1-1-1976

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PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
88:63–66, February 1976

FOUR-COLOR AND Hβ PHOTOMETRY OF THE GALACTIC CLUSTER NGC 6633

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Received 1975 September 22

Photometric measurements of stars in the intermediate-age galactic cluster NGC 6633 are presented. From these data the color excess is found to vary slightly across the cluster with an average of $E_{b-y} = 0^m124$. The distance modulus is found to be 7^m71 and the turnoff occurs at about $(b-y)_0 = 0^m1$. The cluster is slightly metal poor.

Key words: photometry — star clusters

I. Introduction

The intermediate-age galactic cluster NGC 6633 ($\alpha = 18^h25^m$, $\delta = 6°32'$, 1950) is of particular interest because there are six yellow giants within the cluster area. Proper motions indicate that at least four of these stars are probable cluster members (Vasilevskis, Klemola, and Preston 1962) and their color indices indicate spectral types earlier than K0. The temperature scale for such stars is a matter of considerable uncertainty at the present time (see Parsons and Bell (1974) for a comparison of various work on this problem). Basic to the establishemnt of a reliable scale is the knowledge of intrinsic colors of G stars. Thus, the occurrence of such stars in a cluster is of interest in this connection. Additionally, the location of yellow giants in the H-R diagram relative to the main-sequence stars provides material to test the theory of stellar evolution (Schmidt 1976). However, the color excesses of the individual stars are basic to both questions. Hiltner, Iriarte, and Johnson (1958) observed this cluster on the *UBV* system and obtained a color excess of $E_{B-V} = 0^m17$ and a true distance modulus of $m - M = 7^m5$. Unfortunately, the color excess determined in the *UBV* system for the B stars in a cluster is not directly applicable to the cool stars due to bandwidth effects. To avoid this problem and to obtain more precise estimates of both the color excess and the distance modulus, this cluster was reobserved on the *uvbyβ* system. The results of this investigation are reported here.

II. The Observations

The 37 stars observed in the field of NGC 6633 are listed in Table I. The first column of the table gives the designation according to Hiltner et al. (1958) while the second column gives that from Vasilevskis et al. (1962). Proper motion studies have been published by Vasilevskis et al. (1962), and Sanders (1973). The membership of the stars as derived from these papers is indicated in the third column of Table I. The number 1 in that column indicates that both proper motion studies give a probability of membership greater than 2/3 while a 3 indicates that both studies give a probability of less than 1/3. Although the proper motion studies give generally consistent results, there are five stars in Table I for which one paper gives a probability of membership greater than 2/3 while the other gives a value less than that. For these stars a 2 has been entered in the third column of the table. Based on the average membership probabilities we expect that among the 21 class 1 stars there are three nonmembers while two of the five class 2 stars are nonmembers.

The stars in Table I were observed using the photometer on the Behlen Observatory 76-cm telescope between April and August 1975. A standard *uvbyβ* filter set manufactured by Spectro-Film, Inc., was used together with an EMI 9789 photomultiplier. The results were reduced to the standard system using the stars listed by Crawford and Mander (1966) and Crawford and Barnes (1970). The standard reduction techniques described by Crawford and Barnes were followed except for two points. The β index rather than $(b-y)$ was used to correct for the presence of Hγ in the v band. This avoids any difficulty with reddened stars. Second, the reductions were done in terms of the colors $(v-b)$ and $(u-v)$ rather than the indices m_1 and c_1. These indices were obtained from the mean colors after the reductions were completed.

Star H 117 was used as a regional standard and was observed approximately every half hour while the cluster photometry was in progress. It was then used to correct the cluster stars for any small zero-point shifts due to variable transparency or photometer drift. The standard deviations of a single observation (after correction with the regional standard) were 0^m016, 0^m011, 0^m014, 0^m031, and 0^m019, respectively, for V, $(b-y)$, m_1, c_1, and β. The mean indices are listed in the fourth through eighth columns of Table I and the ninth column contains the number of nights

