stellar collisions unless our present ideas on the stellar content of globular clusters are incorrect and/or our simple collision rate calculation is grossly in error. However, both Quintana (personal communication) and Bahcall and Ostriker (personal communication) have suggested that accretion onto a massive black hole in the center of a globular cluster might be responsible for the X-ray emission, a suggestion warranting closer observational and theoretical investigation.

There are two obvious possibilities for identifications with stellar objects within the error box. Variable

[2] Since the central density increases during the life of a globular cluster (Ostriker *et al.* 1972), the number of collisions estimated from the present central density should be an overestimate.

TABLE 6

Central Collision Rates for the X-Ray Globular Clusters

Cluster	3U Source	ρ_c ($M_\odot$ pc^{-3})	Central Velocity Dispersion (km s^{-1})	Collision Rate (number per year)
NGC 1851..............	...	1.00×10^5	9.11	2.0×10^{-10}
NGC 6341 (M92)........	3U 1736+43	2.19×10^4	7.4	2.5×10^{-11}
NGC 6441..............	3U 1746−37	1.37×10^5	18.3	2.7×10^{-9}
NGC 7078 (M15)........	3U 2131+11	3.88×10^4	10.2	1.6×10^{-10}

V6, the brightest around the cluster found by Fourcade *et al.* (1966), does occupy a somewhat anomalous position in the C-M diagram, if it is a member of NGC 6441. Figure 6 shows it to be too blue and possibly too bright if it is typical of the types of variable stars that occur in metal-rich globular clusters (Feast 1973; Lloyd-Evans and Menzies 1973). Any suggestion that V6 occupies an anomalous position in Figure 6 must be treated with caution in view of the fact that TiO blanketing may severely affect the position of a red variable star in the $(V, B-V)$-plane. The second possibility, that of a peculiar emission-line source listed as PK 353−4°1 by Perek and Kohoutek (1967), has been discussed recently by Webster (1974); we note here only that PK 353−4°1 is within the tidal radius of NGC 6441 found by Illingworth (1973). Magnitude estimates from our plates for these candidates will be presented separately.

e) *Mass-to-Light Ratios*

Recently Illingworth (1973) has used sophisticated techniques to derive masses for several southern globular clusters, including 47 Tuc and NGC 6441. In view of our recent revision of the distance modulus of 47 Tuc and our new values for NGC 6441, it seems appropriate to redetermine the M/L ratios. From Paper II we find $(m-M)_{\mathrm{app},V} = 13.16$ mag and $E_{B-V} = 0.04$ mag for 47 Tuc; correcting the integrated magnitudes and masses given by Illingworth (1973) for the revised values, we find $M = 0.53 \times 10^6\, M_\odot$ and $M/L = 1.3$. In the case of NGC 6441, Peterson and King (1973) give $V_t = 7.1$ mag, while Illingworth finds $V_t = 7.36$ mag. Using our distance modulus and revising Illingworth's mass determination accordingly, we find $M = 0.69 \times 10^6\, M_\odot$ and $M/L = 1.9$ and 2.4, respectively. These values are only slightly higher than the average M/L ratio, 1.5 ± 0.6, found by Illingworth for nine other clusters, and hence we conclude that NGC 6441 has a normal M/L ratio.

f) *The Perigalacticon Distance for NGC 6441*

A knowledge of the tidal radius, r_t, the mass of the cluster, M_c, and the mass of the Galaxy, M_G, allows a calculation of the perigalacticon distance, R_p, from the following expression:

$$r_t = R_p\left(\frac{M_c}{3M_G}\right)^{1/3}.$$

From Illingworth (1973) we find $r_t = 7'.6$ and $M_c = 0.69 \times 10^6\, M_\odot$. We shall assume that the distance of the Sun from the center of the Galaxy, $R_\odot$, is 8 kpc and that $M_G = 10^{11}\, M_\odot$. Based on our mean reddening value, $E(B-V) = 0.46$ mag, we find the perigalacticon distance to be 1.5 kpc, which is slightly greater than the present distance, $R_G = 1.2$ kpc, of the cluster from the galactic center. However, with the higher reddening value indicated by superposition of C-M diagrams, $E(B-V) = 0.65$ mag, we find $R_G = 2.3$ kpc and $R_p = 1.2$ kpc.

IV. SUMMARY

Analysis of extensive photoelectric and photographic photometry of the suspected metal-rich globular cluster NGC 6441 has been severely hampered by the crowded nature of the field, which is near the galactic bulge, and by the extreme compactness of the cluster. A definitive color-magnitude study of this potentially very important cluster must probably await, among other things, new observations obtained with the largest possible plate scale under conditions of best seeing with the new large southern hemisphere telescopes. Until such time, our study, if not vitiated by possible systematic errors in the photographic photometry arising from the need to work near the effective plate limit, has suggested the following for NGC 6441: (1) There are features in the C-M diagram characteristic of the most metal-rich globular clusters known in the Galaxy. (2) The foreground reddening is 0.46 ± 0.15 mag, a value bounded on the lower side by the slow apparent growth of reddening within the usual ~100 pc thick layer and on the upper side by potential effects of differences in [Fe/H], etc. in the C-M arrays of 47 Tuc and NGC 6441. Should the $E(B-V)$ value chosen here eventually be proven to be significantly too low, the integrated $(B-V)_0$ of NGC 6441 will be less than that usually associated with the most metal-rich globular clusters. (3) The apparent distance modulus is $(m-M)_{\mathrm{app},V} = 16.2 \pm 0.2$ mag. (4) The integrated absolute magnitude of $M_V = -9.1 \pm 0.2$ makes NGC 6441 among the intrinsically brightest galactic globular clusters, in line with the recent mass determination by Illingworth (1973). (5) No unusual features that might account for its appearing within the error box of an X-ray source have been noted, except the possibly anomalous position of V6 in the C-M diagram and the presence within the tidal radius of an unusual emission-line source (Webster 1974). Simple calculations of stellar collision rates show that it is unlikely that such collisions produce the observed X-ray emission; should the presence of a distant mass-exchange binary within the error box be ruled out by future observations, NGC 6441 would seem to be an ideal candidate for investigation in connection with the suggestion that accretion onto a massive, central black hole might account for the X-ray emission from globular clusters.

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METAL-RICH GLOBULAR CLUSTERS IN THE GALAXY. IV. A COLOR-MAGNITUDE DIAGRAM FOR NGC 6304

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ABSTRACT

From a study to $V = 19.1$ and $B = 20.8$ mag in the *UBV* system of ~385 stars near the G2 globular cluster NGC 6304, we have found a color-magnitude diagram whose characteristics appear similar to those of 47 Tucanae, supporting the conclusion that NGC 6304 is a moderately metal-rich cluster. The reddening, $E(B - V)$, has been estimated to be 0.58 ± 0.05 mag, and the distance modulus is found, assuming $M_{V,\mathrm{HB}} = +0.9 \pm 0.2$ mag, to be $(m - M)_0 = 13.4 \pm 0.2$ mag. The cluster is thus 4.8 kpc from the Sun and 450 pc above the galactic plane, and it has an absolute visual magnitude of -6.8. Cluster membership of the numerous variable stars in this field remains uncertain, although one red and two possible RR Lyrae variables may be cluster members.

