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THE GALACTIC CLUSTER IC 4665 *

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Abstract. Photoelectric measures have been made in three colors of 49 stars and in two colors of eleven stars in the region of IC 4665, and the results have been reduced to the V , $(B-V)$, and $(U-B)$ system of Johnson and Morgan.

Three color-magnitude diagrams have been constructed and used as criteria for the selection of cluster members. Plots of the color indices $(B-V)$ and $(U-B)$ versus Q , a parameter mainly dependent on spectral type for early-type stars and independent of reddening, have been used to estimate the interstellar absorption. These results and the color-magnitude diagrams lead to a distance of 430 parsecs from eighteen cluster members. Several stars, if cluster members, may be subgiants. The values of Q indicate that IC 4665 contains stars of earlier spectral type than the Pleiades.

Introduction. The galactic cluster IC 4665 is classified by Trumpler (1930) as being of type II 2p, that is, a detached cluster with little central concentration and a medium range of brightness of the stars, of which there are less than fifty. It is centered at $\alpha(1950) = 17^{\text{h}}04^{\text{m}}$ and $\delta = +5^{\circ}04'$. Trumpler gives the galactic coordinates as $l = 358^{\circ}.2$ and $b = +15^{\circ}.6$. The object is therefore at a relatively high altitude for a galactic cluster, but plates of the region for nebular counts do not disclose it as being particularly free of absorption. The cluster has been the subject of investigations by Vogt (1924) of photographic magnitudes, by van de Kamp (1936) of relative places for 1934.5, and by Kopff (1943), who gives spectral types, photographic magnitudes and positions, the latter at too close an epoch to van de Kamp's work to allow a satisfactory determination of proper motions. More recently the cluster has been observed photoelectrically by Johnson (1954), to whom we are indebted for making available his results in advance of publication.

A new discussion involving photometric data for IC 4665 is justified by the relative completeness of our sampling of stars, and especially by the existence of new, accurate proper motions obtained at the Lick Observatory by Vasilevskis (1955), and kindly made available to us.

Photometric technique. Some forty-nine stars in the region of the cluster were observed in three

colors in 1953 with the Crossley reflector. After Vasilevskis' final results became available in 1954, Mayall and Kron observed eleven more stars in two colors to supplement the original list. In 1953 magnitudes were measured in the Lick photoelectric system in three spectral regions: yellow, V_i , blue, B_i and ultraviolet, U_i , with only B_i and V_i having been observed in 1954. The filters, employed with a 1P21 multiplier, were as follows:

$V_i = 2.0$ mm Schott GG 14;

$B_i = 0.4$ mm Corning 3060 + 1.0 mm

Schott BG 12 + 0.6 mm;

$U_i = 2.0$ mm Corning 9863.

The deflections were recorded with a Brown potentiometer. Measures were corrected to outside the atmosphere with absorption coefficients k that had been found appropriate for Mt. Hamilton; viz. for V_i , B_i , and U_i , respectively, k was 0.20, 0.36, and 0.70 mag. per air mass. Each star was measured on three nights.

Twenty-five of the stars observed were in common with the Johnson (1954) results and served to bring the present work, represented by Table I, to the V , B , U , system adopted by Johnson and Morgan (1953). The relationship be-

