

THE RETICULUM SYSTEM: AN ANALOG TO THE DRACO DWARF GALAXY NEAR THE LARGE MAGELLANIC CLOUD

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ABSTRACT

A sparsely populated globular cluster in Reticulum found by Sérsic has been investigated photometrically to $V = 19.5$ mag. Although the C-M diagram morphology is somewhat akin to that of Galactic globular clusters of moderate metal deficiency, a detailed comparison with the C-M diagram of the Draco dwarf galaxy appears more satisfactory. With a measured color excess $E(B - V) = 0.02$ we find $V_{HB} = 19.17$ and a true distance modulus $(V - M_v)_0 = 18.48$. Periods are given for 19 of 22 RR Lyrae variables found. Sixteen are of type RRab with $\langle P_{ab} \rangle = 0^d.54$, identifying this cluster as Oosterhof type I.

The Reticulum cluster apparently belongs to a class of "anomalous" clusters first described by Sandage and Wildey in their study of NGC 7006, and properties of this group are further investigated.

Subject headings: clusters: globular — galaxies: Magellanic Clouds — stars: RR Lyrae

I. INTRODUCTION

In a list of peculiar and interacting galaxies found with the Maksutov telescope of the University of Chile, Sérsic (1974) describes an object in Reticulum [R.A. (1950) = 4^h35^m4 , decl. = $-58^\circ56'$] as a "dwarf . . . , probably a member of the Local Group. Diameter $8'$. Brightest stars at $m = 18$. Well resolved." At its position, $l = 269^\circ$, $b = -40^\circ$, the object lies about 11° from the Large Magellanic Cloud. On first appearance it appears to be an outlying member of the LMC; other considerations point to similarities with intergalactic dwarf systems such as Draco, or the clusters Pal 3 and Pal 4. This paper reports a color-magnitude (C-M) diagram to $V = 19.5$, an investigation of the RR Lyrae variables discovered, and presents possible interpretations.

II. THE OBSERVATIONS

A photoelectric sequence (Table 1) was observed with the three-channel photometer attached to the CTIO 1.5 m reflector. This photometer employs a dichroic beam splitter followed by standard filters to separate the B and V bands. The red response of the S-20 photomultipliers was blocked with Corning 9788 filters of 5 mm thickness. Reduction to Landolt's

(1973) equatorial stars led to transformation equations of the form

$$B - V = 1.180 + 0.996(b - v)_0,$$

$$V - v_0 = 21.7 + 0.002(B - V).$$

The quality of the fit was found to be equal to the best obtained at Tololo with the classical 1P21 photomultiplier-filter combination.

Sequence stars fainter than $V = 17$ were observed with a $7''$ aperture once only, a larger list of singly

TABLE 1
PHOTOELECTRIC SEQUENCE

Star	V	B	$B - V$	V_{pg}	B_{pg}
1.....	12.12	12.28	0.16		
22.....	12.51	13.47	0.96		
28.....	13.48	14.08	0.60		
6.....	14.13	15.59	1.46		
2.....	14.53	14.92	0.39		
46.....	16.24	17.54	1.30	16.17	17.45
34.....	16.79	17.45	0.66	16.85	17.34
3.....	17.18	18.01	0.83	17.10	18.00
50.....	17.35	18.37	1.02	17.53	18.34
43.....	17.41	17.71	0.30	17.25	17.62
123.....	17.95	19.48	1.53	18.02	19.59
23.....	18.03	18.99	0.96	18.15	19.11
11.....	18.46	18.95	0.49	18.35	19.04
5.....	19.06	19.81	0.75	19.18	19.92
156.....	19.14	19.13	-0.01	19.24	19.28
24.....	19.25	20.09	0.84	19.26	19.92
45.....	19.71	20.60	0.89	19.56	20.27
14.....	20.43	20.79	0.36	20.24	20.88