Subject headings: clusters: globular — stars: abundances — stars: Population II

I. INTRODUCTION

From comparative studies to the main sequence of metal-poor and metal-rich globular clusters, it should be possible to explore in greater depth both the processes that led during the earliest stages of galactic chemical evolution to the heavy-element enrichment of the star-forming material and the effects of increasing heavy-element enrichment on subsequent evolution of the older galactic stars. Although the properties of the main sequence in the metal-rich globular clusters (which lie predominantly at moderate to large southern declination) can be examined precisely only once the large southern telescopes are fully operational, scientifically important results can be—and have been—obtained with the existing 1.5-m-class telescopes, and, as a result of work to the nineteenth magnitude on a number of clusters, it should be possible to select those clusters that can be studied most advantageously with the larger instruments. In this paper, the fourth of a series concerned with obtaining color-magnitude (C-M) diagrams at Cerro Tololo for metal-rich globular clusters, we describe our observations of NGC 6304 [$\alpha(1975) = 17^{\mathrm{h}}13^{\mathrm{m}}.0$, $\delta(1975) = -29°26'$; $l = 356°$ and $b = 5°$]. Previous papers in the series have dealt with *UBV* investigations of NGC 6352 (Hartwick and Hesser 1972 [Paper I]), NGC 104 or 47 Tucanae (Hartwick and Hesser 1974 [Paper II]), and NGC 6441 (Hesser and Hartwick 1976 [Paper III]). Of the previously studied clusters, NGC 6352 appears from the broad-band photometry to have a disklike metals-to-hydrogen ratio, while NGC 104 has [Fe/H] = -0.48; NGC 6441, a massive cluster that lies within an *Uhuru* X-ray source error box, has a C-M diagram whose characteristics are also reminiscent of the most metal-rich globular clusters known. NGC 6304, the last cluster on our current program, was chosen because both its late integrated spectral type, G2 (Kinman 1959), and its Q-value, -0.09 (van den Bergh 1967), indicate that it is among the more metal-enriched Population II clusters. Furthermore, the field surrounding NGC 6304 is rich in variable stars, particularly of the RR Lyrae type, and we have simultaneously obtained a plate collection that is presently under analysis in order to make an additional probe of the nuclear bulge of the Galaxy in the manner previously described (Hartwick *et al.* 1972).

In § II of the current paper we describe the photoelectric calibrating sequence and the photographic photometry; in § III, the results of the photometry and the reddening determination are discussed; and in § IV we summarize our findings.

II. OBSERVATIONS

a) *Photoelectric Standards*

Forty stars within ~10′ of NGC 6304 were observed photoelectrically during the 1969–1973 seasons using the 41-cm, 91-cm, and 1.5-m telescopes on Cerro Tololo. The observational techniques have been amply described in earlier publications (see particularly Paper III and Hartwick *et al.* 1972). Throughout this long-range study of the metal-rich globular clusters seen through crowded, low galactic latitude windows

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TABLE 1

PHOTOELECTRICALLY MEASURED UBV SEQUENCE STARS FOR NGC 6304

Star	V_{pe}	$(B-V)_{pe}$	$(U-B)_{pe}$	$n(V/B-V/U-B)_{pe}$	V_{pg}	$(B-V)_{pg}$
A	10.25	1.22	0.94	4/4/4		
H	10.70	1.01	0.45	2/2/2		
J	11.47	1.40	1.18	2/2/2		
5	14.88	0.93		3/3/0	14.83	1.01
7	13.95	1.65		2/2/0	13.93	1.67
9	18.95	1.63		1/1/0	18.70	1.63
10	16.28	1.49		2/2/0	16.36	1.50
11	18.73	1.43		1/1/0	19.03	1.41
12	17.47	1.81		1/1/0	17.57	1.95
13	15.35	1.51		3/3/0	15.37	1.49
14	17.15	1.17		1/1/0	17.33	1.10
15	16.61	1.61		2/2/0	16.70	1.62
16	13.57	1.01		3/3/0	13.55	0.98
17	13.88	2.01		2/2/0	13.89	2.04
18	18.87	1.47		2/2/0	18.84	1.57
21	16.04	1.02		1/1/0	16.02	1.03
24	15.46	2.00		1/1/0	15.44	1.90
29	15.48	0.92		2/2/0	15.41	0.98
30	16.55	1.04		1/1/0	16.62	1.00
31	15.16	2.09		2/2/0	15.10	2.06
33	14.21	1.66		2/2/0	14.25	1.65
34	15.27	0.81	0.43	3/3/1	15.25	0.83
35	17.07	1.30		1/1/0	16.84	1.28
36	13.31	0.80		2/2/0	13.39	0.73
38	18.28	2.22		1/1/0	18.27	1.88
40	19.15	1.65		2/2/0	19.03	1.82
41	15.35	2.09		3/3/0	15.36	2.08
42	17.71	1.73		1/1/0	17.69	1.73
43	15.21	1.56		2/2/0	15.27	1.59
44	13.83	1.15		2/2/0	13.86	1.12
45	17.14	1.14		1/1/0	17.14	1.15
51*	16.04	1.12		2/2/0	16.03	1.10
52*	16.55	1.87		2/2/0	16.65	1.89
53*	15.50	1.74		1/1/0	15.55	1.70
54*	14.09	2.17		1/1/0	14.21	2.09
55*	16.07	1.93		1/1/0	16.01	1.95
56*	15.54	0.95	0.40	1/1/1	15.57	0.89
57*	16.48	1.69		1/1/0	16.71	2.13
58*	15.09	2.12		1/1/0	15.18	2.11
4238*	14.72	1.92		2/2/0	14.59	2.01

