1964ApJ...139.1088S

THREE-COLOR PHOTOMETRY OF THE METAL-RICH GLOBULAR CLUSTER NGC 6171

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Received December 9, 1963

ABSTRACT

Photometry of 293 stars shows that NGC 6171 ($\alpha_{1950} = 16^h29^m.7$, $\delta_{1950} = -12°57'$) is a moderately strong-lined globular cluster of Morgan's metal class V. The color-magnitude diagram is considerably different in two characteristics from the diagrams of weak-line clusters of the halo: (1) the horizontal branch in NGC 6171 is heavily populated on the red side of the variable star gap; (2) the giant stars at $(B - V)_0 = +1.4$ rise only $2^m.0$ above the horizontal branch in contrast to the value of $\Delta V = 3^m.0$ that occurs in the weak-line halo clusters.

The reddening is $E(B - V) \simeq 0^m.30$ as determined by the three-color method using foreground field stars and checked by other methods. Adopting this value gives a very small ultraviolet excess of $\langle\delta(U - B)\rangle_{av} = +0^m.06 \pm 0^m.06$ (A.D.) for the cluster giants. Comparison with $\langle\delta\rangle_{av} \simeq 0^m.2$ to $\langle\delta\rangle_{av} \simeq 0^m.3$, which applies to the weak-line clusters, shows that the metal abundance for stars in NGC 6171 is closer to that of Hyades stars than to the halo globular clusters.

NGC 6171 is the only known cluster visible from the north in moderate galactic latitudes where main-sequence photometry can eventually be used to calibrate the absolute magnitudes of globular-cluster giant stars and RR Lyrae variables which have such a small abundance anomaly.

I. INTRODUCTION

In 1955 Johnson and Sandage showed by a comparison of the color-magnitude (C-M) diagrams of M67, M3, and M92 that the shape of a star's evolutionary track in the H-R diagram is affected by changes in the chemical composition. Independently of these observations, theoretical calculations predicting the result were made by Hoyle and Schwarzschild (1955) for two sets of chemical-composition parameters. Since that time, it has been suspected that the giant branches of hypothetical clusters of the same age whose compositions range between M92 and M67 (or NGC 188) might fill the region of the C-M diagram between these clusters (see Fig. 6 of Johnson and Sandage 1955), but the existence of such a continuum of chemical compositions was not known to occur in the galactic system. However, the discovery that the chemical composition of globular clusters varies by large factors from cluster to cluster (Mayall 1946; Deutsch 1955; Morgan 1956, 1959; Kinman 1959) reopened the possibility to test this hypothesis. Although it is not yet obvious that the entire range of chemical compositions exists between M92 and NGC 188 for clusters of the same age, it *is* clear that part of the range is covered.

Observation of the strong-line globular clusters of Morgan's class VII and VIII, so important for this problem, has proved to be exceedingly difficult because the clusters are located predominantly near the direction of the galactic center where the photometric effects of crowding by foreground stars and of interstellar reddening are serious. The crowded fields eliminate the possibility of reaching the main sequences of the clusters, a necessity (1) if the equality of age is to be established (or calibrated out) and thereby eliminated as a parameter of the problem, and (2) if the absolute magnitudes of the various branches are to be established. In addition, the strong interstellar reddening in the direction of the nuclear clusters eliminates the possibility of measuring accurately the ultraviolet excess of the member stars so as to establish the chemical composition, since, at the present time, it is difficult to separate $E(B - V)$ from $\delta(U - B)$ with broad-band photometry when $E(B - V)$ is large.