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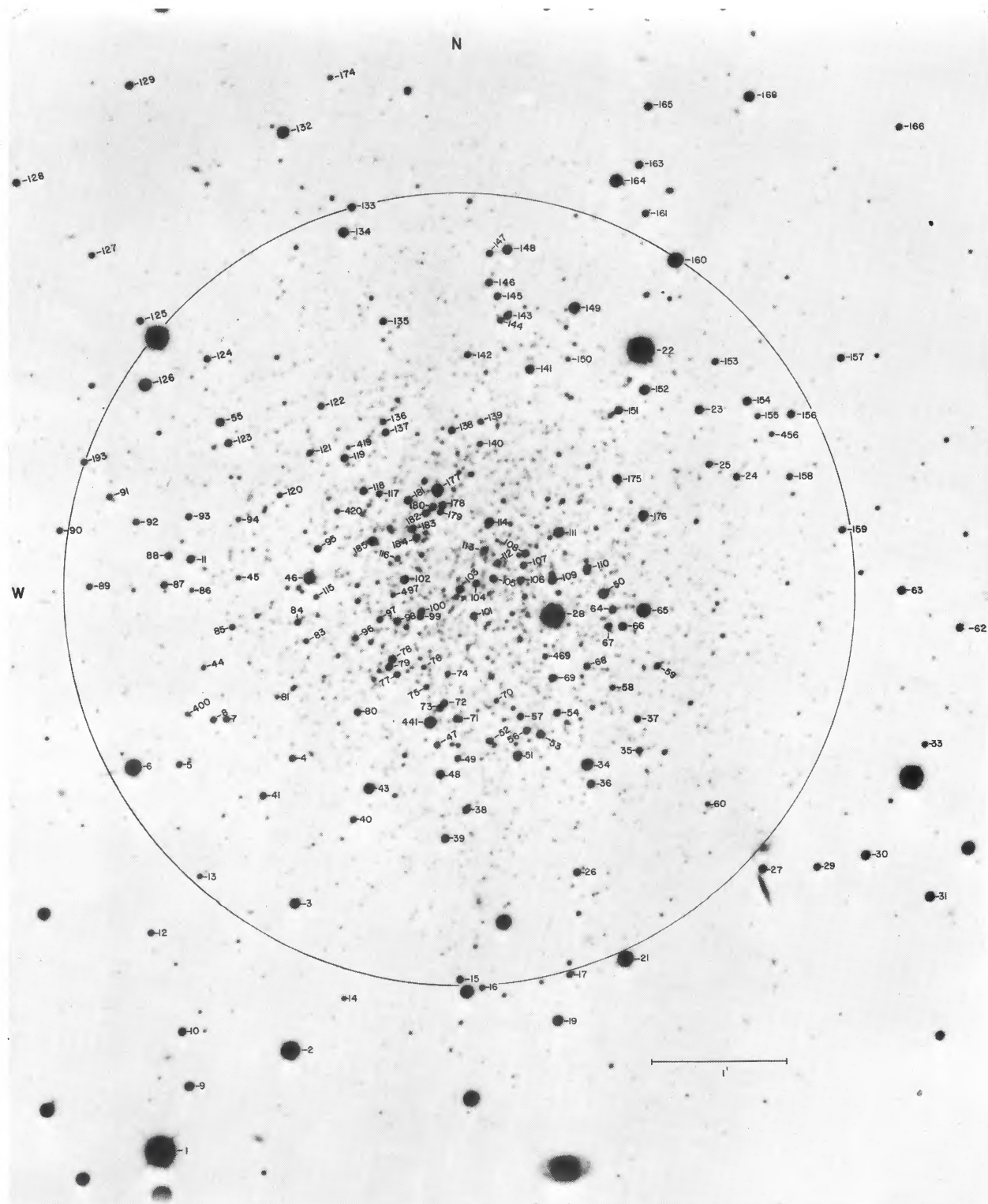


FIG. 1.—A 55 minute exposure of the Reticulum cluster, on dry N_2 baked IIIa-J + GG 385, taken with the CTIO 4 meter reflector. The circle is centered on star 103.

TABLE 2
PRECISION OF
PHOTOELECTRIC PHOTOMETRY

Band	Magnitude interval	Standard Error
V.....	17-18	0.02
	18-19	0.03
	19-20	0.08
B.....	17-18	0.02
	18-19	0.03
	19-20	0.04
	20-21	0.10

observed stars being judged preferable to a shorter list of multiply observed stars. The errors of photometry are shown in Table 2, assuming the discrete counting of photons to be the principal source of error. Systematic errors due to unrecognized faint stars encountered during sky measures were controlled by examining plots of sky measures for all cluster stars as a function of time. The cluster is widely spread with low density of stars at all telescope settings, so that disparate sky measures could normally be recognized and accounted for.

The photographic material was collected with several telescopes during the 1974-1975 season, as listed in Table 3. The numbers 1 and 4 prefix plates obtained with the Cerro Tololo 1.0 and 4.0 m reflectors. Four-digit numbers refer to plates obtained with the Cerro Tololo 1.5 m reflector, and CF denotes the 1.0 m reflector of the Las Campanas Observatory. Schott GG-385 and Schott GG-495 glasses were used with blue and yellow emulsions, respectively. The IIIa-J emulsions were baked in dry N_2 at 65°C for four hours. (See Appendix for their calibration.)

All stars measured in this program are identified in Figure 1. A circle of 2.9 radius separates the stars into two groups: faint stars lying inside the circle are more likely to be cluster members, while those lying outside are more likely to be field stars. A few stars

identified in the figure were not listed in Tables 4 or 5 because they were too faint to measure (with only one or two measures of low weight) or because they were clearly double.

III. COLOR EXCESS

Foreground reddening was determined from *UBVR* photometry of 14 field stars with colors in the range $0.1 < (B - V) < 0.5$, lying within 1° of the cluster. For comparison, eight Hyades stars lying in the same color range were observed concurrently. The use of the *R*-band permits separation of blanketing from interstellar absorption effects, as follows.

Figure 2 shows the relation between $(B - V)$ and $(V - R)$ for the observed stars. The Hyades stars (*open symbols*) form an upper envelope of the distribution. The direction of the reddening line (Johnson 1964), indicated by an arrow at the upper left of the diagram, lies virtually parallel to the Hyades sequence (*solid line*), so that the displacement of the Reticulum field stars below the Hyades line cannot be interpreted as reddening. From the work of Böhm-Vitense (1970) and Böhm-Vitense and Szkody (1974) the color of stars is found to drop below the Hyades relation as metal deficiency increases. The blanketing line indicating the change in abundance from $0.1 Z_\odot$ to $1.0 Z_\odot$ has a slope $\Delta(B - V)/\Delta(V - R) \approx 7 \pm 2$ (arrow at the lower right of the Fig. 2). An estimate for the blanketing required to move each Reticulum field star to the Hyades is now obtained measuring the distance between the star and the Hyades line along the blanketing line. This blanketing information can now be used to "remove" the effects of ultraviolet excess in the $(U - B, B - V)$ -diagram, as shown in Figure 3. The "blanketed" stars are now seen to lie slightly below the Hyades relation (*solid line*), and this displacement is taken as a measure of reddening: $E(B - V) = 0.018 \pm 0.005$; the quoted error is the internal standard error. The true uncertainty of our reddening estimate is greater than this, since the