TABLE 2

PHOTOGRAPHIC PHOTOMETRY FOR NGC 6304 STARS

Star	V	B-V	Star	V	B-V
1101	14.62	1.94	1235	14.99	1.02
1102	16.98	1.48	1236	16.63	1.80
1103	17.52	0.86	1237	16.85	1.48
1104	17.48	1.49	1238	16.87*	1.14*
1105	17.45	1.82	1239	15.76	2.10
1106	17.09	1.32	1240	17.49	1.30
1107	16.79	1.49	1241	17.03	1.41
1108	17.47	1.74	1242	17.19	1.75
1109	16.95	1.58	1243	15.79	1.58
1110	15.87	1.53	1244	16.73	1.35
1201	17.52	1.95	1245	16.91	1.37
1202	15.66	2.11	1246	16.99	1.43
1203	16.75	1.71	1247	16.15	0.78
1204	16.99	1.39	1248	16.17	2.02
1205	16.87	1.74	1249	16.86	1.83
1206	17.52	1.86	1250	16.06	1.84
1207	17.82	1.60	1251	16.36	1.75
1208	14.63	2.00	1252	17.45	1.50
1209	15.24	1.63	1261	18.82	1.09
1210	16.80	1.68	1262	18.93	1.51
1211	15.90	2.07	1263	18.68	1.52
1212	16.14	1.46	1264	18.00	1.67
1213	16.22	1.44	1265	18.71	1.33
1214	16.82	1.83	1266	18.61	1.53
1215	17.33	1.53	1267	18.15	1.45
1216	16.42	2.00	1268	18.43	1.38
1217	16.12	1.51	1269	18.30	0.96
1218	17.73	1.40	1270	18.26	1.16
1219	16.42	1.77	1271	18.88	1.59
1220	17.48	1.10	1272	18.56	1.45
1221	16.94	1.45	1273	18.07	0.62
1222	17.54	1.65	1274	18.56	1.37
1223	17.94	1.91	1275	18.33	1.23
1224	18.05	1.28	1276	18.73	1.92
1225	16.90	1.46	1277	18.39*	1.30*
1226	15.63	2.07	1278	18.90	1.76
1227	15.17	1.71	1279	18.78	1.39
1228	16.57	1.10	1280	18.86	1.29
1229	16.82	1.51	1281	18.80	1.78
1230	17.51	1.50	1282	18.96	1.44
1231	16.09	1.81	1283	18.80	1.57
1232	14.51	1.97	1284	18.82	1.63
1233	16.48	1.25	1285	17.79	1.27
1234	16.18	1.45	1286	18.52	1.37

TABLE 2 (continued)

Star	V	B-V	Star	V	B-V
1287	18.23	0.93	2229	16.16	1.40
1288	18.40	1.48	2230	16.97	1.71
1289	18.29	1.29	2231	16.08	1.36
1290	18.31	1.51	2232	16.84	1.56
2101	17.83	1.32	2233	17.32	1.56
2102	17.28	1.36	2234	17.76	1.08
2103	16.67	1.54	2235	15.04	1.64
2104	15.88	1.58	2236	14.63	1.97
2105	15.72	1.60	2237	17.18	1.11
2106	15.70	1.70	2238	16.94	1.40
2107	17.12	1.71	2239	16.86	1.78
2108	15.92	1.37	2240	16.09	1.60
2109	15.99	1.58	2241	16.05	2.03
2110	17.28	1.56	2242	14.25	1.53
2111	17.36	1.38	2243	16.99	1.47
2112	16.70	1.48	2244	17.52	1.17
2113	16.04	1.51	2245	16.33	1.46
2114	17.12*	1.35*	2246	15.66	1.91
2201	15.02	1.81	2247	15.97	1.61
2202	15.60	1.06	2248	14.79	1.80
2203	17.43	1.63	2249	15.97	1.58
2204	17.20	1.49	2250	16.42	2.12
2205	15.71	1.11	2251	16.57	1.49
2206	16.70	1.45	2252	17.48	1.74
2207	16.47	1.73	2253	17.69	0.51
2208	17.15	1.40	2261	17.93	1.15
2209	17.28	1.73	2262	18.25	1.37
2210	17.46	1.68	2263	18.58	1.12
2211	17.95	1.51	2264	18.82	1.39
2212	16.74	2.06	2265	18.48	1.17
2213	17.75	1.86	2266	18.52	1.20
2214	14.00	1.70	2267	18.82	1.43
2215	16.16	1.48	2268	17.88	1.25
2216	17.47	1.64	2269	18.84	1.11
2217	17.19	1.48	2270	18.82	1.19
2218	17.22	1.68	2271	18.06	1.35
2219	17.18	1.43	2272	18.00	1.35
2220	17.22	1.68	2273	18.65	1.37
2221	17.40	1.42	2274	18.07	1.19
2222	16.96	1.47	2275	18.09	1.34
2223	16.01	1.42	2276	18.40	1.30
2224	16.52	1.57	2277	18.13	1.34
2225	16.45	1.53	2278	18.43	0.95
2226	17.68	1.34	2279	17.88	1.04
2227	16.97	1.37	2280	18.10	1.37
2228	15.81	1.44	2281	18.87	1.18

TABLE 2 (continued)

Star	V	B-V	Star	V	B-V
2282	18.17	1.52	3232	17.78	1.88
2283	18.70	1.29	3233	17.59	1.51
2284	18.29	1.42	3234	16.06	1.99
3101	15.98	1.44	3235	16.94	1.54
3102	17.87	1.61	3236	17.10	1.73
3103	16.95	1.49	3237	18.09	1.30
3104	17.28	1.26	3238	14.89	1.92
3105	15.32	1.82	3239	16.14	1.57
3106	15.51	1.67	3240	16.05	1.43
3107	16.22	1.56	3241	17.62	1.49
3108	17.47	1.40	3242	16.96	1.35
3109	17.72	1.55	3243	14.44	1.70
3110	15.96	1.47	3244	14.57	1.84
3111	16.57	1.86	3245	15.86	1.64
3112	16.00	1.45	3246	14.86	1.00
3201	17.71	1.71	3247	17.24	1.75
3202	15.35	1.76	3248	15.65	1.42
3203	17.59	1.45	3249	16.42	1.97
3204	16.53	1.54	3250	16.33	1.55
3205	17.74	1.79	3261	18.36	1.35
3206	14.05	2.04	3262	18.75	1.14
3207	17.32	1.83	3264	19.02	1.29
3208	17.54	1.18	3265	19.20	1.43
3209	17.48	1.91	3266	18.88	1.29
3210	16.87	1.73	3267	18.86	1.32
3211	16.86	1.57*	3268	18.90	1.17
3212	16.78	1.77	3269	18.34	1.39
3213	15.08	1.63	3270	17.87	1.34
3214	16.70	1.53	3271	18.10	1.33
3215	16.52	1.52	3272	18.44	1.08
3216	15.88	1.01	3273	18.58	1.21
3217	16.90	1.68	3274	18.61	1.28
3218	16.83	1.08	3275	18.57	1.07
3219	16.92	1.46	3276	18.26	1.50
3220	16.65	1.89	3277	18.64	1.39
3221	15.50	1.50	3278	18.34	1.71
3222	16.43	1.70	3279	17.94	1.44
3223	15.65	1.71	3280	18.51	1.39
3224	15.64	1.45	3281	18.38	1.40
3225	17.54	1.75	3282	18.81	1.09
3226	17.62	1.66	3283	18.40	1.41
3227	15.07	1.14	3284	18.39	1.14
3228	16.95	1.53	4101	17.24	1.49
3229	16.08	1.38	4102	16.96	1.56
3230	16.10	1.36	4103	17.40	1.29
3231	16.39	0.87	4104	16.20	1.65

