THE GALACTIC CLUSTER IC 4665*

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ABSTRACT

This cluster contains about thirty-five visual members with spectral types from B4 V to F0 V. Star counts in the cluster region and in a nearby control region indicate that there are no fainter members and that the late-type giant stars in the cluster region are probably not members. Radial velocities by the authors and by Trumpler show an unusually high fraction of spectroscopic binaries. The rotational velocities by Deutsch for cluster members are low for their spectral types. These three properties (short main sequence, high binary frequency, and low rotational velocities) are the reverse of the characteristics of the Pleiades.

I. INTRODUCTION

IC 4665 is a nearby galactic cluster approximately as old as the Pleiades, with which it has often been compared. According to Trumpler's (1930) classification, the cluster is poor in number of members and shows little concentration toward a nucleus. Its position in Ophiuchus and apart from the Milky Way (cluster center: $l^{II} = 30\overset{\circ}{.}6$, $b^{II} = 17\overset{\circ}{.}1$) makes it a convenient object to study. In addition to numerous early photographic studies, the cluster has been observed photoelectrically by Johnson (1954) and Hogg and Kron (1955). Vasilevskis (1955) has published an excellent astrometric study; the proper motions determined therein provide the principal criteria for cluster membership despite their small and non-unique values, which average $-0\overset{''}{.}0081$ and $-0\overset{''}{.}0047$ annually in right ascension and declination, respectively.

It was thought by the authors that radial velocities and MK spectral types might aid materially in separating cluster members from field stars; except for a few extreme cases, this hope was not fulfilled because the radial velocities and spectral types are not drastically different from those of the interspersed field stars. A second aim was to determine certain characteristics such as binary frequency, velocity dispersion, and luminosity function for comparison with the Pleiades.

The next section gives results, based on star counts, on the extent of the main sequence and on possible giant members. Section III describes the spectroscopic techniques and basic data; the spectroscopic results are given and described in the last section.

II. STAR COUNTS

Before discussing the stars individually, it is profitable to see what star counts indicate about the richness and faint magnitude limit of the cluster. A convenient source of stellar positions and approximate magnitudes for this region of the sky is the Observatoire de Toulouse volumes of the *Catalogue photographique du ciel*. The total numbers of stars within certain magnitude ranges and in a 1°-square region centered on the cluster (1900 position: $17^{h}41\overset{m}{.}4$, $+5°42'$) are listed in Table 1. One square degree closely approximates the area of IC 4665. For comparison, a neighboring 4-square-degree region centered (1900 position: $17^{h}44^{m}$, $+8°$) at the same galactic latitude was counted; the numbers of stars per square degree in the same magnitude ranges are also listed in

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Table 1. The excess of the IC 4665 counts over the control-region counts gives the expected number of cluster members provided (1) the foreground and background star counts do not vary rapidly with galactic longitude, (2) interstellar absorption associated with the cluster does not seriously affect the brightness of the background stars, and (3) the magnitude calibrations for the two regions do not differ seriously. In regard to the first two reservations, the Palomar Sky Survey prints and plates do not show any nebulosity in the vicinity of the cluster or obscurations more numerous or dense than in the control region. In regard to the third reservation, stellar magnitudes in overlapping regions of adjacent *Catalogue photographique du ciel* zones yield mean differences of as much as 0.5 mag.; the mean differences near plate centers are likely to be less than this amount because of the known difficulty of obtaining accurate magnitudes near the edges of plates. We conclude that systematic errors in the magnitudes may produce a vertical shift between the second and third columns of Table 1 by roughly $\frac{1}{4}$ of an interval.