TABLE 3
PHOTOGRAPHIC MATERIAL

Plate	Emulsion	Exposure (min)	Julian Date 2442000+	Plate	Emulsion	Exposure (min)	Julian Date 2442000+
1-307	IIaD	120	308.77	1-377	103a0	150	338.79
1-308	IIIaJ	111	308.85	1-385	103a0	120	339.69
1-314	IIaD	120	309.75	1-386	103a0	150	339.79
1-315	IIIaJ	129	309.85	1-393	103a0	120	340.70
1-356	IIa0	135	329.71	4-289	IIIaJ	10	401.63
2582	103a0	60	334.72	CF 964	103a0	120	401.68
2583	103aD	180	334.81	CF 965	103a0	120	401.77
2585	103a0	75	335.67	CF 967	103a0	120	402.72
2586	103aD	180	335.76	4-399	IIIaJ	10	415.67
2587	103a0	60	335.85	CF 969	103a0	120	416.62
1-365	103a0	120	336.71	CF 971	103a0	120	417.67
1-366	103a0	150	336.82	CF 985	103a0	120	478.56
1-371	103a0	150	337.71	CF 992	103a0	120	479.55
1-372	103a0	110	337.82	CF 999	103a0	120	480.55
1-376	103a0	150	338.69	4-843	IIaD	35	486.50

TABLE 4
PHOTOGRAPHIC PHOTOMETRY OF STARS WITHIN CIRCLE

Star	V	B-V	Star	V	B-V	Star	V	B-V
3	17.10	0.90	74	19.52:	0.51:	133	18.64	0.89
5	19.18	0.74	75	19.87:	0.51:	134	17.39	0.84
8	19.73:	0.08:	76	20.15:	0.69:	135	19.09	0.48
11	18.35	0.69	78	18.39	0.84	136	19.50:	0.66:
13	19.74	0.66:	79	18.89	0.65	138	18.90	0.78
15	19.12	0.59	83	19.72:	0.60:	139	19.84:	0.56:
23	18.15	0.96	84	19.18	0.71	140	19.91:	0.59:
24	19.26	0.66	85	19.33	0.67	141	18.16	0.77
26	18.75	0.69	86	20.27:	0.64:	143	18.65	0.79
34	16.85	0.49	87	18.87	0.66	145	19.21	0.43
36	19.19	0.35	88	18.73	0.58	147	19.20	0.78
37	19.51	0.43	89	19.16	0.77	148	17.71	0.76
39	18.43	0.71	91	19.00	1.06	149	17.00	0.92
40	19.21	0.63	93	18.97	0.79	151	17.90	1.83
43	17.25	0.37	94	19.95:	0.75:	152	17.34	1.02
44	19.44	1.45	95	18.87	0.83	153	19.33	0.64
45	19.56	0.71	96	19.95:	1.06:	154	18.23	0.83
46	16.17	1.28	98	19.19	0.21	155	19.28	1.38:
47	19.28	0.74	101	19.33:	0.53:	156	19.24	0.04
48	18.19	0.75	102	18.19	0.82	158	19.46	0.56
50	17.53	0.81	103	18.57	0.84	159	19.04	0.77
51	17.84	0.80	104	19.13	0.44	160	15.80	0.39
52	19.34	0.64	105	18.92	0.75	175	18.13	0.79
53	18.47	0.97	106	19.22	0.70	178	18.95	0.68
54	19.03	0.83	107	19.13	0.76	179	19.51:	0.71:
55	18.24	0.58	109	18.30	0.87	180	18.81	0.83
56	18.91	0.78	111	17.21	1.07	181	19.15	-0.00
58	19.75:	0.77:	113	19.13	0.55	182	18.71	0.84
59	19.26	0.69	114	17.93	0.82	183	19.23	0.14
60	19.58	1.45:	115	19.86:	0.65:	184	18.69	0.85
65	16.43	0.34	116	19.82:	0.56:	185	17.84	0.85
66	18.61	0.52	118	18.75	0.76	193	18.99	0.81
67	19.18	0.40	119	19.24	0.12	400	20.15	0.71:
68	19.19	0.73	120	19.69	0.61	419	19.88:	1.43:
69	19.16	0.15	121	19.30:	0.75:	420	19.92:	0.48:
70	20.06:	0.79:	122	19.36:	0.68:	441	16.83	0.38
71	18.90	0.81	123	18.02	1.57	456	19.66:	1.23:
73	19.06	0.54	124	19.22	0.44	469	19.98:	0.59:
			126	16.31	0.55	497	19.97:	0.68:

uncertainty in the slope of the deblanketing lines is difficult to estimate independently.

Our approach may be criticised on several grounds. First, the models of Böhm-Vitense (1970) and Böhm-Vitense and Szkody (1974) apply to the photometric system of Sandage and Smith (1963), and not the system of Johnson (1966). Since $(V - r)_{ss} \approx 1.01(V - R)_J - 0.04$, for the color range of our data we have assumed that the deblanketing line has the same slope in both photometric systems:

$$\frac{\Delta(V - R)_J}{\Delta(V - B)} \approx \frac{\Delta(V - r)_{ss}}{\Delta(V - B)}.$$

TABLE 5
PHOTOGRAPHIC PHOTOMETRY OF STARS OUTSIDE CIRCLE

Star	V	B-V	Star	V	B-V
9	17.61	0.55	63	18.03	0.79
10	18.33	1.33	90	18.56	1.48
12	18.93	0.83	125	18.85	0.84
14	20.24:	0.64:	127	18.81	1.36
16	19.63	0.49	128	18.22	1.45
17	19.50:	0.61:	129	18.37	0.71
19	17.23	0.58	132	16.37	1.10
21	15.14	0.78	161	18.92	0.87
27	18.28	0.77	163	18.85	0.68
29	19.13	0.45	164	16.29	0.83
30	17.88	0.31	165	18.22	1.03
31	17.73	0.38	166	17.95	1.53
33	19.41:	0.71:	168	17.36	0.39
62	18.01	1.01	173	19.10	0.48