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TABLE 2 (continued)

Star	V	B-V	Star	V	B-V
4105	16.43	1.69	4238	14.59	2.01
4106	15.26	1.79	4239	16.41	1.19
4107	16.12	1.68*	4240	16.60	1.63
4108	17.04	1.44	4241	15.94	1.65
4109	16.89	1.83	4242	16.15	1.77
4110	17.45	1.04*	4243	16.10	1.53
4111	17.27	1.18	4244	16.12	1.52
4112	15.56	1.53	4245	16.19	1.44
4113	17.19	1.47	4246	15.81	1.54
4201	17.05	1.85	4247	17.45	1.08
4202	16.17	1.50	4248	17.60	1.76
4203	14.97	2.10	4249	16.34	1.42
4204	15.18	1.67	4250	17.95	1.88
4205	16.57	1.36	4261	18.83	1.31
4206	17.04	1.59	4262	17.67	1.33
4207	14.54	0.97	4263	18.79	1.36
4208	16.99	1.54	4264	18.63	1.25
4209	16.47	0.76*	4265	18.26	1.81
4210	15.68	1.67	4266	18.25	1.31
4211	16.50	1.07	4267	18.89	1.16
4212	17.35	1.97	4268	18.67	1.12
4213	15.42	0.58	4269	18.72	1.25
4214	16.52	1.42	4270	18.01	1.17
4215	15.05	1.79	4271	17.89	1.92
4216	16.83	1.80	4272	17.96	1.40
4217	16.54	1.68	4273	18.54	1.39
4218	16.14	1.41	4274	18.27	1.49
4219	15.38	1.77	4275	17.66*	1.98
4220	15.01	1.86	4276	18.41	1.22
4221	16.11	1.54	4277	18.96	1.45
4222	17.27	1.46	4278	18.02	0.95
4223	14.24	2.05	4279	17.91	1.37
4224	16.11	1.08	4280	18.45	1.48
4225	17.29	1.79	4281	17.65	1.99*
4226	17.02	1.22	4282	18.49	1.57
4227	16.29	1.38	4283	18.63	1.36
4228	15.86	1.86	4284	18.41	1.41
4229	15.59	1.53	4285	17.77	1.09
4230	16.62	1.53	9001	18.05	1.43
4231	17.24	1.92	9002	18.13	1.56
4232	15.16	1.73	9003	17.67	1.77
4233	17.33	1.61	9004	18.35	1.27
4234	17.94	1.61	9006	17.16	1.64
4235	17.20	1.37	9008	16.54	1.69
4236	17.17*	1.25	9019	18.87	1.73
4237	16.97	1.69	9020	18.33	1.14

TABLE 2 (continued)

Star	V	B-V	Star	V	B-V
9022	17.75	1.49	9048	18.77	1.56
9023	18.75	1.46	9049	18.83	1.51
9024	15.44	1.90	9050	18.74	1.21
9025	18.34	1.44	9051	16.03	1.10
9026	17.62	1.16	9052	16.65	1.89
9027	18.24	1.39	9053	15.55	1.70
9028	17.79	1.15	9054	14.21	2.09
9032	17.44	1.33	9055	16.01	1.95
9037	18.40	1.78	9056	15.57	0.89
9039	19.00	1.72	9057	16.71	2.13
9046	18.55	1.42	9058	15.18	2.11
9047	18.67	1.63			

in the interstellar absorption, we have followed the precept (Gascoigne 1966) that it was preferable to secure single measures of as large a sample of faint stars as possible, rather than measures of a few stars on many nights. This should tend to minimize systematic errors that might arise in the photoelectric scale due to the difficulties of properly accounting for the variable background at the faintest magnitudes. The NGC 6304 field presented great difficulties in that it was possible to find few stars on deep plates that allowed the measurement of sky brightness in more than two directions apparently free of contaminating stars.

The resulting sequence of 40 stars is presented in Table 1, where an asterisk following a star number indicates that the star was not used in the subsequent transformation of the photographic data. The sequence extends from $10.7 \leq V \leq 19.1$ mag and $11.4 \leq B \leq 20.8$ mag, with 25 percent of the stars having visual magnitudes fainter than 17.0. Errors in transformation to the *UBV* system were less than 0.02 mag. The median standard deviation of an individual photoelectric measure can be estimated, from stars having multiple photoelectric observations, to be about 0.02 mag in both V and $(B - V)$ for $V < 16.0$ mag; while for stars fainter than that magnitude the median error becomes about 0.04 mag in V and 0.06 mag in $(B - V)$, if two suspected variables are excluded from the color measurements. The median absolute difference between the photographically determined values and the photoelectric values are about 0.04 mag in both V and $B - V$ for stars brighter than the sixteenth visual magnitude, while for the fainter stars they are about 0.08 mag in V and 0.02 mag in $(B - V)$; the latter value would appear to be an unrealistically low limit to the actual errors.

The stars of Table 1 are identified in Figure 1 (Plate 3); also included in that figure are a number of stars that were selected from inspection of deep plates as being potentially suitable for photoelectric measurement and whose photographically determined magnitudes will be presented below. The star labeled B appears from the two photoelectric measurements available to be a red variable. From the comparison of photoelectric and photographic values for star 57 of Table 1, we suspect it may also be a variable; however, since the individual photographic values show low scatter, it may be that the discrepancy is due to crowding.

b) *Photographic Measurements*

As for other clusters we have studied, the plate material utilized herein was obtained with the f/7.5 Ritchey-Chrétien focus of the 1.5-m telescope; for the V and B plates, 103aD + GG14 and IIaO + GG13 plate-filter combinations, respectively, were used. Stars were measured on three plates in V and two plates in B; all exposure times were 30 min. The reduction procedures were the same as those for Paper III. The measured stars are identified in Figure 2 (Plate 4), and the results of the photographic measures are given in Table 2 for ~385 stars; those stars whose identifying numbers begin with 90 are to be found in Figure 1. The median standard errors in the photographic photometry are ±0.02 mag in V and ±0.03 mag in $(B - V)$. In the table, all values whose standard errors exceed 0.10 mag are denoted by an asterisk, as they may be of future use in identifying variable stars.