TABLE 1

STAR COUNTS IN IC 4665 AND IN A NEIGHBORING CONTROL REGION

m_{pg}	STARS PER SQUARE DEGREE			
	IC 4665	Control	Excess	Cluster Members
6 0– 6 9	2	0.00	2 00	1
7 0– 7 9	6	0 25	5.75	5
8 0– 8 9	9	1.75	7 25	4
9 0– 9 9	6	3 50	2 50	4
10 0–10 9	12	7 25	4 75	5
11 0–11 9	37	32 50	4 50	7
12.0–12 9	74	74.50	− 0.50	1
Total			26 25	27

The final column in Table 1 lists the number of stars within the 1°-square region centered on IC 4665 that have proper motions indicating "probable" or "possible" cluster membership (Vasilevskis 1955). Close visual pairs were counted as single stars because similar pairs would not have been resolved in the *Catalogue photographique du ciel* zones. The individual entries in, as well as the totals of, the last two columns in Table 1 agree remarkably well; from their agreement we conclude: (1) that most or all of the stars labeled by Vasilevskis as "probable" or "possible" members are, in fact, cluster members, and (2) that the lower end of the cluster main sequence terminates at about $m_{pg} = 12$.

Another question that may be partially answered by this type of statistical method is whether the late-type stars present in the region of IC 4665 are cluster members. To the limit of the *Henry Draper Catalogue*, namely, photoelectrically $B = 10.2$ in this part of the sky, there are only two G0–M stars in the square degree centered on the cluster and an average of 3.0 G0–M stars per square degree in the 4-square-degree zone used for control. Therefore, there is no excess of late-type stars brighter than $B = 10.2$ in the cluster region. Of the forty-three late-type stars too faint to be in the *Henry Draper Catalogue* and with proper motions measured by Vasilevskis, only nine stars have proper motions indicating that they could be members; this is about the fraction of field stars for which one would expect their proper motions to fall within the broad limits of the cluster proper motions. We conclude that most or all of the late-type stars in the field of IC 4665 are not cluster members.

III. SPECTROSCOPIC OBSERVATIONS

At least two spectra were obtained for every early-type cluster member (according to the proper-motion criteria) brighter than $B = 11.0$ except for two stars (Nos. 72 and 76B). The 167 spectra of 33 stars were obtained with the Kitt Peak 36-inch telescope's Cassegrain spectrograph; their dispersion is 128 Å/mm and the slit dimensions, projected on the plate, are 10 μ by 0.29 mm. The spectra were measured for radial velocities on an oscilloscope-type profile comparator manufactured by Grant Instruments, Oakland, California; the digitized output was reduced on the observatory's CDC 160A computer. Most of the measures were made by the junior author (MSS), but the two authors agreed in their measurements of the same spectra.

A calibration of the radial velocities has been determined from sixty-two spectra of Vega, Procyon, or 9 Aurigae (a single-lined spectroscopic binary with an unpublished orbit) obtained nightly during the course of the IC 4665 observations; these standard stars yielded an instrumental correction (standard − observed) of $+10.6 \pm 6.4$ (p.e. per spectrum) km/sec. The systematic correction, adopted as $+10.0$ km/sec, corresponds to 1.1 μ per spectrum; the random error of 0.67 μ per spectrum is reasonable for the measurement of about five stellar lines per spectrum. The stellar lines used almost exclusively were the hydrogen Balmer lines and the Ca II K-line (when it greatly exceeded in strength the weak interstellar line).

The accuracy of the IC 4665 radial velocities, as judged by the consistency of the measures from various lines on each plate, corresponds to a mean probable error per spectrum of ± 5.9 km/sec. This accuracy depends only slightly on the stellar-line widths for spectra measured with the Grant comparator; the range was from ± 5.3 to ± 6.9 km/sec for stars measured at least five times.

The Kitt Peak radial velocities are listed in Table 2, whose columns give (1) the identification number by Kopff (1943), (2) the mid-exposure Julian Date from JD 2430000, and (3) the radial velocity corrected to the Sun and with an instrumental correction of $+10.0$ km/sec.

Trumpler had also obtained many radial velocities (81 measures on 19 stars) of stars in the IC 4665 region, with a dispersion of 80 Å/mm; Dr. H. F. Weaver has kindly made Trumpler's results available to us before publication. The Kitt Peak velocities average $+2.3$ km/sec larger than Trumpler's velocities for six constant-velocity stars measured by both him and us. Trumpler's measures indicate a mean scatter about a star's mean velocity of ± 4.9 (p.e. per spectrum) km/sec.