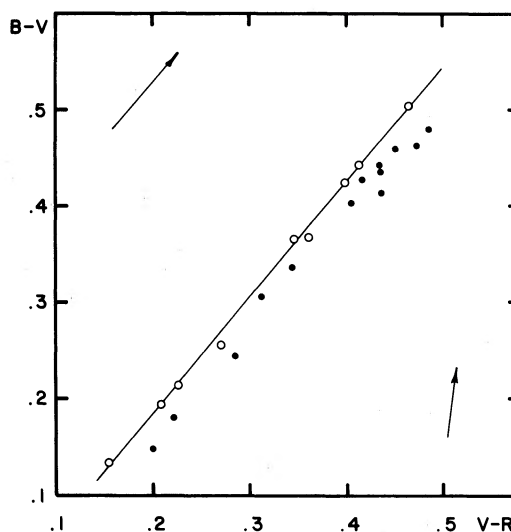


FIG. 2.— $(V - R, B - V)$ -diagram of stars to determine foreground reddening in Reticulum. Since the reddening line (arrow at upper left) lies parallel to the Hyades relation (open circles, solid line), the displacement of Reticulum field stars (dots) below the Hyades stars is interpreted as line blanketing. The direction of the blanketing line is shown by the arrow at the lower right.

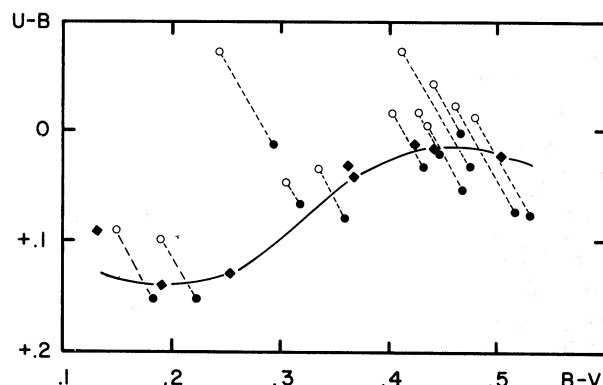


FIG. 3.—($U - B$, $B - V$)-diagram of stars to determine foreground reddening in Reticulum. Original data for field stars (open circles) were blanketed to the Hyades using corrections taken from Fig. 2 (solid symbols; see text). A color excess $E(B - V) = 0.02$ was determined by comparison of the blanketed colors with the Hyades (diamonds, solid curve) following usual practice.

Should the true deblanketing vector be oriented differently from our value by not more than 5° , the resulting change in the reddening estimate $\delta E(B - V)$ is only 0.006 mag.

The ultraviolet excess is known to be strongly dependent on surface gravity. In a sufficiently extensive sample of stars, evolved stars are likely to occur. As such stars lie well removed from the majority of stars, they are readily identified and eliminated, as Figure 3 shows.

IV. THE COLOR-MAGNITUDE DIAGRAM

The color-magnitude diagram for the stars (excluding variables) lying within the circle of Figure 1 (Table 4) is shown in Figure 5. Measures of lower

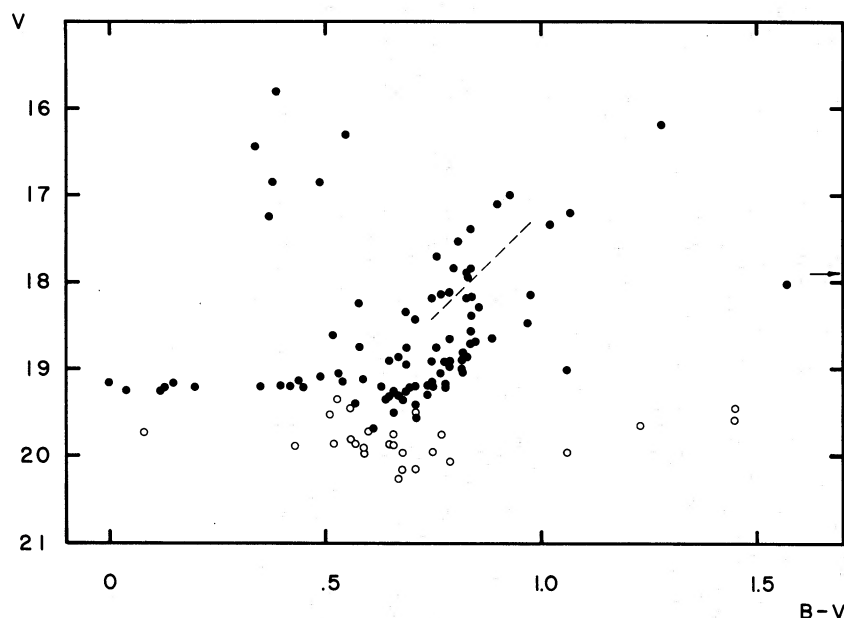


FIG. 5.—Color-magnitude diagram of stars inside the circle of Fig. 1, uncorrected for color excess. Measures of lower weight are shown by open circles.