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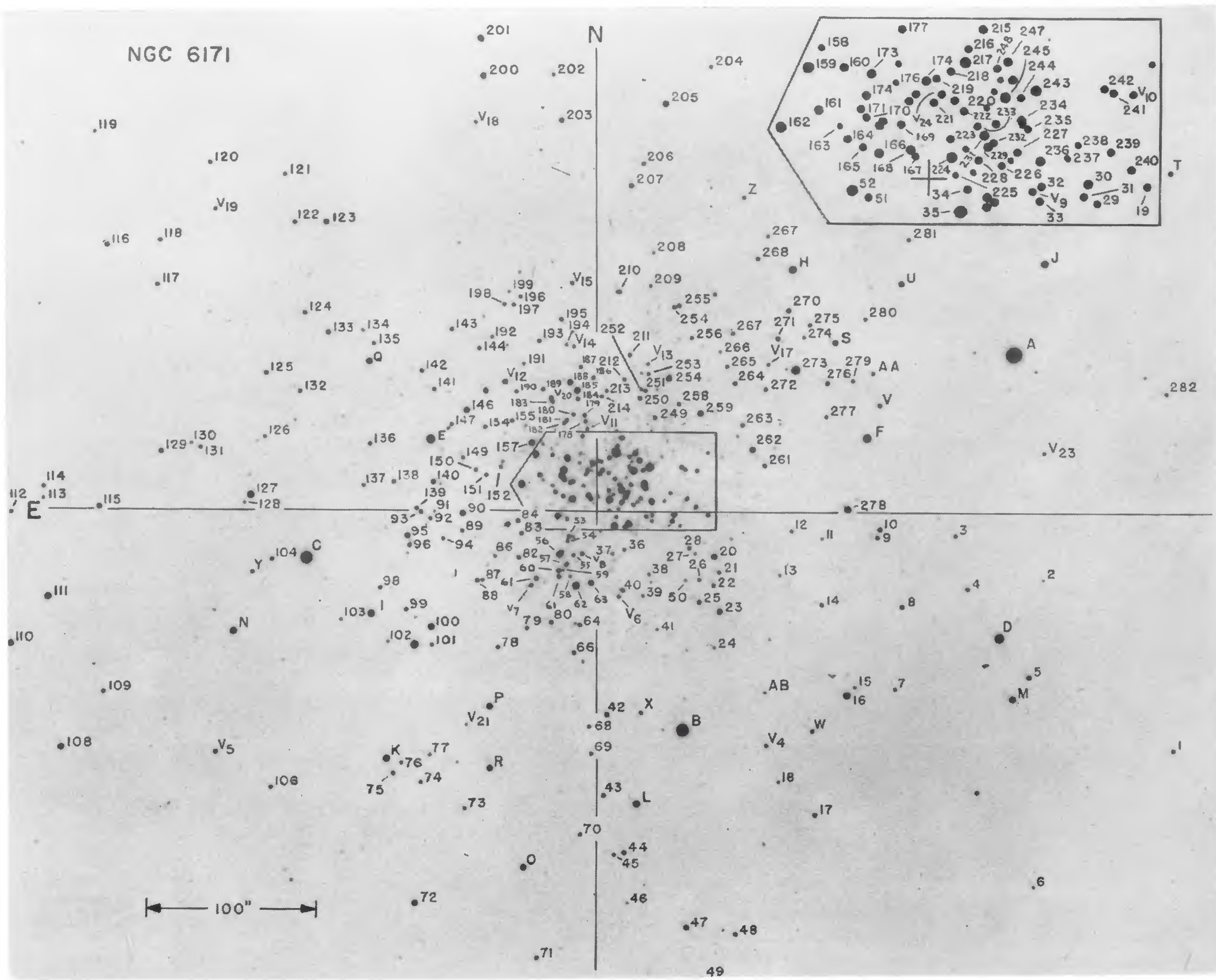

FIG. 1.—Identification chart for stars in Tables 1 and 2. Letters denote stars of the photoelectric sequence. The RR Lyrae stars found by Oosterhoff are designated by his numbers but prefixed by the letter *V*. Where possible, the identifying numbers appear in the upper right of the star image. The reproduction is from a 2-min exposure on 103a-D behind a GG11 filter taken with the 200-inch Hale reflector.