TABLE I

Photometric Data for Stars in NGC 6633

Star										Photometric Membership			
Hiltner et al.	Vasilevskis et al.	Membership Class	V	b-y	m_1	c_1	β	n	E_{b-y}	V_0-M_V	This Paper	Hiltner et al.	δm_0	Notes
7	47	1	10.75	0.264	0.181	0.802	2.784	4	0.106	7.77	x	x	-0.016	
10	52	1	10.49	0.230	0.143	0.893	2.812	4	0.108	7.87	x	x	0.030	
12	57	1	10.46	0.161	0.089	1.134	2.839	2	0.092	7.55	x		0.091	1
13	59	1	10.57:	0.223	0.134	0.974	2.817	3	0.114	8.54		x	0.038	
14	60	3	8.34	0.669	0.314	0.393	2.554	3				x		2
17	62	1	9.02	0.163	0.153	1.073	2.854	2	0.094	7.57	x	x	0.027	
25	71	1	10.08	0.202	0.147	0.945	2.842	4	0.111	7.64	x	x	0.028	
31	80	2	8.78	0.158	0.124	1.170	2.873	3	0.116	7.77	x	x	0.048	
32	81	1	7.58	0.102	0.086	0.807	2.800	3	0.142	6.29		x		
33	84	3	8.27	0.164	0.133	1.173	2.858	4	0.109	7.68	x	x	0.042	
42	91	1	9.50	0.213	0.120	1.059	2.824	2	0.120	8.08	x	x	0.051	
45	93	1	9.00	0.176	0.115	1.193	2.875	3	0.137	8.05	x	x	0.051	
51	95	1	9.52	0.171	0.171	1.010	2.863	3	0.101	7.43	x	x	0.006	
56	97	2	8.23	0.516	0.182	0.668	2.670	2				?		2
65	105	1	9.70	0.202	0.130	0.999	2.852	3	0.125	7.51	x	x	0.041	
66	106	1	8.20	0.075	0.053	0.472	2.731	4	0.148	8.12	x	x		
86	130	1	9.31	0.143	0.171	1.098	2.906	3	0.115	7.38	x	x	0.002	
87	132	1	9.63	0.230	0.130	0.966:	2.867:	4	0.160:	6.79:		x	0.029	
92	137	1	8.54	0.243	0.101	1.104	2.793	3	0.130	7.74	x	x	0.061	
96	139	3	9.48	0.208	0.169	0.846	2.783	3	0.058	7.15			0.011	
97	140	1	8.46	0.190	0.122	1.221	2.858	3	0.140	7.88	x	x	0.042	
106	149	1	9.83	0.172	0.168	1.049	2.883	3	0.121	7.72	x	x	0.003	
109	151	1	9.10	0.202	0.134	1.047	2.851	3	0.129	7.29	x	x	0.036	
113			10.13	0.312	0.157	0.809	2.822	2	0.185	6.33		?	-0.006	
116	156	1	8.35	0.702	0.343	0.422	2.570	2				x		2
117			5.72	0.023	0.082	0.642	2.741	*	0.077	5.59				
122			8.70	0.694	0.316	0.437	2.561	1				x		2
126	169	1	10.17	0.239	0.145	0.930	2.805	2	0.115	7.94	x	x	0.024	
134	182	2	8.99	0.663	0.261	0.451	2.558	1				x		2
137	186	1	8.61	0.227	0.130	1.180	2.851	3	0.163	7.49		x	0.029	
139			7.65	0.322	0.151	0.417	2.627	2	0.015	3.93			0.033	
140	187	2	8.81	0.664	0.294	0.434	2.574	1				x		2
147	199	2	8.73	0.202	0.102	1.192	2.856:	2	0.148	7.88	x	x	0.061	
151			10.94	0.320	0.110	0.867	2.749	1	0.145	8.73		x	0.031	
153			9.46	0.382	0.149	0.361	2.593	1	0.472	12.93				3
155			9.08	0.103	0.058	0.666	2.746	1	0.157	8.53				
159			8.14	0.098	0.166	0.980	2.855	1	0.023	6.36		x	0.034	

*Regional standard. Values here are mean from 4 full-weight and 4 half-weight nights.

NOTES ON INDIVIDUAL STARS

1. Marginally an A star. If we consider it a B star we find $E_{b-y} = 0.212$ and $V_0 - M_V = 8.51$ which is inconsistent with cluster membership.
2. Yellow giant if a cluster member.
3. Variable according to Hiltner et al. (1958).

on which a star was observed.