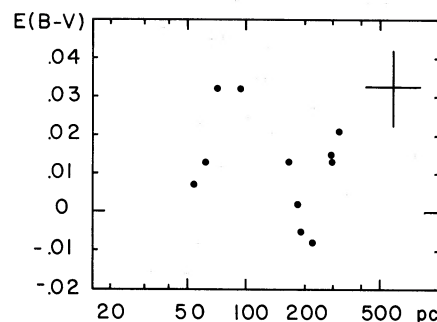


FIG. 4.—Estimate of color excess for each star as a function of height above the galactic plane. Distance estimates were based on the assumption that stars are not evolved. Cross at upper right is an estimate of the standard error in each coordinate.

weight are represented by open circles. The diagram is reminiscent of a globular cluster of intermediate metal deficiency, with an evenly populated horizontal branch of Dickens (1972) class 4 or 5 and a short, exceedingly steep, and poorly populated giant branch. Star 46, at $V = 16.17$ and $B - V = 1.28$, lies well inside the cluster, and is probably a member.

The apparent paucity of stars in the giant branch is probably of no unusual significance. The ratio of horizontal branch stars including variables (44) to giants at and above the horizontal branch (39) is 1.1, a value comparable to 0.9 ± 0.3 determined by Iben *et al.* (1969) for several globular clusters in the Galaxy.

A detailed comparison to other systems is left for § VIII.

V. THE DISTANCE

We estimate the distance to Reticulum by two methods. The average of the apparent visual magnitude

of the horizontal-branch stars is $V = 19.17 \pm 0.06$. Taking $(M_V)_{HB} = 0.6$ (Sandage 1970; Harris 1974), and $A_V/E(B - V) = 3$, the true distance modulus is $(V - M_V)_0 = 18.51$, corresponding to a distance of 50 kpc.

We can also compare the Reticulum variables with the RR Lyrae variables of the Large Magellanic Cloud. For Reticulum the average $\langle B \rangle_R = 19.41$. Graham (1973) finds $\langle B \rangle_{LMC} = 19.56$ for the RR Lyraes of the LMC field. If one takes the same M_B and reddening for both groups, and adopts a true distance modulus for the LMC of 18.60, based on the $P-L-A$ and $P-L-C$ relations of Cepheids (Sandage and Tammann 1971), then the difference $\langle B \rangle_{LMC} - \langle B \rangle_R = 0.15$ is consistent with the earlier distance estimate, and shows that Reticulum lies slightly in front of the Large Magellanic Cloud. Taking the distance to the LMC equal to 52 kpc, the separation of the cluster from the LMC is 10 kpc, comparable to that of the outlying globular cluster NGC 1841 (Gascoigne 1966). The latter is often taken as the southernmost cluster belonging to the Large Magellanic Cloud. The extent of the LMC halo, as indicated by a separation between Reticulum and NGC 1841 of 25° and a difference of 0.4 mag in distance modulus, is 23 kpc.

VI. VARIABLE STARS

Reticulum contains a surprisingly large proportion of RR Lyrae variables, which account for more than half of the horizontal branch. Blinking 20 plate pairs yielded 27 suspected variables, which were subsequently measured by iris photometer on 25 plates.

Table 6 identifies the variables and gives the amplitudes for 22, and periods for 19 of them. Of these, four are of Bailey type *c*, and 15 of type *ab*. Star 98, lying at the blue edge of the RR Lyrae gap, shows large scatter, and may also be a *c*-type variable. Other stars suspected of variability are 37, 52, 67, and 145. The individual measures for each star are given in Table 7.

All variables have nearly the same mean magnitude, and no Population II Cepheids or red variables are present in Reticulum. In some instances no periods could be found for a variable, probably because it is not possible in a data set as small as 25 plates to cover all possible periods with the same detection sensitivity. In at least one case, that for star 108, there is some evidence for changes of phase and amplitude. A period search conducted on different (but not exclusive) subsets of the data yielded periods ranging from 0.466 to 0.469 days.

Typical light curves are shown in Figure 6.

The mean period for the *ab*-type variables is 0.536 days, and identifies Reticulum with Oosterhoff class I. It should be noted that the RR Lyraes of the LMC field as well as globular clusters are likewise of Oosterhoff class I (Graham 1973), and this is taken as indicative of intermediate metallicity.

It is difficult to estimate the completeness of the variable search. Detection of *c*-type variables is not favored. Star 4, taken as a photoelectric standard

TABLE 6
PROPERTIES OF VARIABLE STARS

Star	Period (days)	$\langle B \rangle$	ΔB	Remark
4	0.35324	19.38	0.58	RRc
7	0.61860	19.54	1.02	
25	0.50515	19.42	1.27	
35	0.53489	19.43	1.03	
38	0.51227	19.42	1.37	
41	0.35224	19.31	0.55	RRc, large scatter
49	0.52262	19.38	1.25	
57	0.51004	19.48	1.16	
64	0.51398	19.46	1.25	large scatter
72	...	...	0.7	RRc?
77	0.5449	19.40	0.50	spurious period?
80	0.57165	19.42	1.06	large scatter
92	0.51362	19.24	1.14	ill defined light curve
97	0.59533	19.50	0.80	
99	...	...	...	too few observations
108	0.4687	19.33	1.55	large scatter
110	...	...	0.9	
112	0.56056	19.42	1.06	
117	0.51039	19.36	1.10	
137	0.54509	19.34	1.14	
142	0.55627	19.44	1.13	
146	...	...	1.2	
157	0.34450	19.56	0.64	RRc

early in the investigation, proved later to be a variable of type *c*. We believe that all *ab*-type variables were found, but feel that several type *c* variables may remain undetected.