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TABLE I. PHOTOELECTRIC MAGNITUDES AND COLORS FOR STARS IN IC 4665

Star No. (Kopff)	V	(B-V)	(U-B)	p.m.	Membership Criterion		V:Q	Assignment Adopted
					V:(B-V)	V:(U-B)		
22	8 ^m .78	+0 ^m .071	-0 ^m .21	+	+	+	+	+
23*	8.06	+0.061	-0.15	+	+	?	?	?
24	9.34	+1.251	+1.26	-	-	-	-	-
26	8.07	+1.261	+1.23	-	-	-	-	-
27	10.32	+0.271	+0.17	?	+	+	+	+
32*	8.33	+0.041	-0.15	?	?	+	+	?
35	10.56	+0.21		?	-			-
36*	9.64	+1.26		?	?			-
37	11.36	+0.541	+0.12	+	+	+	+	+
38	10.73	+0.531	+0.10	+	?	+	?	?
39*	9.38	+0.296	+0.21	?	?	-	+	-
43*	9.09	+0.161	+0.05	?	+	?	+	?
48	11.58	+0.49		+	?			?
49*	7.70	+0.021	-0.44	?	+	+	+	+
50*	9.09	+0.251	+0.13	+	?	-	+	-
51*	9.85	+0.33		+	?			?
53	11.41	+0.49		+	+			+
56*	7.51	+0.121	+0.09	-	-	-	-	-
57	11.13	+0.481	+0.07	+	+	+	+	+
58*	7.59	+0.011	-0.51	+	+	+	+	+
61	9.47	+0.61		?	-			-
62*	6.86	+0.011	-0.58	+	+	+	+	+
63	10.56	+0.356	+0.24	?	+	+	+	+
64*	7.36	+0.016	-0.47	+	+	+	+	+
65*	10.60	+0.436	+0.15	?	?	+	+	?
66	10.41	+0.301	+0.18	+	+	+	+	+
67*	8.80	+0.226	+0.17	+	?	-	-	-
68*	7.94	+0.441	-0.00	-	-	-	+	-
69*	7.88	+1.031	+0.82	-	-			-
70	10.27	+1.271	+1.01	-	-			-
72*	7.76	-0.004	-0.56	-	?	?	?	-
73*	7.13	+0.031	-0.50	+	+	+	+	+
76*	8.21	+0.121	-0.32	+	+	+	?	+
78	10.66	+0.551	+0.40	-	-	?	+	-
81*	8.86	+0.121	-0.27	+	+	?	-	?
82*	7.99	+0.071	-0.45	+	+	+	?	+
83*	10.21	+0.281	+0.21	?	+	+	+	+
86	10.39	+0.53		+	+			?
88	10.87	+0.431	+0.18	+	+	+	+	+
89*	9.84	+0.231	+0.16	?	+	?	+	?
90*	8.32	+1.736	+2.02	-	-			-
91	9.33	+1.736	+2.10	-	-			-
95	9.88	+1.68		+	?			?
96	8.91	+0.811	+0.51	-	-			-
99	7.53	+1.631	+1.70	-	-			-
100a†	10.97	+0.641	+0.18	-	-	+	?	-
101	10.76	+1.14		+	-			-
102	9.29	+0.11		+	+			+
105*	7.49	+0.031	-0.42	-	+	+	+	?
108	7.49	+0.451	+0.18	-	-			-
109	9.79	+0.686	+0.14	-	-			-
115	9.15	+0.436	+0.17	-	-			-
117	8.73	+1.596	+1.87	-	?	-	-	-
118	10.32	+0.30		+	+			+
119	8.90	+0.686	+0.18	-	-			-
120	10.16	+1.126	+0.93	+	?			?
121	8.61	+0.371	+0.31	-	-			-

* These stars have been measured by H. L. Johnson.

† 100a: $\alpha = 17^h45^m37^s$; $\delta = +4^\circ53'$ (1950).

tween our adopted photoelectric value V_l and the JM values V was found to be

$$V = V_l + 0.048 - 0.025 (B_l - V_l);$$

$$\pm 0.001 \pm 0.006 \text{ (p.e.)}$$

with a p.e. in V of ± 0.012 mag. The color range was from 0.0 to $+1.7$ mag. The colors were also in satisfactory correlation:

$$B-V = 1.000 (B_l - V_l) + 0.661;$$

$$\pm 0.001 \quad \pm 0.001$$

and

$$U-B = 1.085 (U_l - B_l) - 0.848.$$

$$\pm 0.002 \quad \pm 0.007 \text{ (p.e.)}$$

The probable error in $(B-V)$ was ± 0.009 mag. and that in $(U-B)$ was ± 0.02 mag. The probable errors of all coefficients were computed on the simplifying assumption that only one set of data had observational errors. These expressions were used to compute the values shown in Table I from the photoelectric results, which gave tabulated values on the desired V, B, U system of Johnson and Morgan and so may be compared directly with their results for the unreddened main-sequence stars and for the stars in this cluster and others.

Cluster membership. As a criterion to determine cluster membership for a star it has been customary to depend upon homogeneity of proper motions or of radial velocities. More recently, dependence has been placed upon plots of photoelectric color-magnitude data, as instituted by Eggen (1950). If the results for certain stars fall on or about lines defined by work on better-known clusters, perhaps with some adjustment of the zero points of the axes, then these stars are regarded as being probable cluster members. The amount of adjustment given to the axes is regarded as a measure of the relative modulus of the cluster combined with the effects of interstellar absorption, or as an indication of real differences among the stars of different clusters. By any method, agreement of the data furnishes a necessary but not sufficient condition of membership. However, several independent criteria of membership, if in agreement, furnish strong evidence of membership.