III. RESULTS

a) *Color-Magnitude Diagram and Variable Stars*

The C-M diagram for the stars of Table 2 is presented in Figure 3. Not surprisingly for a field in the

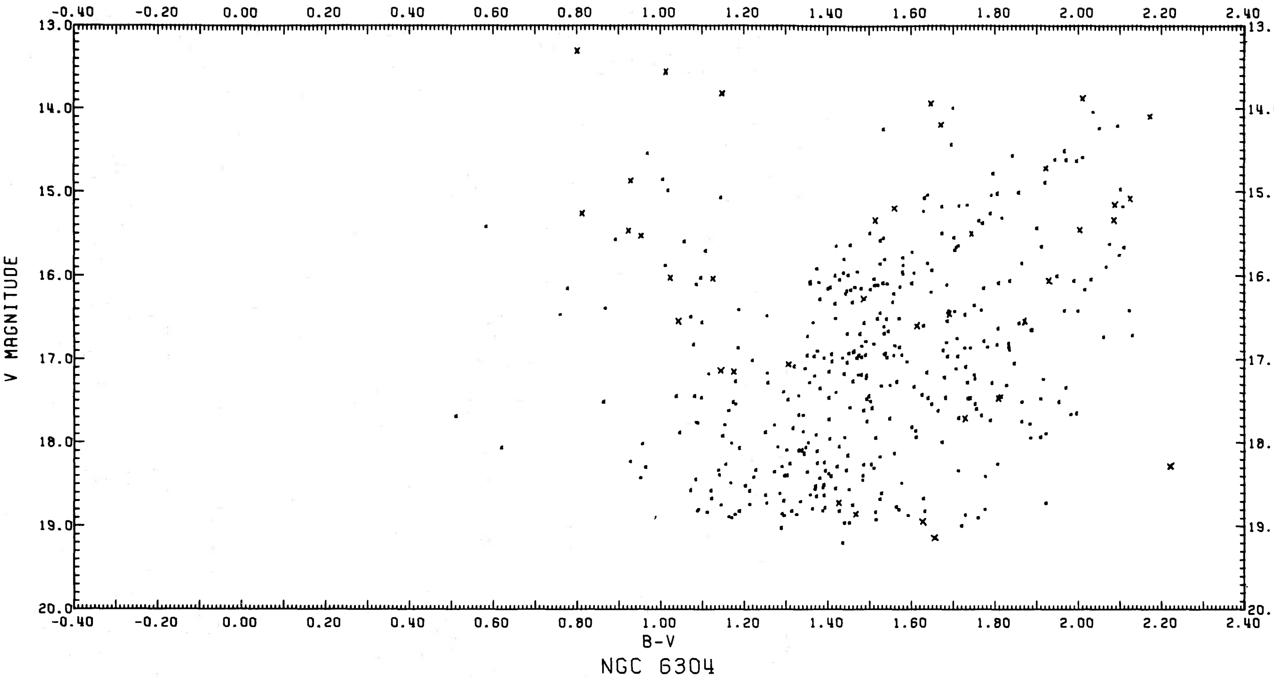

FIG. 3.—The C-M diagram for the program stars of Table 2; the photoelectric standards of Table 1 are denoted by crosses.

direction of the galactic bulge, contamination by nonmembers of a cluster is high. However, several cluster features are evident: a gently sloped giant branch running from $V = 16.0$ and $(B - V) \approx 1.6$ to $V = 14.2$ and $(B - V) \approx 2.1$ mag, a very stubby red horizontal branch at $V = 16.2$ and $(B - V) \approx 1.47$ mag, and an ill-defined subgiant branch. The topology of the C-M diagram is very similar to that of 47 Tucanae (Paper II), and supports, in accord with the high Q-value and the integrated spectral type, the contention that NGC 6304 is metal-rich.

To examine further the location and reality of the

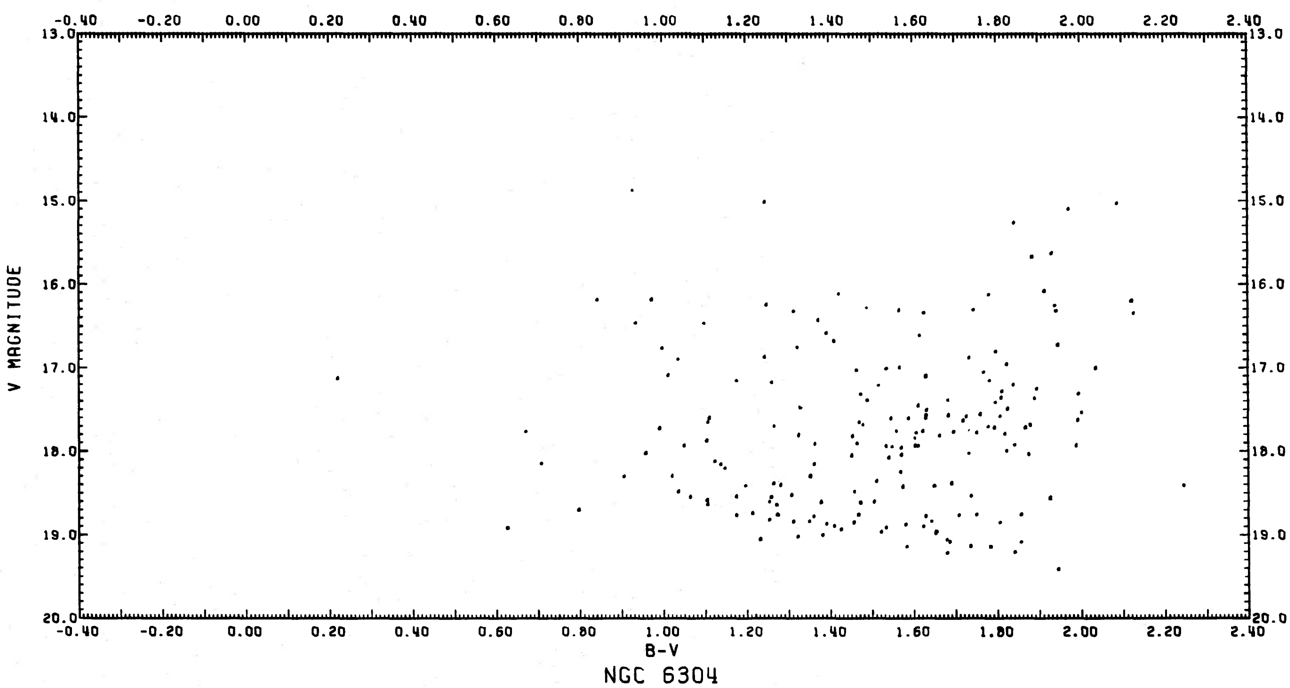

FIG. 4.—The C-M diagram for the homogeneous sample of field stars described in the text

sequences identified in Figure 3, a homogeneous sample of ~185 field stars was measured in two regions of total area 6.3 square arc-minutes located ~9′.9 SE and SW of the cluster. The field-star C-M diagram, Figure 4, clearly does not show the above-mentioned features. Furthermore, we attempted statistically to account for the contamination of Figure 3 by field stars in the following manner. The C-M diagram was divided into areas of dimensions 1.0 mag in V and 0.2 mag in $(B - V)$. Then the number of field stars in each cluster area (after normalization of those numbers for the area sampled in the field star measurements to those sampled in the cluster measurement) was determined and used to subtract on a random basis stars from Figure 3. A persistence of those features which were identified in Figure 3 with cluster sequences in the field-star corrected diagram, Figure 5, lends additional support to the original identifications.