VII. CLUSTER MASS AND RADIUS

The tidal and core radii of Reticulum, as defined by King (1966), were determined from star counts to $B \approx 23$ mag over the entire area of Figure 1 and a portion of sky to the south, for control. By a procedure analogous to that of King *et al.* (1968) we determine core and tidal radii of 1'.5 and 4'.6, respectively, which correspond to 22 and 67 pc at the assumed distance of 50 kpc. The core radius is among the largest for known globulars, and the low value of $\log(r_t/r_c) \approx 0.5$ is representative of the lowest central concentrations for globular clusters (Harris 1974).

An approximate mass for Reticulum is estimated by comparing the population at and above the horizontal branch with that of M3 (Sandage 1954). Reticulum has about 9 percent the number of stars of M3 in this portion of the diagram. The total light is estimated by summing the light from 53 giants inside the circle of Figure 1 lying above the horizontal branch with $(B - V) > 0.6$. Sandage (1957) found that in M3 such stars account for 48 percent of the combined cluster light. The contribution from cluster members lying outside the circle can be calculated from King (1966) to be $\Delta m \approx -0.07$ mag. If we allow a further correction of -0.2 mag for stars which could not be measured by iris photometry because of image contamination, then the total cluster light is $V_{\text{tot}} = 12.8 \pm 0.2$. Thus Reticulum has about 7 percent of the light of M3. Assuming an age and a helium abundance about equal to that of M3, then the masses of the stars reaching the tip of the giant branch are about the same as for M3. The luminosity functions of Reticulum and M3 are indistinguishable to about 0.5 mag below the horizontal branch (Fig. 7), and we

TABLE 7
VARIABLE STAR DATA

JULIAN DATE (helio.) 2442000+	v.4	v.7	v.25	v.35	v.38	v.41	v.49	v.57	v.64	v.72	v.77	v.80
308.855	19.45	19.46	19.39	18.88	19.52	19.41	19.68	19.72	19.92	19.21	19.26	19.74
309.844	19.65	19.84	19.67	19.76	19.79	19.30	19.86	19.85	19.81	19.09	19.57	19.93
329.711	19.55	19.59	19.33	19.13	20.10	19.36	20.05	19.91	18.95	...	19.43	19.60
334.722	19.30	19.13	19.04	19.50	19.70	19.60	19.53	19.35	19.81	19.43	19.61	19.24
335.671	19.77	19.89	18.65	18.98	19.42	19.23	19.18	18.83	19.89	19.41	19.31	19.75
335.850	19.33	19.93	19.86	19.93	20.04	19.62	20.06	19.80	18.67	...	19.83	18.88
336.707	19.57	19.32	18.73	18.82	19.35	19.06	19.08	18.85	...	...	19.28	19.63
336.818	19.43	19.72	19.45	19.33	19.77	19.44	19.67	19.37	19.33	19.31	19.39	19.83
337.714	19.64	19.61	18.68	19.26	19.25	19.00	18.76	18.64	19.66	...	19.22	19.54
337.816	19.48	19.13	19.42	19.00	19.80	19.38	19.49	19.53	19.57	19.06	19.19	19.81
338.692	19.26	19.46	18.97	...	18.89	19.45	19.02	19.10	...	19.39	19.40	18.89
338.794	19.63	19.97	19.29	19.38	19.42	19.34	19.03	19.07	19.81	19.47	19.21	19.36
339.688	19.12	19.02	19.07	19.62	18.71	19.55	...	19.50	...	19.25	19.51	19.49
339.793	19.41	19.52	19.07	19.87	19.43	19.57	18.71	18.84	19.94	19.62	19.63	19.04
340.703	19.23	20.07	18.98	19.79	18.69	19.45	20.05	19.72	19.90	18.95	19.60	19.94
401.628	19.62	19.55	19.73	19.68	18.92	19.25	19.77	19.69	19.39	19.12	19.56	19.41
401.685	19.59	19.51	19.98	19.89	18.76	19.84	19.76	20.02	19.15	19.13	19.46	19.37
401.776	19.37	19.67	19.71	19.72	19.28	19.18	19.87	...	19.51	...	19.63	19.66
402.718	19.58	19.30	19.89	19.81	18.88	19.63	19.69	19.72	19.20	19.21	19.35	18.81
415.667	19.02	19.75	19.62	19.77	19.58	19.42	19.94	19.77	19.69	19.64	19.14	19.53
416.620	19.13	19.54	19.23	19.53	19.35	18.98	18.85	...	19.22	19.33	19.44	19.42
417.671	19.45	19.09	19.59	19.55	19.48	19.26	18.66	19.83	19.45	19.46	19.61	19.25
478.557	19.33	19.98	19.69	19.18	19.06	19.41	19.75	19.43	20.02	...	19.56	19.83
479.551	19.29	19.10	...	18.98	18.87	19.52	...	19.33	...	...	19.33	19.60
480.548	19.33	19.63	...	19.62	18.81	19.47	...	19.01	...	...	19.10	19.05