Summaries of the radial velocity measures in the present study plus Trumpler's measures are given in Tables 3 and 4. These tables give the mean radial velocities, the number of measures (n), and the dispersion of the measures per star, expressed as a probable error per spectrum. Not included in this summary are a few published measures or means listed primarily by Wilson (1953).

The same spectra used for radial velocities were also used for spectral classification by means of a comparison with MK standards (Johnson and Morgan 1953) that were photographed with the same equipment and techniques, and with reference to a preliminary edition of an atlas of MK standards being prepared by A. B. Meinel. The principal standards used were λ Cyg (B5 V), 19 Tau (B6 V), α Leo (B7 V), ξ Peg (B8 V), α Del (B9 V), 4 Aur (A0 V), HR 875 (A1 V), θ And (A2 V), α PsA (A3 V), β Ari (A5 V), τ Her (B5 IV), 16 Tau (B7 IV), and γ Gem (A0 IV). In addition, approximate spectral types, based on the assumption of location on the main sequence, were estimated for a few faint stars on two objective-prism plates of the IC 4665 region taken at the Warner and Swasey Observatory; these types are labeled "OP" in Tables 3 and 4. Additional spectral types from other sources are as noted in these tables.

TABLE 2

RADIAL VELOCITIES

Kopff No	JD 2430000	Radial Velocity (km/sec)
20	8217 735	+48
22	7421 777	+24
	7493 904	− 2
	8189 719	−38
	8191 871	−19
	8193 835	− 3
23 (A+B)	7420 782	+36
	7487 640	−22
	7456 573	− 5
23A	8189 729	−25
	8217 751	−18
23B	8189 737	−11
	8217 764	−18
27	7420 812	−18
	7512 854	+22
	7524 751	+12
32	7429 810	+ 2
	7458 748	−15
	7488 699	− 8
	8189 746	+ 1
	8190 821	− 5
	8191 888	− 3
	8193 848	− 4
	8217 819	−17
	8266 719	+10
35	7458 812	+ 9
	7515 839	+24
	8301 648	−24
36	7494 918	+ 2
	7598 596	− 8
	8301 742	−49
39	7458 767	+10
	7487 746	+15
	8193 952	− 7
41	7421 808	−32
	7488 805	−29
	7514 729	−36
43	7421 841	+ 3
	7488 857	− 8
	7493 936	− 8
	8191 906	+34
49	7421 851	−16
	7488 710	− 3
	7494 705	− 8
	7524 703	+21
	7597 638	+30
	7598 563	+20
	8189 754	+ 2
	8190 826	−53
	8191 917	−37
	8193 855	−11
	8217 824	+32
	8266 710	−57
	8273 724	−31
	8301 597	+29
	8301 602	+30
	8302 592	+21
	8302 602	+16
50	7421 870	+ 4
	7458 916	+26
	7488 874	− 2
	8190 812	+11
51	7429 833	0
	7458 883	+ 6
	7489 792	−17
58	7421 879	−16
	7488 717	−29
	7494 715	+ 9
	7514 661	− 1
	7523 823	−20
	8189 760	−13
	8190 844	− 4
	8191 922	+16
	8193 861	−27
	8217 828	−17
	8273 732	− 8
61	7523 633	−30
	7556 660	+11
62	7421 884	− 3
	7488 962	−31
	7494 725	+ 4
	7514 656	− 5
	8189 764	+ 6
	8190 848	−18
	8191 931	−23
	8193 865	−33
	8217 842	− 3