Hiltner et al. (1958) measured V magnitudes of all the stars we have observed. The mean difference between their V magnitudes and the present values is $0^m.007 \pm 0^m.024$ (standard deviation of a single star) in the sense that our magnitudes are fainter. Thus, the magnitude scale used here appears to be in good agreement with the *UBV* system. Johansen and Gyldenkerne (1970) have listed photometric indices for eleven of the stars which were measured here. Although they did not use standard filters, they did transform their results to the standard *uvbyβ* system. A comparison of the present results with theirs gives differences (Johansen and Gyldenkerne − this paper) of $-0^m.005 \pm 0^m.009$, $-0^m.057 \pm 0^m.022$, $0^m.072 \pm 0^m.039$, and $0^m.009 \pm 0^m.045$ for $(b-y)$, m_1, c_1, and β. In view of the fact that Johansen and Gyldenkerne did not use standard filters and had considerable difficulty in transforming to the standard system for m_1 and c_1, the agreement is probably reasonable.

III. Discussion

The indices m_1 and c_1 (Strömgren 1966) were used to distinguish the A and F stars from the B stars. In

fact, only two of the stars with class 1 membership (H 32 and H 66) turned out to be B stars. The calibrations of intrinsic color indices in terms of the four-color and β indices given by Crawford (1970) were used to derive the intrinsic color indices. The color excesses are listed in the tenth column of Table I. The mean excess for the class 1 stars is $E_{b-y} = 0^m124 \pm 0^m017$ (standard deviation for one star). This corresponds to $E_{B-V} = 0^m177$ which agrees well with the value found by Hiltner et al. (1958) of 0^m17. However, there is a small but statistically significant variation in E_{b-y} across the cluster. The stars near star H 14 have a mean excess of $0^m103 \pm 0^m004$ (standard error of the mean), those near H 32 have a mean excess of $0^m122 \pm 0^m008$, while those near H 92 have a mean excess of $0^m132 \pm 0^m006$. Thus, the absorption increases slightly from west to east.

As mentioned in the introduction, the intrinsic color indices of yellow giants are required for the determination of a temperature scale for these stars. The present photometry was used to determine the color excess in the regions of the yellow giants in NGC 6633. For H 14 nearby cluster members give $E_{b-y} = 0^m103 \pm 0^m004$ (standard error of the mean), for H 56 we find $E_{b-y} = 0^m136 \pm 0^m014$, and for the H 116 we find $E_{b-y} = 0^m128 \pm 0^m008$. There are no cluster members near the other three yellow giants so we cannot estimate their color excesses any more accurately than the cluster mean.

The absolute magnitudes of the B stars were found using the calibrations in terms of the β index given by Fernie (1965) and Crawford (1973). Crawford (1970) has published a calibration of the absolute magnitudes of A stars in terms of the zero-age main sequence and the quantity δc_0. We have used this calibration to obtain the absolute magnitudes of the A stars. The true distance modulii of the stars are given in the eleventh column of Table I. The mean modulus for the class 1 stars is $7^m71 \pm 0^m06$ (standard error of the mean). Stars H 13, H 32 , and H 87 have been omitted because they obviously deviate from the cluster. The individual stars have a scatter which can be characterized by a standard deviation of 0^m25. If the average is only taken of the A stars with $(b-y)_0 > 0.08$ we find a modulus of $7^m77 \pm 0^m08$ while those with $(b-y)_0 < 0.08$ give $7^m61 \pm 0^m08$. The deviation of these values from the mean is not significant in view of the scatter and we adopt a modulus of 7^m71 which corresponds to a distance of 350 pc. This compares reasonably well with the modulus of 7.5 found by Hiltner et al. (1958).

In an analysis of the α Persei cluster, Crawford and Barnes (1974) found that the parameter δc_0 was not correlated with absolute magnitude in the way assumed by the calibration. They attributed this to the effect of something other than luminosity on c_0 and suggested rotational velocity as a probable cause. To determine whether such a difficulty exists in NGC 6633 a plot was made of $V_0 - M_V$ (ZAMS) against δc_0 for the class 1 cluster members. It was found that the slope of the relation was very close to 8. Since this agrees with the δc_0 dependence of the Crawford (1970) calibration, we conclude that the calibration is valid in NGC 6633. As a further check we have carried the observational errors cited in section II (with three observations per star on the average) through the calibration. We find that a standard deviation of 0^m18 should be expected in the absolute magnitudes of individual stars. Since this is similar to what was found above from the scatter in distance modulus, 0^m25, we must again conclude that the calibration applies in this cluster and no other factor affects the derived absolute magnitudes.