JULIAN DATE (helio.) 2442000+	v.92	v.97	v.99	v.108	v.110	v.112	v.117	v.137	v.142	v.146	v.157
308.855	19.70	19.80	19.10	18.68	19.76	19.76	19.74	19.66	19.83	19.56	19.30
309.844	19.55	19.29	19.72	19.23	19.72	19.87	19.75	19.36	19.94	19.65	19.31
329.711	19.48	19.79	...	20.08	19.57	18.85	19.73	20.02	18.99	19.65	19.59
334.722	18.72	...	...	19.58	19.21	19.49	19.28	19.58	18.82	19.74	19.61
335.671	18.88	19.82	...	19.71	19.42	19.89	18.59	19.84	19.94	19.97	19.48
335.850	19.58	19.83	...	20.03	19.42	18.91	19.83	19.31	18.82	19.96	19.76
336.707	18.73	19.41	...	19.54	19.18	19.52	18.84	19.52	19.71	19.68	19.24
336.818	18.97	19.72	...	19.88	19.07	19.95	19.50	19.85	19.87	18.94	19.72
337.714	18.88	19.31	...	19.86	19.41	19.28	18.75	19.45	19.36	19.76	19.21
337.816	18.98	19.36	...	19.59	19.46	19.82	19.47	...	19.77	18.61	19.58
338.692	...	...	...	19.52	...	18.80	18.88	19.00	18.89	19.52	19.34
338.794	18.50	19.78	19.12	18.82	19.55	19.37	19.10	19.47	19.45	18.62	19.35
339.688	19.64	19.39	...	19.39	19.34	...	19.02	18.82	19.51	19.23	...
339.793	18.57	19.76	19.76	18.99	19.64	18.94	18.93	19.11	18.94	18.86	19.24
340.703	19.99	19.22	19.62	18.82	19.51	19.94	19.10	19.68	20.07	18.55	19.90
401.628	19.72	19.71	...	19.32	18.67	19.24	19.65	19.56	19.72	19.47	19.44
401.685	19.70	19.72	...	19.05	19.32	19.71	19.56	19.78	20.09	20.02	19.89
401.776	19.77	19.71	...	19.76	19.74	19.68	19.70	19.16	19.74	18.81	19.20
402.718	19.63	19.02	18.70	19.74	19.60	19.23	19.68	19.77	19.68	19.22	19.66
415.667	19.70	19.78	19.49	18.41	18.85	19.35	19.74	19.37	19.95	19.73	19.52
416.620	...	...	19.47	18.58	19.20	18.95	...	19.02	19.30	...	19.31
417.671	19.80	19.36	19.57	19.45	19.55	19.62	19.77	18.77	18.97	19.84	19.20
478.557	19.02	19.69	...	19.20	19.02	19.80	18.73	19.97	19.86	19.44	19.33
479.551	18.93	19.14	...	19.46	19.35	19.31	19.12	...	...	19.59	...
480.548	18.81	...	...	...	19.32	18.83	19.33	19.39	...	...	...

assume them to be effectively the same. The mass of Reticulum, based on these assumptions is $2 \times 10^4 M_{\odot}$.

The cluster has probably never approached either the Large Magellanic Cloud or the Galaxy very closely. Using equation (12) of King (1962) and setting the limiting radius r_{lim} equal to the measured tidal radius, we find a closest approach to the LMC of 5 kpc, and to the Galaxy of 16 kpc. In this the mass of the Galaxy and the LMC were taken to be 1.8×10^{11} and $5 \times 10^9 M_{\odot}$ (Thackeray 1971), respectively.

VIII. DISCUSSION

In broad outline the color-magnitude diagram of Reticulum resembles that of a globular cluster of intermediate metal abundance. The horizontal branch (HB) compares reasonably well with that of M3 and NGC 7006, as shown in Table 8. In the former, blue HB stars are somewhat more numerous than red HB stars (Sandage 1970), while in NGC 7006 (Sandage and Wildey 1967) the converse holds. As in Reticulum,

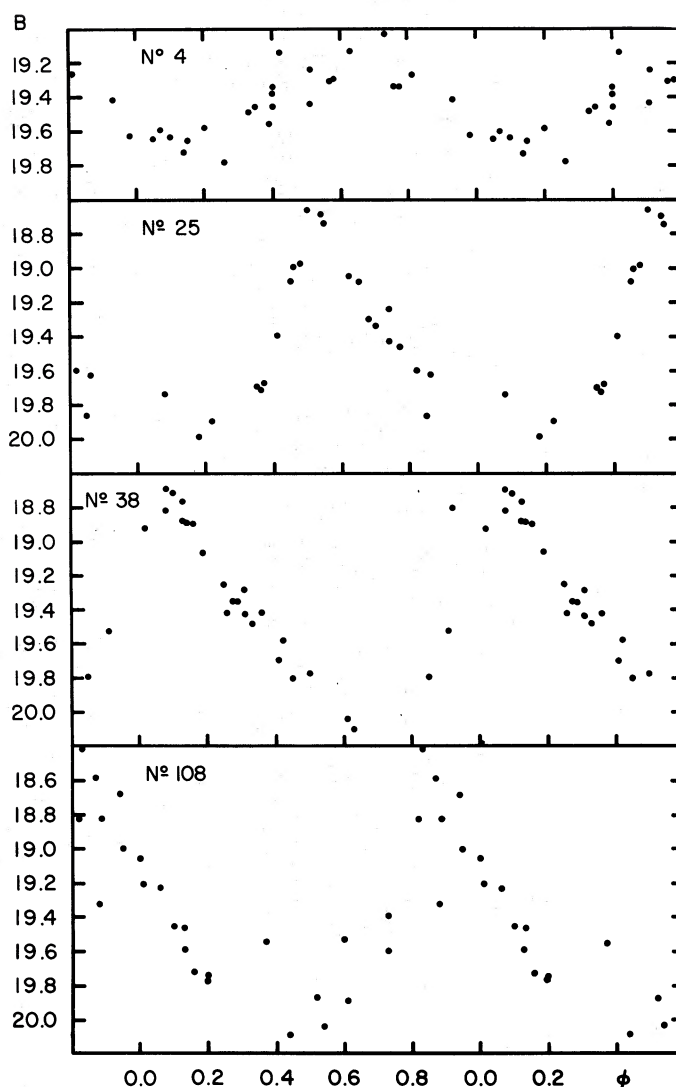


FIG. 6.—A sample of four light curves. Star 4 is a type *c* variable. Stars 38 and 108 represent the best and worst fitted light curves. In general the *RRab* variables have curves similar to those of stars 25 and 38.

both clusters have relatively densely populated RR Lyrae gaps. In Reticulum, no HB stars are found on the blue side of $(B - V) = +0.07$; a similar situation exists in other clusters, as for example NGC 6981 (Dickens 1972). However, in NGC 6981 the ratio of blue to red HB stars is 21/12, in contrast to a ratio of less than unity for NGC 7006 and Reticulum.