TABLE 2—*Continued*

Kopff No	JD 2430000	Radial Velocity (km/sec)
63	7429 877	− 6
	7597 606	−10
64	7421 888	+ 2
	7498 808	+ 5
	7515 877	−22
	8189 777	−50
	8190 851	−12
	8191 937	−14
	8192 833	−32
	8193 890	−30
	8217 832	−13
	8281 861	−31
65	7523 651	−13
66	7457 854	+13
	7577 692	+12
67N	7429 916	− 9
	7489 821	−16
	7499 884	−46
	7505 882	−21
	8189 792	−20
	8192 844	−20
	8273 748	−45
67S.	7429 933	+ 1
	7489 862	−32
	7523 789	−68
	8189 822	−10
	8192 859	− 8
73	7421 896	−14
	7457 701	−14
	7489 949	−26
	7524 806	−37
	8189 833	−43
	8190 859	−19
	8192 886	−16
	8193 895	−26
	8217 848	− 6
76	7421 903	+18
	7457 715	− 7
	7556 760	−10
	7597 648	+11
	7598 630	+ 2
	8189 840	−15
	8190 862	−11
	8192 894	−15
	8193 903	−10
	8217 853	−10
	8219 867	+ 3
	8273 760	+ 6
	8301 608	+ 6
	8302 625	−55
81	7421 912	− 3
	7489 729	− 9
	7505 831	+13
	7557 746	+16
82	7422 860	+13
	7457 731	− 9
	8189 847	−17
	8190 870	+ 2
	8192 902	− 2
	8193 926	−26
	8217 859	− 4
83	7422 881	+ 4
	7457 754	− 5
89	7422 922	−24
	7489 753	−13
	7512 882	+ 7
102	7457 906	+19
	7512 771	− 1
	7557 679	− 2
105	7422 904	− 5
	7505 814	− 3
	7512 814	+11
	8189 853	−16
	8190 875	− 5
	8192 908	−32
	8193 931	−22
	8217 866	+17
118	7458 949	+16
	7495 814	− 4
	8266 764	−20

IV. DISCUSSION

a) *Cluster Members and the Luminosity Function*

The separation of the non-members investigated and listed in Table 3 from the cluster members listed in Table 4 was made on the basis of the following criteria:

1. Stars designated "probable" or "possible" members on the basis of the proper motions determined by Vasilevskis were considered members unless other criteria conflicted with this assignment, such as in the case of Kopff Nos. 61, 36, 103, 95, 17, 120, 86, 31, 41, 59, 19, 35, 38, and 101. Stars designated "non-members" by Vasilevskis were generally not observed, except in the case of Nos. 56, 72, 68, and 90; other criteria subsequently showed that these stars are, in fact, not members.

TABLE 3

DATA ON NON-MEMBERS

Kopff No.	HD or BD	V	Spectral Type	Radial Velocity (km/sec)		
				Mean	n	p e
56	161542	7 51	A1*	−27.0	4	± 1 9
68	161622	7 94	F3*	− 7 6	3	± 4 5
90	161820	8 32	gK2*	+12 8	2	± 2 2
61	161552	9 47	F0 V	− 9 6	2	±14 0
36	+5°3472	9 64	G8 III	−18 1	3	±14 8
103	+6°3534	9 8	G9†			
95	+6°3531	9 88	K5†			
17	+5°3462	9 9	K3†			
120	+5°3514	10 16	G7†			
86	+6°3529	10 39	F8†			
31	+5°3470	10 4	K1†			
41	+6°3518	10 4	F2 III:	−32 7	3	2 0
59		10 4	K5†			
19	....	10 5	K0†			
35	+6°3516	10 56	A2 V	+ 3 1	3	±13 6
38		10 73	F0op			
101		10 76	G3†			

* Spectral type by Trumpler (unpublished)
† Spectral type by Kopff (1943).

2. Spectral types or colors showed some stars to be too early (No. 35) or too late (Nos. 56, 68, 61, 86, 41, and 38) to be cluster main-sequence stars; this decision is based on current evolutionary concepts, not on independent data. In addition, all the G and K stars were rejected because of the statistical argument of Section II.