Nevertheless, some progress has been made on the bright end of the C-M diagrams of the strong-line globular clusters. Observations of NGC 6356 (Sandage and Wallerstein 1959), 47 Tuc (Wildey 1961; Tifft 1963), NGC 6712 (Smith and Sandage 1962), and NGC 6723 (Gascoigne and Ogston 1963) have shown that the character of the C-M diagrams differs considerably from the halo clusters. In particular, the height ΔV of the giant branches (read at $[B - V]_0 = +1.4$) above the horizontal branch is only $2^{m}.0$ instead of $3^{m}.0$ for the halo clusters with extreme metal weakening. However, this fact does not establish that the giant stars in the metal-rich clusters are fainter in absolute magnitude than their weak-line counterparts because no calibration through a main-sequence fit is available.

What is needed to accomplish the calibration is at least one strong-line globular cluster sufficiently far from the galactic plane so that faint photometry is possible. It is particularly important that the ultraviolet excess of the main-sequence dwarfs be observed so that the blanketing effects can be allowed for in deriving a photometric parallax. NGC 104 (47 Tuc) and NGC 6723 are two good candidates, but they are not visible with the large telescopes in the northern hemisphere.

Until recently, no suitable northern candidate was known, but it now appears that NGC 6171 ($\alpha_{1950} = 16^{h}29^{m}.7$, $\delta_{1950} = -12°57'$; $l^{II} = 3°$, $b^{II} = +23°$) is such a cluster. It is in relatively high galactic latitude where the crowding is small, and it has a high metal abundance, as suggested by the following data which were available before the present investigation was begun.

a) Mayall (1946) gives an integrated spectral type of G2, which Kron and Mayall (1960) later revised to G3 to put the types on Morgan's system of 1959. Kinman (1959) gives a type of G0–1 based on the CH/Hγ ratio.

b) The cluster has previously been studied by Oosterhoff (1937), who searched the cluster for variable stars. His work showed that many of the RR Lyrae stars are nearly as bright in blue light at maximum as the brightest giants in the cluster, a circumstance which suggests that ΔV is small, characteristic of the strong-line globular clusters (see Table 4 of Sandage and Wallerstein 1959).

c) Van Agt (1961) studied the topology of the H-R diagram using the technique of the pseudo–C-M diagram. He showed that most of the stars on the horizontal branch are on the red side of the variable star region, which is again characteristic of clusters of this type.

d) Kukarkin (1961) has determined the periods of the RR Lyrae stars and shows that $\langle P \rangle_{\mathrm{av}\, a,\, b}$ is $0^{d}.53$, which is somewhat shorter than the mean of Oosterhoff's (1944) short-period group, again signaling relatively high metal content.

The present paper gives the results of photoelectrically calibrated photometry of NGC 6171 done in the spring of 1963. The results confirm the suspicion that the cluster has a relatively high metal content. Because of the importance of NGC 6171 for many further studies, we have decided to discuss our preliminary data now rather than to wait for 2 or 3 years until the main-sequence photometry can be completed.

II. THE DATA

Twenty-eight photoelectric standards were determined in and near NGC 6171 with the 100- and 200-inch telescopes using a conventional refrigerated 1P21 photometer. The measurements were made on five different nights and were reduced to the *UBV* system by observing about fifteen standard stars for zero-point and color transformations on each night. Because the program was initially designed for reconnaissance, only one observation per star was obtained.

Table 1 gives the results and Figure 1 shows the identification of the sequence stars. The reproduction is from a 2-min exposure taken with the Palomar 200-inch Hale reflector on Eastman 103a-D emulsion behind a Schott GG11 filter. The results of measurement on photographic plates of 265 program stars, also identified in Figure 1, are given in Table 2. The measurements were made with an iris diaphragm photometer on four yellow plates (103a-D + GG11) with exposure times of 4 min, 2 min, 1 min, and 30 sec, and two blue plates (103a-O + GG13) with exposure times of 2 min and 1 min. The cluster, although more open in structure than any other strong-line cluster visible from the north, is still sufficiently compact that crowding difficulties exist near the center. The effect of crowding was eliminated for the central stars by plotting the difference in the magnitudes derived from the 4-min and 2-min exposures versus the distance from the cluster center, and then eliminating the measurements on the 4-min plate for stars closer to the center than was reliable as determined from the plot. The same procedure was