After we obtained the original 1953 three-color photometric data it became evident that an advantage would be gained if accurate proper motions for all stars selected for observation by us were available. Consequently, Dr. Vasilevskis kindly determined new proper motions from a

long time-base, and from voluminous and homogeneous positional material. The detailed report by Vasilevskis is also given in this issue. The proper motions were not large, but the precision was sufficiently high to permit selection of cluster members from the proper-motion data alone with considerable confidence. These identifications are given in the fifth column of Table I for those stars for which photometric data are available. The list includes all stars for which the new proper motions indicated cluster membership, or probable membership.

The use of three-color photometry instead of two-color photometry naturally increases the number of color-magnitude diagrams that can be formed from the data, especially if use be made of certain parameters as well as the direct results. Thus, Becker (1951) proposes the formation of a "color difference," $CD = (U-B) - (B-V)$, or the difference between the two color indices. If this quantity is plotted against the absolute magnitude on, for example, the V scale, then the curve changes the sign of its slope at two points. This result is explained by Becker in terms of CD being a function of the variations of the intensity distribution of the star's spectrum from black-body radiation. The Balmer absorption increases from type B0 to a maximum at about A0 or A1. Hence, in this range, the disproportionately fainter ultraviolet component caused CD to become more positive for intrinsically fainter stars. From this point the Balmer absorption decreases to the late F-types, and the decrease outweighs the general depression of the shortwave ultraviolet in the same type interval, causing a reversal of slope in the magnitude- CD diagram. However, by about type G0, the general depression dominates and the CD commences to increase again. Obviously, such a diagram, with its two points of slope reversal, can be more critically used to determine the modulus of a cluster than the more usual color-luminosity array. By a suitable choice of wave lengths the value of CD can be made independent of interstellar reddening for a given ratio of total to selective absorption. Even if this condition is not reached absolutely, CD is much less influenced by the interstellar reddening than is the usual color index, and a superposition of the CD vs. $(B-V)$ diagrams for two clusters will give a close approximation to the difference in reddening.

Johnson and Morgan defined another parameter, Q , as follows:

$$Q = (U-B) - E_u/E_y (B-V),$$

Figure 1. Diagram of V vs. $(B-V)$. Heavy points refer to stars adopted as members of IC 4665, open circles questionable members, and small points nonmembers. The dashed line is from Johnson and Morgan's results on main-sequence and cluster stars.

where, in addition to the symbols already explained, E_u and E_y are the color excesses for $(U-B)$ and $(B-V)$, respectively. This Q is approximately the same as the CD , because Becker, by a suitable choice of filters, makes E_u nearly equal to E_y . Thus Johnson and Morgan find that in a diagram with coordinates $(B-V)$ and $(U-B)$ a series of reddened B stars of given spectral type will lie on a straight line of the form

$$(U-B) = E_u/E_y (B-V) + Q.$$

The value of Q depends on the spectral type, while E_u/E_y is effectively constant with spectral type, at least over the range from Bo to Ao inclusive. Johnson and Morgan find that $E_u/E_y = 0.72$, a value that has been adopted for the present results. A Q vs. V diagram is effectively a color-luminosity array, and it can be used to give a modulus for a cluster, while the Q vs. $(B-V)$ diagram will give information on reddening.

In the present work three diagrams have been used as photometric criteria of cluster membership, viz. V vs. $(B-V)$, V vs. $(U-B)$, and V vs. Q . These diagrams (Figs. 1, and 2) have certain disadvantages; for example, all will be likely to give dubious results with unresolved binaries, and the $(B-V)$ and $(U-B)$ figures will be subject to disturbance by any differential reddening within the cluster. The V vs. Q diagram is presumably free from this latter defect. The results of Johnson and Morgan have been used to define the lines shown dotted in Figures 1 and 2. In the V vs. $(B-V)$ and V vs. $(U-B)$ diagrams the lines refer to JM results for unreddened stars, and adjustments have been made in the zero of both coordinates to fit the lines to our results. These estimates serve, of course, to give estimates of

the modulus and of the amount of interstellar reddening. The curve in the V vs. Q diagram is based on the JM results for the Pleiades. The slope of the dotted curve in the upper part of Figure 2b has been slightly modified to include the bulk of the stars in the present diagram. The JM results for the Pleiades contain only a few stars in this region and it seems appropriate to define the curve by the larger number of IC 4665 stars. Certain stars that deviate widely from the V vs. $(B-V)$ sequence have been omitted from Figures 1 and 2. In assessing probable membership a deviation of up to 0.1 mag. in color has been tolerated. Stars showing a deviation of 0.1 to 0.2 mag. in color have been regarded as doubtful members, while stars with color deviations greater than 0.2 mag. have been considered as definitely non-members.