3. One 3″ visual binary (Nos. 67N, 67S) of components nearly equal in magnitude gives every indication of membership, although non-realization of its duplicity led previous observers to reject it from membership because its combined magnitude placed it nearly a magnitude above the main sequence for its color.

A bright K2 III star, β Ophiuchi, near IC 4665 in the sky, has a proper motion that differs greatly from that of the cluster.

There are thirty-five visible members in IC 4665 plus at least thirteen spectroscopically detectable companions. Using Hogg and Kron's determination of the cluster distance (430 pc), we find that the cluster main sequence extends from $M_v = -1.8$ to $+2.9$. In comparison, the Pleiades main sequence (Mitchell and Johnson 1957; Pesch 1961; Herbig 1962) extends from $M_v = -2.7$ to at least $+9.7$. The Pleiades luminosity function has a peak at $M_v = +5$, whereas that of IC 4665 is relatively flat from -1 to $+2$.

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TABLE 4

DATA ON CLUSTER MEMBERS

KOPFF No.	HD, BD, OR ADS	V	SPECTRAL TYPE	RADIAL VELOCITY (km/sec) Mean	n	p e.	Character
62	161573	6 86	B4 V	−12 9	13	± 8 1	Constant
73	161677	7 13	B6 V	−19 0	14	± 7 8	Constant
64	161603	7 36	B5 V	−19 3	15	± 9 3	Variable
105	162028	7 49	B6 V	− 6 8	8	±10 3	Variable
58	161572	7 59	B6 V	−11 7	17	± 8 5	Variable
49	161480	7 70	B5 V	− 8 8	26	±21.4	Variable
72	161660	7 76	B8s*	−13 5	4	± 4 0	Constant
82	161733	7 99	B6 V	−13 0	13	± 8 4	Constant
23A	161184 ADS10741A	8 0	B8 V	−21 4	2	± 2 3	(Constant)
76A	161698 ADS10783A	8 21	B8 V	− 8 4	18	±11 5	Variable
32	161261	8 33	shell	− 5 1	13	± 5 1	Constant
22	161165	8 78	B9 V	− 7 8	5	±14 2	Variable
23B	161184 ADS10741B	8 8	B9 V	−14 6	2	± 2 5	(Constant)
81	161734	8 86	B9 V	− 1 6	10	±11 1	Variable
43	161426	9 09	A0 V	− 5 6	8	±11 2	Variable
50	161481	9 09	A0 V	− 1 3	8	± 8 9	Variable
102	161940	9 29	A1 V	+ 5 1	3	± 6 6	Constant
39	161370	9 38	A2 V	− 6 0	7	±10 2	Variable
67S	161621 ADS10779A	9 6	A2 V	−19 4	10	±13 8	Variable
76B	161698 ADS10783B	9 8	.				
89	161786	9 84	A2 V	−10 1	3	± 8 8	Variable
51	161482	9 85	A2 V	− 3 7	3	± 6 4	Constant
67N	161621 ADS10779B	9 9	A3 V	−24 5	10	± 8 3	Constant†
83		10 21	A3 V	− 8 2	5	± 6 7	Constant
27		10 32	A3 V	+ 5 5	3	±11 2	Variable
118	.....	10 32	A3 V	− 2 9	3	± 9 8	Variable
66	+5°3486	10 41	A3 V	+12 2	2	± 0 4	(Constant)
63	.....	10 56	A5 V	− 8 0	2	± 1 7	(Constant)
65	+5°3485	10 60	A5 V	−13 0	1		
88		10 87	A3op				
34		11 0	F0op				
57		11 13	A*				
37		11 36	F0op				
53		11 41	F0op				
48		11 58	F0op				

* Spectral type by Trumpler (unpublished)