TABLE 1

STANDARDS IN NGC 6171

Name	Photoelectric Values				Photographic Values		Remarks
	V	$B-V$	$U-B$	n	V	$B-V$	
A	10 63	1 48	1.54	1	.		Non-member
B	11 69	0 74	0 18	5			Non-member
C	11 78	1 18	0 74	2	. . . . .	....	Non-member
D	12 88	1 24	0 75	1	12.90	1 22	Non-member
E.	13 20	1 85	1 88	1	13 22	1 99	
F	13 40	1 72	1 81	1	13 38	1 76	
G	13 43	1 70	1 83	1	13 46	1 68	
H	13 89	1 61	1.58	1	13 79	1.69	
I	13 93	1 45	1.27	1	13 90	1 41	
J	13.97	1.55	1.43	1	13 99	1.58	
K	13 99	1 43	1 37	1	14 02	1 46	
L.	14 01	1 44	. . .	1	14 02	1 46	
M	14 22	1 08	0 71	1	14.27	0 97	Non-member
N	14 25	1 50	1 38	1	14 22	1 51	
O	14 39	1 45	1 48	1	14.34	1 46	
P	14 41	1 08	0 61	1	14 42	0 95	Non-member
Q	14 43	1 62	1 73	1	14 40	1 60	
R	14 58	1 30	1.02	1	14 61	1.22	
S	14 77	1 43	1 16	1	14 75	1 44	
T	14 85	1 26	0 86	1	14 93	1 30	
U	14 87	1 25	0 86	1	14 78	1.29	
V.	15 34	1 10	0 65	1	15 42	1 09	
W	15 53	0 99	0 40	1	15 62	0 85	
X	15 70	1 06	0 53	1	15 69	0 84	
Y	15 71	0 88	0.37	1	15 74	0 77	
Z	15 88	1 11	0 67	1	15 84	1 09	
Aa	15 94	1 22	0 83	1	15 95	1 28	
Ba	16 41	1.12	.	1	16 41	1 11	

used for the 2-min versus the 1-min plate and the 1-min versus the 30-sec plate. The magnitudes in Table 2 should therefore be systematically correct as far as crowding is concerned.

The usual check was made for the presence of a color and/or magnitude equation between the photographic and the photoelectric values. The second part of Table 1 gives the photographic values of the sequence stars determined by reading back through the calibration curves. No magnitude equation was detected, but the presence of a slight color equation for stars bluer than $B - V = 1.1$ is suggested. However, no corrections were applied to the Table 2 values because, unfortunately, the photoelectric data do not contain blue enough stars to carry the correction to the bluest program stars. Although this calibration will be tightened up next season, the presence of a color equation for the bluest stars is not important for the present discussion.