Based on the data derived above we can now consider which stars are cluster members. By arbitrarily adopting the criterion that both color excess and distance modulus should be within two standard deviations of the mean, we have indicated in the twelfth column of Table I those stars which are photometric members. For comparison, similar information from Hiltner et al. (1958) is indicated in the thirteenth column. There are four class 1 stars which fail to meet the requirements for membership. This is consistent with what was expected from the proper motion studies. On the other hand, none of the eight stars without proper motion data appear to be members. This should not be surprising in view of the fact that they are all outside of the main area of the cluster. By comparing the twelfth and thirteenth columns of the table we see that there are quite a few stars which are members according to the *UBV* data but not according to the present data. This simply reflects the greater amount of information contained in *uvbyβ* photometry than in *UBV* photometry.

The difference between m_0 for the zero-age main sequence and for a particular star, denoted as δm_0, is a measure of line blanketing compared with the Hyades stars. The values of δm_0 are listed in the fourteenth column of Table I. It can be seen that δm_0 is predominantly positive with a mean value of 0^m031. This would indicate that NGC 6633 is metal deficient compared with the Hyades. From Strömgren's (1966) calibration of [Fe/H] in terms of δm_0 and δc_0 we find a mean for NGC 6633 of $\log [\mathrm{Fe/H}]_{6633} - \log [\mathrm{Fe/H}]_{\mathrm{Hyades}} = -0.20$. Wallerstein and Conti (1964) obtained a value of -0.29 for star H 116 which is in good agreement. Thus NGC 6633 is slightly metal deficient compared with the Hyades.

Figure 1 presents the color-magnitude diagram for this cluster. The solid circles are the class 1 members

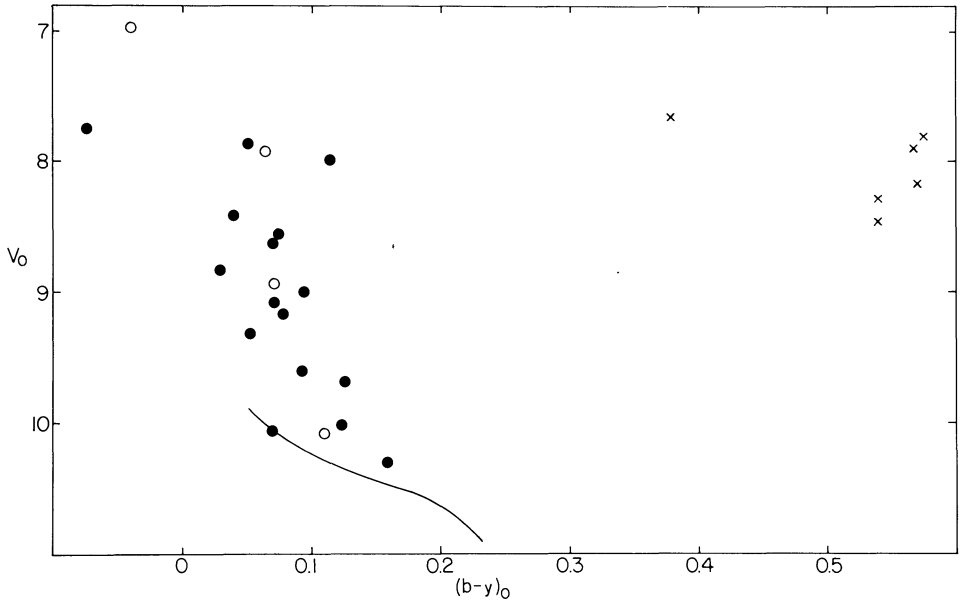

FIG. 1 — The color-magnitude diagram for NGC 6633 corrected for reddening. The symbols are defined in the text.

for which the present photometry indicates membership while the open circles are the class 1 members for which the photometry does not indicate membership. All of the yellow giants are plotted as crosses. The solid line is the zero-age main sequence given by Crawford and Barnes (1974) shifted by the distance modulus of $7^m.71$. It can be seen that the faintest stars observed here are just barely on the zero-age main sequence and the turnoff occurs at about $(b-y)_0 = 0^m.1$. Judging by their positions, the two B stars are not likely to be members in spite of the proper motion data.

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