Of the variable stars listed in Hogg's (1973) catalog as belonging to NGC 6304, only one was measured by us in this program. V15, corresponding to star 1202 in Table 2 and Figure 2, may be one of the red variables that characteristically are found in metal-rich globular clusters (cf. Feast 1973). As mentioned previously, Mrs. Hogg's catalog lists many RR Lyrae variables which have been found, principally by Terzan (1966, 1968), around NGC 6304. In view of the apparent lack of a blue extension of the horizontal branch in the C-M diagram, Figure 3, even the RR Lyrae stars closest to the cluster center may also be field stars. This, however, is a very tentative conclusion because stars 1247 and 4209 lying at $V \approx 16.3$ mag and $(B - V) \approx 0.77$ mag, both show unusually large plate-to-plate scatter and *may* be variable stars; both of these stars are within 1′.5 of the cluster center. We have undertaken a systematic study of the variables in this field, utilizing data taken in a manner similar to that used in our study of the field RR Lyrae variables near NGC 6522 (Hartwick *et al.* 1972); and those results will be reported separately.

b) *The Interstellar Reddening near NGC 6304*

Direct long-exposure photographs show that the interstellar absorption near NGC 6304 is remarkably uniform for its galactic coordinates; however, it is to be expected that the absorption will be appreciable, even if uniform. A careful determination of $E(B - V)$ is therefore essential if we are to be able to fully intercompare NGC 6304 with other globular clusters. Essentially four methods are available to us at this time for estimating the effect: photoelectric measures of foreground stars; comparison of the C-M diagram with those of clusters whose $E(B - V)$ values are well known; the use of the (spectral type, integrated color)-relations; and, finally, the [integrated neutral hydrogen, $E(B - V)$]-relationship. Taking each of these methods in turn, we shall attempt to obtain a reliable value of $E(B - V)$ for NGC 6304.

Three stars in Table 1 (H, 34, and 56) can be unreddened assuming that they are main-sequence stars; however, without knowledge of their spectral types, the solutions for two stars are degenerate. The two solutions yield average values of 0.40 ± 0.09 mag and 0.55 ± 0.05 mag for $E(B - V)$. Second, three Cepheids [BF Oph ($l = 357°$, $b = +8°.6$), RV Sco

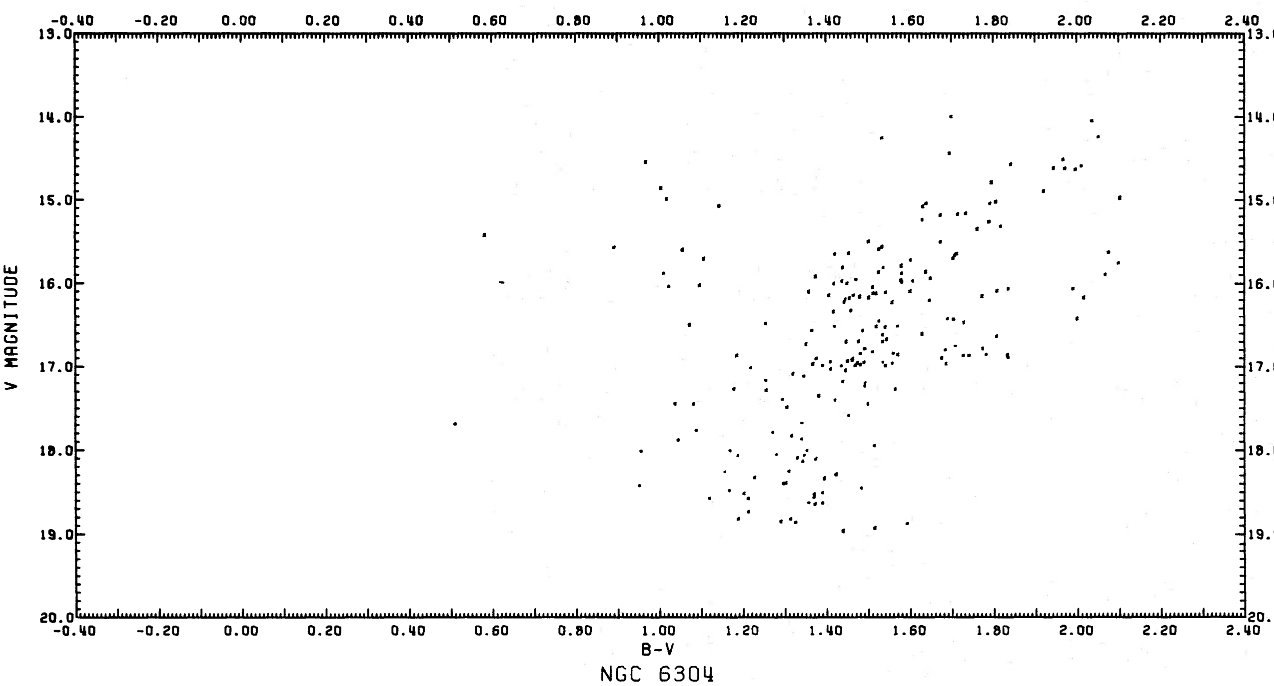

FIG. 5.—The C-M diagram of Fig. 3 after subtraction at random of points in accordance with the relative distribution of field stars within a magnitude and color interval, as described in the text.

($l = 350°$, $b = +5°7$), and V482 Sco ($l = 354$, $b = 0°2$)] lying within a few degrees of the cluster yield an average reddening of 0.36 ± 0.04 mag (Fernie and Hube 1968). On the average, however, these stars are ~900 pc from the Sun as well as having large angular distances from the cluster; and thus they may be expected to be only indicative of possible values, probably lower limits, of the actual color excess for the cluster. Finally, 43 early-type stars selected from both the HD catalog and objective prism spectroscopy have been measured with *uvby*–Hβ photometry (Hesser 1976). It is found that the reddening rises very steeply from zero to ~0.23 mag between 150 and 225 pc and then rises less rapidly to ~0.47 mag at the effective limit, 900 pc, of the photoelectric work [although it should be noted that one star 2 kpc distant yielded an $E(B - V) \approx 0.3$ mag]. Since the line of sight to NGC 6304 cuts the nominal 100-pc-thick absorbing layer at a distance of ~1150 pc, the four-color photometry does not extend to sufficient distances to guarantee that the growth of reddening has ceased. Two alternate interpretative approaches may be taken with respect to the *uvby*–Hβ photometric data. An average of the most distant stars observed can be formed that will presumably be a good *lower* limit to the actual $E(B - V)$; for nine stars with distances between 700 and 2000 pc, $E(B - V) = 0.38 \pm 0.09$ mag. Alternatively, we may linearly project the apparent growth of reddening between 225 and 900 pc to 1150 pc yielding $E(B - V) = 0.59$ mag.