The results are shown in the 6th, 7th, and 8th columns of Table I, where the symbol + indicates that a star is a member by the criterion shown at the head of the column, while - indicates non-membership and ? indicates a doubtful case. Stars satisfying all three criteria have been adopted as certain members, while those which have given a doubtful result by one criterion but are members by the remaining two have been noted as doubtful members. Stars that satisfy only one or no criterion have been indicated as non-members. An exception is the binary system 82-83 where a ? in the V vs. Q column for 82 has not been allowed to be a governing factor in deciding on membership for both 82 and 83. The high degree of correlation with the membership criterion from Vasilevskis' proper motions is evident, thus indicating that the relatively new photometric method of selecting cluster members compares favorably with the proper motion method, and that the two methods, when employed together, furnish a powerful means of selecting cluster members.

Modulus, reddening, distance, and dimensions. Values of the modulus $m-M$ and of the reddening E for the cluster may be obtained from the V vs. $(B-V)$, the V vs. $(U-B)$ and the V vs. Q diagrams by comparison with the JM results (Johnson and Morgan 1953) for main sequence and Pleiades stars as follows:

Diagram	$m-M$	Reddening E
V vs. $(B-V)$	8.5 mag.	0.18 mag.
V vs. $(U-B)$	8.7	0.10
V vs. Q	8.2	—

The reddening may also be derived from the $(B-V)$ vs. Q and the $(U-B)$ vs. Q arrays, Figures

Figure 2. Plots of various combinations of the photometric data for the stars of the region of IC 4665. The lines refer to Johnson and Morgan's results on main sequence and cluster stars. In Figure 2b, the dotted portion of the curve represents an extension, based on IC 4665, of Johnson and Morgan's curve for the Pleiades.

2c and 2d. The $(B-V)$ vs. Q diagram drawn for the Pleiades from the JM results does not fit the present points very well, but it is assumed that the turning point in the two sets of results occurs at the same intrinsic color. The fit of the $(U-B)$ vs. Q diagram is, however, quite satisfactory. The Q diagrams lead to the following results, after allowance for a reddening of $+0.04$ mag. (JM) on the $(B-V)$ scale, and of $+0.03$ mag. on the $(U-B)$ scale for the Pleiades:

Diagram	Reddening E
$(B-V)$ vs. Q	0.19 mag.
$(U-B)$ vs. Q	0.13

Thus the reddening figures derived from the V diagrams and the Q diagrams are in satisfactory agreement. The value of $E = 0.17$ mag. has been adopted for the reddening of the $(B-V)$ index from a combination of the four sets of results, the $(U-B)$ reddening being converted to the $(B-V)$ scale by use of the factor $E_u/E_v = 0.72$.

The values of the modulus and of the reddening may be combined to give the distance, r , from the expression

$$m-M = -5 + 5 \log r + \chi E,$$

provided the ratio, χ , of the total to selective absorption is known. This quantity is available from the work of Whitford (1948) who gives relative interstellar absorption coefficients for the wave lengths corresponding to the U , B , and V systems as approximately 1.2, 1.0, and 0.7 mag. respectively, so that the ratios referred to the V scale are, for the $(U-B)$ reddening $\chi = 3.5$ and for the $(B-V)$ reddening $\chi = 2.3$. Taking moduli from the above results and the reddening from the mean of the V and the CD diagrams, we obtain the following figures:

Diagram	Modulus	Reddening E	$\chi \times E$	r
V vs. $(B-V)$	8.5 mag.	0.19 mag.	0.44 mag.	409 pc
V vs. $(U-B)$	8.7	0.12	0.42	453
V vs. Q	8.2	—	—	436

Adoption of the mean of these results leads to a round figure of 430 parsecs for the distance of the cluster. This may be compared with the figures of 280 parsecs given by Trumpler (1930) and 315 parsecs listed by Collinder (1931).

The eighteen cluster members are spread out over an area of nearly one degree in diameter. For a spherical cluster this diameter leads to a linear diameter of 7.8 parsecs and to a density of about 0.2 stars per cubic parsec, which is, of course, a lower limit because the measures do not include all of the stars in the cluster. So low a

value for the density raises the question of the stability of the cluster, and this possibility might be studied with the aid of the new proper motions.

The present data do not indicate that there is any basic observable difference between the stars of IC 4665 and the stars of the Pleiades.

An additional interesting point is that IC 4665 may contain subgiant stars. The new proper motions indicate that a group of rather red stars with $(B-V)$ greater than +1.00 mag. (such as Nos. 95 and 120) are possible cluster members. The colors and absolute magnitudes of these stars are about right for them to be subgiants.

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