TABLE 2

COLORS AND MAGNITUDES OF 265 STARS IN AND NEAR NGC 6171

Star	V	B−V	Star	V	B−V	Star	V	B−V	Star	V	B−V	Star	V	B−V
1	15 71	0 59	59	16 25	1.09	119	16 16	1 24	178	15 69	0 83	235	14 85	1 38
3	15 69	1 19	60	15 49	0 96	120	15 67	0 86	179	15 52	1 02	236	14 33	1.35
4	15 64	0 62	61	15 32	1 36	121	15.84	1 00	180	15 71	0 87	238	15 98	1 28
5	15 22	1.32	62	13 90	1 60	122	15 55	0 99	181	15 74	1 15	239	15 59	0 90
6	16 25	0 84	63	14 68	1 36	123	14 84	0 85	182	15.53	1 39	240	15 52	1 18
7	16 00	1 18	64	15 67	0.28	124	15 61	1.29	183	15 60	0 84	241	15 74	1.12
8	15 26	1 12	66	15 66	0 85	125	15 38	0.84	184	15.76	0 92	242	15 40	1 03
9	15 65	1 25	68	15 96	1.19	126	15 88	0 72	185	14 46	1 40	243	13 47	1 73
10	15 21	1 27	69	15 89	1 16	127	14 01	1.51	186	15 77	0 92	244	15 59	0 39
11	16 50	0 66	70	15 83	1 11	128	16 33	. ..	187	15 76	0 92	245	13 79	1 71
12	16 08	1.17	71	15 74	0 97	129	15.26	1 01	188	14.70	1 26	246	14 67	1 30
13	16 48	1 03	72	14.62	1 46	130	16 39	0 88	189	15 75	0 78	247	14 95	1 04
14	15 68	0 80	73	16 00	1.25	131	15 83	0 80	190	15 80	1 28	248	15 61	0 94
15	16 44	1 00	74	16 01	0 97	132	15 62	1 00	191	16 04	1.36	249	15 50	0 78
16	14 27	1 42	75	15 61	1 04	133	15 11	1 28	192	16 04	1 22	250	15 46	1 41
17	15 16	1 31	76	16 06	1 21	134	16 29	. .	193	15 68	1 00	251	15 90	1 30
18	16 30	1 11	77	16 33	0 92	135	15 92	1.24	194	16 12	1 19	252	16 10	1 21
19	15 42	0 96	78	15 73	0 94	136	15 65	0 72	195	15 66	0 97	253	16 05	1 27
20	14 67	1 37	79	15 79	0 90	137	16 07	1 33	196	15.90	1 36	254	15 62	1 01
21	15 81	1 14	80	15 40	1 39	138	15 66	0 86	197	15.78	0 89	255	15 58	1 08
22	15 76	1 19	81	15 11	1 14	139	15 66	0 99	198	15 92	1 12	256	15 85	0 83
23	14 70	1 35	82	15 51	1 36	140	15 11	1 37	200	14 53	0 79	257	14 66	1 44
24	16 45	1 11	83	15.76	0 88	141	15 65	1 02	201	14 49	1 25	258	15 70	0 76
25	15 38	1 20	84	15 39	1 44	142	15 44	1.32	202	15 92	0 30	259	14 63	1 24
26	16 16	1 10	85	15 54	1 02	143	15 65	0 64	203	15 16	1 36	260	16 17	0 25
27	16 30	0 37	86	16 29	1 11	144	15 72	0 91	204	15 77	0 98	261	15 52	0 96
28	15 73	1 16	87	16 14	1 25	145	14 98	1 32	205	14.56	1 50	262	14 62	1 15
29	16 25	1 25	88	15 66	1 33	146	14 56	1 50	206	15 84	1 04	263	15 65	0 94
30	14 70	1 33	89	15 72	0 95	147	15 82	0 81	207	15 17	1 42	264	15 46	1 33
31	15 34	1 29	90	14 42	0.88	149	15.76	0 82	209	16 10	.. .	265	15 75	1 02
32	15 54	1 19	91	16 52	1 14	150	15 60	1 21	210	15 58	1 34	267	15.72	0 91
33	15 81	1 27	92	15 76	1 28	151	15 85	0 80	211	15 62	0 96	268	15 59	1 05
34	15 80	1 12	93	15 60	0 95	152	16 00	1.36	212	15 80	0 93	269	15 96	1 34
35	13 92	1 54	94	15 90	1.09	154	15 67	1 05	213	15 98	1.21	270	14 97	1 38
36	16 02	1 13	95	14 83	1.21	155	15.74	0 82	214	15 96	1.34	271	15 14	1 09
37	16 24	1 21	96	15.51	1 21	157	14.56	1.32	215	15.16	1.27	272	15 70	0 84
38	16 13	1 11	98	15 66	0.62	158	16 35	1.18	216	15 55	1.10	273	13 15	1 97
39	16 32	1 19	99	15.73	1 23	159	14.15	1 51	217	12 90	2 07	274	16 18	1.22
40	15 61	1 19	100	14 17	1 41	160	15 90	1.12	218	15 66	0.96	275	15 78	0 86
41	16 49	1 16	101	15.84	1 16	161	15 24	1.34	219	15.74	1 27	276	15 42	1 16
42	15.02	1 32	102	16 39	0 91	162	13 96	1.63	220	15.15	0 86	277	15 95	1 25
43	15 40	1.32	103	16 32	1.18	163	16 25	0.92	221	15 45	0 82	278	14 10	1 54
44	15.28	1.32	104	15 74	0 95	164	15.60	0.82	222	15 57	1 05	279	15 70	0 90
45	15 91	1 05	106	15 77	0.60	165	15.69	0 93	223	15 75	1 12	280	15 85	1.35
47	14 93	0 88	108	14 64	0 82	166	14 17	1 57	224	14 05	1 28	281	15.80	0 92
48	15 60	0 90	109	15 56	1 50	167	15 29	1 27	225	16 20	1 20	282	16 00	1.30
50	16 51	1.09	110	14 49	1.23	168	14 86	1 45	226	15 60	0 79			
51	15 71	1.27	111	14 27	0 73	169	16 06	1 25	227	15 85	1.31			
52	14 40	1.46	112	15 98	0 92	170	14.57	1.65	228	15 11	1 46			
53	15 84	0.23	113	16 38	0 77	171	14.53	1.31	229	15 27	1.02			
54	15.77	1 17	114	15 85	0 81	172	13 87	1 59	230	15 34	1.16			
55	15 89	1 22	115	15 02	1 17	173	14 28	1.40	231	13 96	1 65			
56	14 20:	1 52:	116	15 26	1 12	175	15 40	1.15	232	15 76	1 29			
57	15.43	0 87	117	15 69	1.22	176	16 26	1.21	233	15 67	1 23			
58	16 27	1.15	118	15.81	0 93	177	15.81	1 13	234	14 33	1 49			