Superposition of the C-M diagrams of NGC 104 (Paper II) and NGC 6304 leads to a reddening of 0.57 mag, allowing for the 0.04 mag reddening adopted in Paper II for 47 Tuc. Although the C-M diagram, Figure 3, for NGC 6304 does not show heavily populated and thus well-delineated sequences, there is no evidence from the superposition with 47 Tuc of significant deviations from the latter's well-defined sequences, whereas such deviations were apparent for NGC 6441 (Paper III). Thus this superposition value of the reddening may be less affected by differences in chemical composition and, hence, be nearer the actual value than similar estimates for NGC 6352 (Paper I) or 6441 (Paper III).

Analyses of van den Bergh's (1967) integrated photometry of globular clusters have all met with remarkable success in yielding, from the use of an (integrated color, spectral type)-relationship, values of $E(B - V)$ in accord with independent determinations for the halo clusters (Harris and van den Bergh 1974; Racine 1973; Burnstein and McDonald 1974). Unfortunately—for the disklike globular clusters—accurate, independent reddening estimates are essentially unavailable, and it is impossible to evaluate the reliability of the method. Recent analyses of the integrated color data by Racine (1973), Harris and van den Bergh (1974), and Burnstein and McDonald (1974) yield $E(B - V)$ values of 0.57, 0.43, and 0.63 mag, respectively, for NGC 6304. Despite the close agreement of the first and third values with those derived from the *uvby*–Hβ photometry and the superposition with 47 Tuc, all of the values must be considered uncertain until further independent checks of late G-type cluster reddenings have been made.

Finally, the integrated neutral-hydrogen column density in the direction of NGC 6304 has been measured by Knapp and Kerr (1974), and interpreted by them—using in large part Racine's (1973) work as a calibration—as yielding a color excess of 0.43 mag.

From consideration of all the available data and the limitations thereof, we choose a value of $E(B - V) = 0.58 \pm 0.05$ mag for use in subsequent interpretations of the NGC 6304 C-M diagram.

c) *Distance Modulus and Absolute Magnitude*

Having failed to reach the main sequence, we must make certain assumptions if we are to derive additional parameters from the available data. If the horizontal branch of NGC 6304, which appears at $V = 16.2$ mag in Figure 3, has the same absolute magnitude as that of 47 Tuc, +0.9 ± 0.2 mag (Paper II), then, using 3.3 for the ratio of total to selective absorption, we find $(m - M)_0 = 13.4 \pm 0.2$ mag, corresponding to a distance from the Sun of 4.8 kpc, 450 pc above the galactic plane. From the integrated magnitude, $V = 8.48$ (Kron and Mayall 1960), the absolute visual magnitude of NGC 6304 is found to be −6.8.

IV. SUMMARY

This photometric study of the G2 globular cluster NGC 6304 has yielded the following results: (1) The C-M diagram closely resembles that of NGC 104, 47 Tucanae (Paper II), and other metal-rich clusters, in having a predominantly red horizontal branch and gently sloping giant branch indicative of a high [Fe/H] ratio. This finding is in accord with both its spectral type and its *Q*-value. Since field star contamination is severe, it is more difficult to ascertain the structure of the subgiant branch or the presence of any unusual features in the C-M diagram. (2) From a study of four different methods of estimating the color excess due to interstellar reddening, we choose a value of $E(B - V) = 0.58 \pm 0.05$ mag, based principally upon measurements of foreground early-type stars in the *uvby*–Hβ system (Hesser 1975) and on superposition with the C-M diagram of 47 Tuc. (3) The apparent distance modulus of NGC 6304 is $(m - M)_{\text{app.}V} = 15.3$; assuming $M_{V,\text{HB}} = +0.9$ mag, the true distance modulus is $(m - M)_0 = 13.4$ mag, and the absolute integrated magnitude for the cluster is $M_V = -6.8$ mag. (4) What fraction of the rich concentration of RR Lyrae variable stars in the vicinity of NGC 6304 represents cluster members remains unclear. The structure of the horizontal branch would appear to rule out RR Lyrae star members in the cluster, but two stars within 1′5 of the cluster center are good candidates, based upon their position in the C-M diagram, for cluster members. One star, V15, may be a red giant variable of the type found in other metal-rich globular clusters. Analysis of the properties of the variables in this field is currently under way, and the results will be presented at a later date.

As in the past we wish to record our gratitude to the night assistants at CTIO for their outstanding aid during the last six years; to Mrs. M. Reeves for her careful photographic photometry; and to Srta. L. Vega and Sr. P. Ugarte P. for their aid with the photoelectric data reduction. We also thank Srta. N. Cruz, Sra. S. Amenabar, and Sr. E. Rojo for their aid in preparing the paper for publication. Finally, we are grateful to the referee, G. D. Illingworth, and N. R. Walborn for their criticisms of the original manuscript.