† 67N: Trumpler suggested that the velocity of this star is "probably variable," but it is possible that scattered light from its nearby variable-velocity companion (67S), 3″ distant, may have containmated his spectra of 67N

b) Spectroscopic Binaries and Rotational Velocities

Experience on more extensive spectrographic material with the Kitt Peak equipment has shown that, on the average, the scatter of measures on a constant-velocity star is given with high precision by the internal probable error, i.e., by the probable error per spectrum determined from the scatter of the velocities derived from various spectral lines. The mean internal probable error for the Kitt Peak spectra is ± 5.9 km/sec; for Trumpler's spectra it is probably $\frac{3}{4}$ of that, and for the combined material it is about ± 5.4 km/sec. If the stars are arranged in order of increasing probable error in their measured velocities, it is found that the first thirteen stars (through ± 8.4 km/sec) have a mean probable error $\sim \pm 5.4$ km/sec. Therefore, these thirteen stars are assumed to be the constant-velocity stars, and the remaining well-observed stars to be the spectroscopic binaries.

Of the twenty-three members with three or more observations each, at least fourteen, or 61 per cent, have variable velocities. This fraction is somewhat higher than the 51 and 54 per cent variable-velocity stars that Petrie (1960) found to be the mean for B- and A-type stars, respectively. We conclude that the frequency of spectroscopic binaries in IC 4665 is probably slightly high, unlike that of the Pleiades B stars for which the binary frequency is probably very low (Abt and Hunter 1962).

Deutsch (1955) has estimated the rotational velocities of 19 stars in the region of IC 4665 on spectra of 35–70 Å/mm dispersion. He estimates (private communication) these rotational velocities to have probable errors of ± 75 km/sec. The mean rotational velocity and spectral type for sixteen B4–A3 cluster members is $V \sin i = 108$ km/sec and B8 V, respectively. For main-sequence field stars of the same spectral types, the mean rotational velocity (Slettebak 1955) is 165 km/sec. Even after consideration of the large uncertainty in the estimated rotational velocities, we conclude that the rotational velocities in IC 4665 are probably low, unlike the Pleiades B stars for which the rotational velocities are unusually high (Abt and Hunter 1962).

c) Velocity Dispersion

The mean radial velocity (weighted by the number of measures) for the thirteen constant-velocity cluster members is -12.4 km/sec. This motion is due primarily to the peculiar motion of the Sun, namely, 19.4 km/sec toward $l^{\mathrm{I}} = 24°$ and $b^{\mathrm{I}} = 21°$ (Allen 1955). The cluster radial velocity with respect to the local standard of rest is only $+5.1$ km/sec.

For the eighty-six measures of the thirteen constant-velocity cluster members, the scatter of the measures corresponds to a probable error of ± 8.7 km/sec per spectrum. This value is only slightly higher than the mean internal probable error of ± 6.7 km/sec per spectrum for the same stars, and it indicates that most of the scatter is due to measuring errors, i.e., there is little velocity left for peculiar motions of the cluster stars. Probably most of the discrepancy between these two probable errors is due to the inclusion of several unrecognized binaries.

It is appropriate to ask whether we should expect any detectable peculiar motion of the cluster stars. The virial theorem has been applied to the cluster in a form similar to that given by Schwarzschild (1954), except that the integrals in strips were replaced by sums over individual stars. The stellar masses were assumed to obey the mass-luminosity relation derived by Strand (1957), and the spectroscopic companions were assumed to have one-third the mass of their primaries. The resulting total cluster mass is approximately $130 M_{\odot}$. With a cluster distance of 430 pc, the effective cluster radius is 10.3 pc. and the root-mean-square radial velocity is only 0.13 km/sec, which obviously would not be detectable with the much lower precision of the present measurements.

On the other hand, we can ask whether the cluster has had time to come into equilibrium, so that the virial theorem is applicable. An application of Chandrasekhar's (1942) expression for the mean relaxation time in a cluster gives 440×10^6 years for IC 4665, whereas the cluster age, if similar to that of the Pleiades (Limber 1962), is only about 60×10^6 years. Michie (1964) has pointed out that the Chandrasekhar expression for the relaxation time may give too large a value because only the encounters within the mean stellar separation are considered. However, even if the cluster is not quite in dynamical equilibrium, its peculiar stellar velocities are probably still not detectable in the present material.

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