III. THE C-M AND TWO-COLOR DIAGRAMS

Figure 2 is the color-magnitude diagram obtained from the data. As was expected from the studies previously cited, the diagram differs in several striking ways from those of the halo globular clusters, such as M3, M13, or M92.

a) The horizontal branch is heavily populated on the red side, confirming van Agt's results. The branch resembles that of NGC 6356 (Sandage and Wallerstein 1960) and 47 Tuc (Wildey 1961), although it is not as extreme in the concentration of stars on the red side of the variable star domain; it does contain RR Lyrae stars, and there are a few stars on the blue side of the gap.

b) The giant branch does not rise as steeply nor reach as bright a magnitude above the horizontal branch as it does in the halo clusters. Figure 2 shows that $\Delta V = 2^{m}.05$ at

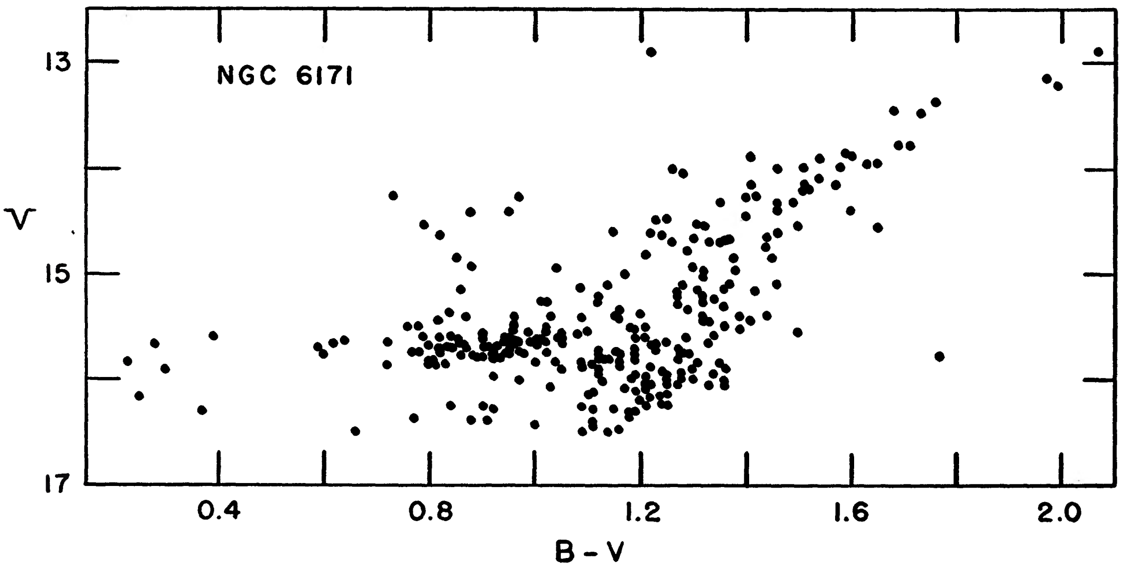

FIG. 2.—The color-magnitude diagram of NGC 6171. No corrections of any kind have been applied to the data.