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PLATE 1

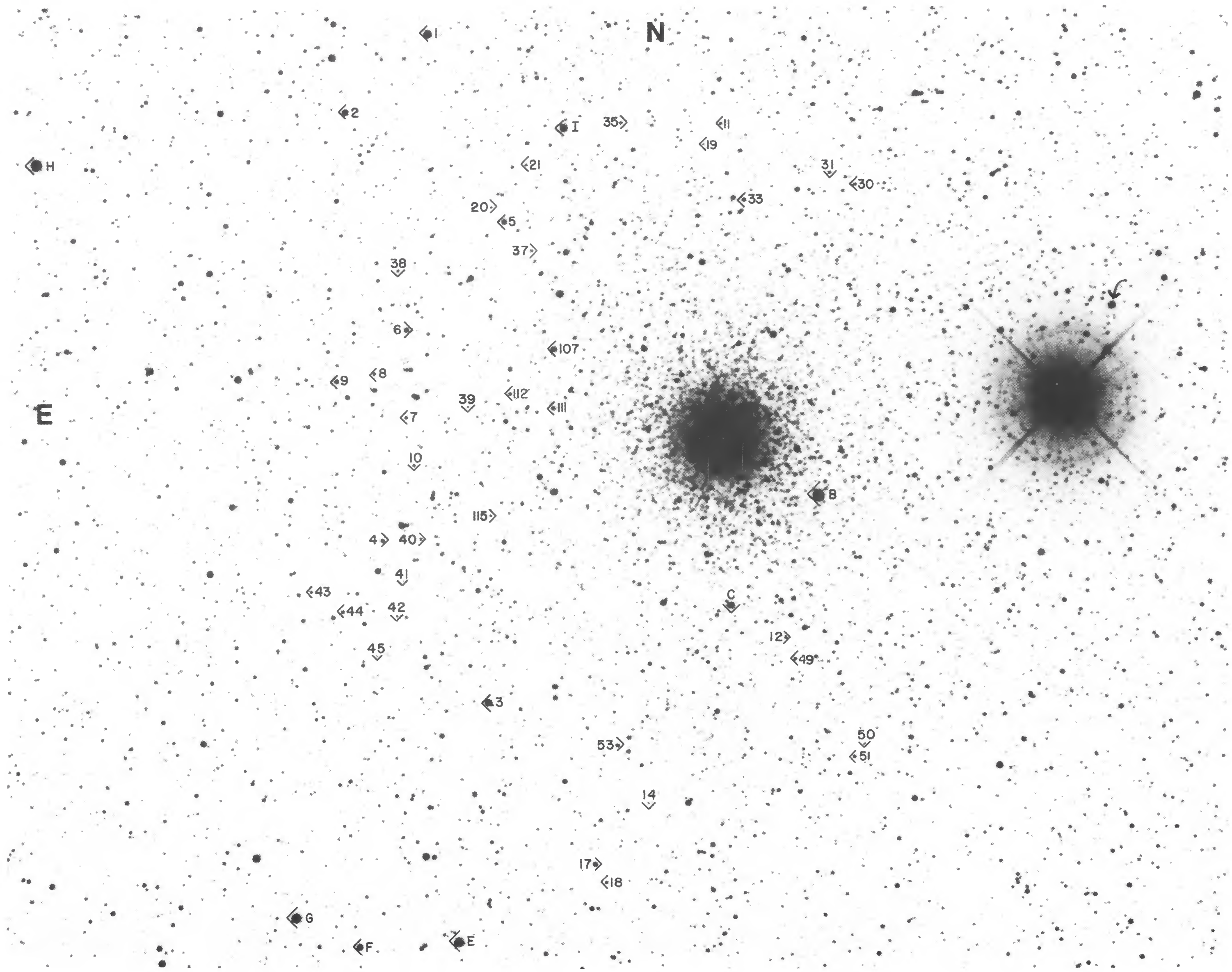

FIG. 1.—A 30-min visual (103aD + GG 14) exposure of NGC 6441 taken at the f/7.5 focus of the 1.5-m telescope, upon which the photoelectric sequence stars of Table 1 are identified. The bright star is approximately 4′.4 from the cluster center, and Webster's X-ray candidate (§ III*d*) is marked with an arrow and appears immediately NW of the bright star.

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PLATE 2

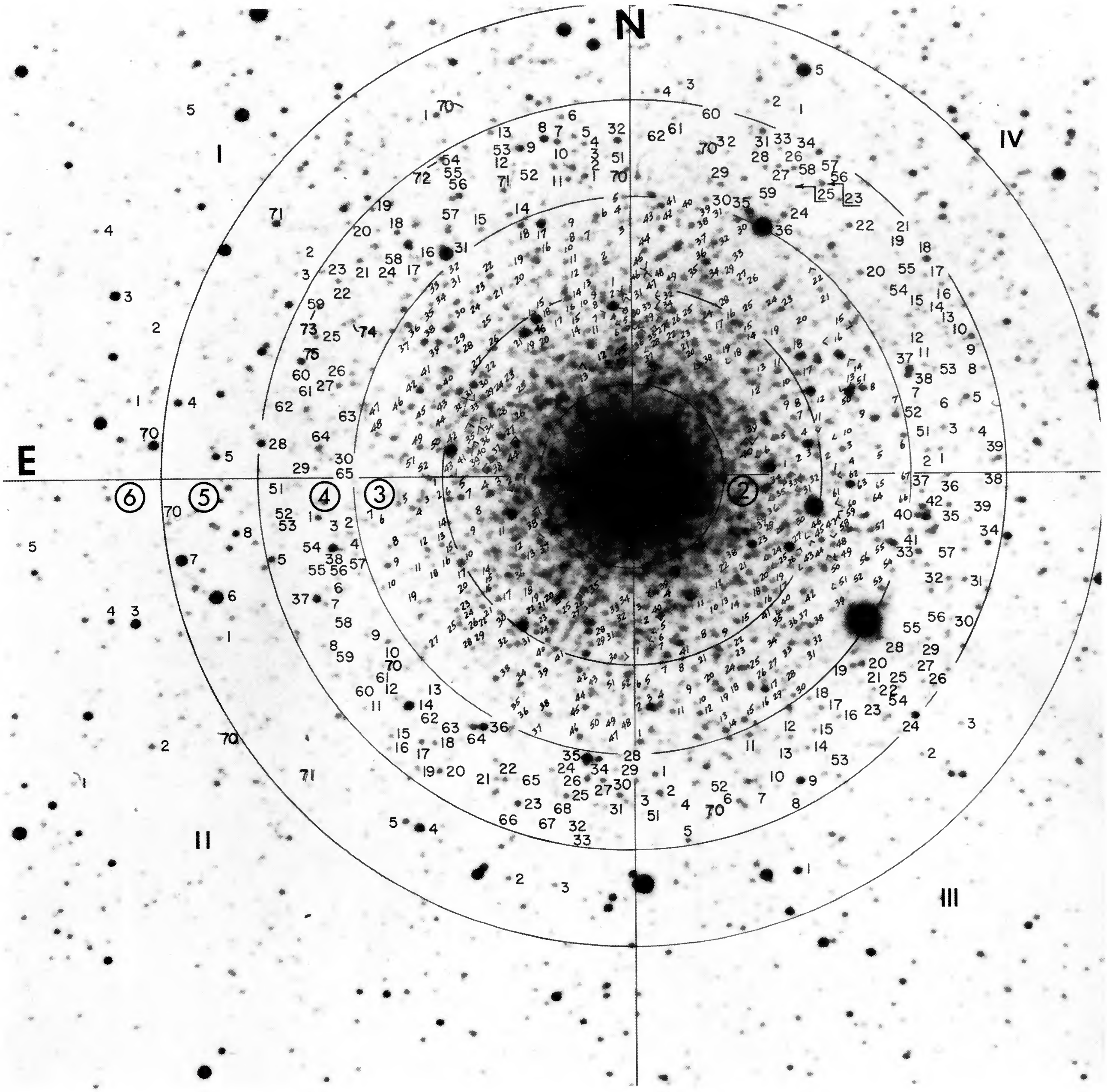

FIG. 2.—A 15-min visual (103aD + GG 14) plate, also taken at f/7.5, showing the stars measured photographically in NGC 6441. The outermost circle has a radius of ~2.′5 and each successively smaller circle decreases in radius by 0.′5. The first two digits of the four-digit stellar identification numbers in Table 2 refer to the quadrant and ring numbers, respectively, of this chart.

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