$B - V = +1.7$ ($[B - V]_0 = +1.4$ if $E[B - V] = 0.30$, as below), which is known to be characteristic of high metal abundance.

Figure 2 is almost identical in shape with the C-M diagram of NGC 6712 (Smith and Sandage 1962), which has been typed as class V in metal abundance by Morgan (1959). This classification indicates that the spectroscopists see slightly weaker Fraunhofer lines in NGC 6712 (and presumably in NGC 6171) than in NGC 6356 (which is of Morgan class VI). This type difference is consistent with the differences of Figure 2 from the C-M diagram of NGC 6356 (Sandage and Wallerstein 1960). Although NGC 6171 does not appear to be as rich in metal abundance as the true disk clusters of classes VII and VIII, it does have a higher metal abundance than the halo globular clusters and it is of importance for the problem at hand.

The $U - B$ values of Table 1 permit a preliminary determination of both the reddening and the ultraviolet excess. Figure 3 shows the $U - B$, $B - V$ diagram. The six open circles are field stars listed in Table 1. The closed circles are stars presumed to be cluster members on the basis of their position in the C-M diagram. The completely unexpected result is that the field stars and the cluster stars nearly intermingle in the diagram. If the field stars are assumed to have no ultraviolet excess of their own, then the reddening is $E(B - V) \simeq 0^{m}.30$, as shown by the dotted line, which is the Hyades intrinsic line (Sandage and Eggen, Table III, 1959) shifted along a reddening trajectory of slope 0.72. The unshifted Hyades relation is shown as a solid line. If this value of the reddening is adopted for NGC 6171, then the giant stars of the cluster have $\langle\delta(U - B)\rangle_{av} = +0^m.06 \pm 0^m.06$ (A.D.), which is very small compared with giants in NGC 4147 (Sandage and Walker 1955, Fig. 5), or M3 (Johnson and Sandage 1956) where δ varies between $0^m.20$ and $0^m.30$. An alternative interpretation is that the field stars have an appreciable $\delta(U - B)$ of their own. In this case, $E(B - V)$ would be smaller than $0^m.30$ and the ultraviolet excess of the giants in NGC 6171 would be somewhat greater than $+0^m.06$. However, the following independent data show that $E(B - V) \simeq 0^m.30$ is approximately correct and, therefore, that the field stars do not have any *large* excess of their own.

The cosecant law for $b^{II} = +23°$ leads to $E(B - V) = 0^m.16$, but it is known that this value is very much too low because NGC 6171 is in an abnormal region of galactic

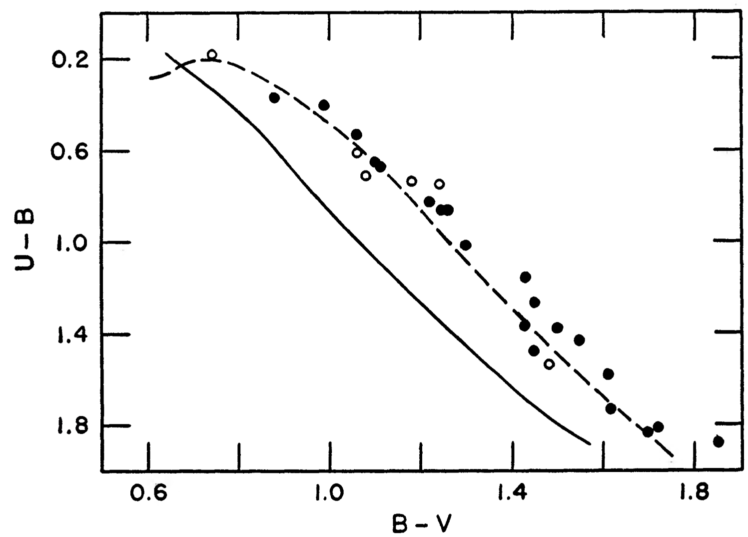

FIG. 3.—The $U - B$, $B - V$ diagram showing the photoelectric standards of Table 1. The open circles are field stars; the closed circles are giant stars of the cluster. The solid line is the intrinsic Hyades relation; the dotted line is the intrinsic relation shifted by $E(B - V) = 0^m.30$ along a reddening trajectory of slope 0.72.

absorption. The cluster is located in the Ophiuchus flare at the boundary of Hubble's zone of avoidance (Fig. 3 of Hubble 1934). Hubble's galaxy counts show $\Delta m_{pg} \simeq 1^m.4$ or $E(B - V) \simeq 0^m.36$ if the underlying distribution of galaxies is normal. This value is confirmed by Steinlin's new discussion (1962) of the zone of avoidance where about 4 galaxies per square degree occur in the field of NGC 6171 to the magnitude limit of the Lick survey, whereas the normal high latitude distribution is about 30 galaxies per square degree—numbers which imply that $\Delta m_{pg} \simeq 1.67 \log 30/4 + 0.25 = 1^m.19$ or $E(B - V) \simeq 0^m.30$.

The position of the RR Lyrae region in Figure 2 also gives information on $E(B - V)$. The gap extends from $B - V = 0.40$ to $B - V = 0.60$. As previously mentioned, there appears to be a small color equation between Table 1 and Table 2 which amounts to $\epsilon(B - V) \simeq +0^m.15$ at $B - V \simeq 0.8$. Arbitrarily extending this correction to the observed color of the gap gives $E(B - V) \simeq 0^m.35$, with the usual assumption that the unreddened edges of the region occur at $(B - V)_0 = +0.20$ and $(B - V)_0 = +0.40$. We therefore believe that $E(B - V) \simeq 0.30$ derived from Figure 3 is reliable and that the $\delta(U - B)$ for the giants in the cluster is smaller than for the halo clusters. Extensive observations for a precise determination of the reddening and the ultraviolet excess will be conducted next season.

IV. DISCUSSION AND SUMMARY

The preliminary data discussed herein show that NGC 6171 is a metal-rich globular cluster. It is the only such cluster now known in the northern hemisphere where the main sequence can be studied with all necessary accuracy to obtain an absolute magnitude calibration of the giant stars and of the RR Lyrae variables—a problem which is the major remaining barrier to the study of the effect of chemical composition on the shape of the evolutionary tracks for stars near $1M_{\odot}$.

Although an accurate distance modulus must wait until this calibration is complete, it is of interest now to estimate the height of NGC 6171 above the galactic plane because the work of Morgan (1956, 1959), Kinman (1959), Preston (1959), and Eggen, Lynden-Bell, and Sandage (1962) shows that stars or clusters which have very high abundances of the metals are not expected to exist high in the galactic halo. Taking $M_{V_0} = +1$ for the RR Lyrae stars of small ΔS and using $E(B - V) = 0^{m}.3$ with the observed position of the horizontal branch at $V = 15.7$ gives $(m - M)_0 = 13.8$ for NGC 6171. The height of this cluster above the plane then becomes 2200 pc. Thus NGC 6171, which is intermediate in metal abundance, is also intermediate in geometrical position within the galaxy, lying between the extreme subsystems of the disk and halo—a result which is consistent with what we now suspect to be a one-to-one correlation between chemical composition and height above the plane at which a star or a cluster is born. Of course, the distance of any object from the plane varies with time because of orbital motion about the galactic center. In the case of NGC 6171 it seems likely that the cluster is near the maximum height it can ever reach because the radial velocity (Mayall 1946), when compared with the known solar motion for clusters of small ΔS (Preston 1959; Kinman 1959), suggests that the W-velocity of the cluster is small. If this is so, then the cluster must have been formed near its present height rather than in the disk or in the distant halo. The cluster's intermediate chemical composition is then one more example of the correlation of the abundance of the nuclear species as a function of place of formation in the galaxy.

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