The giant branch is more problematical. That of M3 or NGC 7006 rises less steeply above the horizontal branch than Reticulum. The paucity of stars makes numerical comparison difficult. One is reminded of Gascoigne's (1966) diagrams of the red clusters of the Large Magellanic Cloud (LMC). Those found by him to be most deficient of giants are NGC 2209, 2231, and Hodge 11. Walker (1971) has observed NGC 2209 to $V \approx 21.9$, and was able to show that the cluster is of intermediate age, reminiscent of the Hyades. NGC 2231 has recently been

studied by Hesser (1975) who finds a color-magnitude diagram closely similar to that of NGC 2209. In Gascoigne's (1966) investigation the color-magnitude diagram of NGC 1466 presents a more satisfactory comparison: not only does it have an evenly populated horizontal branch, but its giant branch lies blueward of that for M13 [$(B - V)_{0.9} \sim 0.8$] as is the case of Reticulum; further, there are as few giants as in Reticulum. The tip of the giant branch of NGC 1466

TABLE 8
DISTRIBUTION OF HB STARS IN THREE CLUSTERS

Cluster	<i>N</i> (blue)	<i>N</i> (RR)	<i>N</i> (red)	$\langle P_{ab} \rangle$
M3.....	30	47	23	0.55
Reticulum.....	6	25	10	0.536
NGC 7006.....	12	26	38	0.57

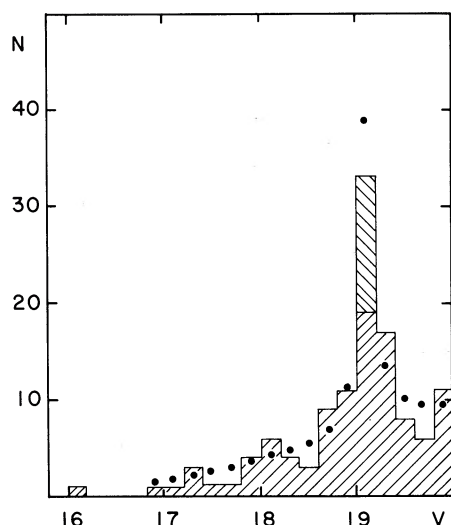


FIG. 7.—Luminosity function of Reticulum (shaded bars) compared with that of M3 (dots, Sandage 1957). Variables at $V \sim 19.1$ are indicated by different shading.

is at $(B - V) \approx 1.6$, and six stars are redder than $(B - V) = 1.2$; in Reticulum only one star is redder than $(B - V) = 1.2$. Star 46, with $(B - V) = 1.28$, lies 3.0 mag above the horizontal branch; at this color the giants of NGC 1466 are but 2.5 mag brighter than the horizontal branch. In summary, the giant branch of Reticulum is too steep to compare well with that of Galactic or LMC globular clusters.

The color-magnitude diagram of the Draco dwarf galaxy (Baade and Swope 1961) shows a distribution of stars of comparable steepness. At 1 mag or more above its horizontal branch, the asymptotic-branch stars (which lie 0.15 mag blueward of the giant branch, or 0.7 mag above it) outnumber the purely hydrogen-burning giants five to three. Were a similar distribution to apply to Reticulum, its asymptotic branch could be separated from the giant branch by the broken line in Figure 5. The remaining giants then lie along a more "normal" sequence. As in Draco, the distribution of giants at the level of the horizontal branch is seen to form a clump at $V = 19$, $B - V = 0.8$ (Caputo and Castellani 1971). With its predominantly red horizontal branch we find that Draco, then, is a more satisfactory analog to Reticulum.

The spatial distribution of stars in Reticulum offers another point of comparison with other systems. When clusters of low central condensation and large core radii are examined, the faint outlying clusters found by Abell (1955) in the Palomar Sky Survey share certain properties with Reticulum. Pal 3 and Pal 4 (Burbidge and Sandage 1958) are both clusters of low central concentration and large core radii. Their masses were estimated by comparing luminosity functions to the horizontal branch with that of M3. Applying a newer value of the mass-to-light ratio $\mathfrak{M}/L_V = 1.5$ (Illingworth 1973), these clusters have masses of 6.5×10^4 and $1.6 \times 10^4 \mathfrak{M}_\odot$, closely similar to that of Reticulum. Both are markedly deficient in blue-horizontal-branch stars, and have

giant branches almost as steep as that of Reticulum. The cluster Pal 13 (Ciatti, Rosino, and Sussi 1965), almost a caricature of a globular cluster, has no giants, and six horizontal-branch stars, of which four are RRab variables, and two lie to the red of the variable gap. Although there are only partial data on the spatial distribution of stars $r_c = 3.2$ pc (Peterson and King 1975), the appearance of the cluster is about as open as that of Pal 3, Pal 4, and Reticulum.

The galactocentric distance of these clusters is greater than 25 kpc in every case. Using von Hoerner's formula (King 1962) and the tidal radii of Peterson and King (1975), one may calculate perigalactic distances for Pal 3 and Pal 4 of 28 and 31 kpc.

Sandage and Wildey (1967), in their paper on NGC 7006, pointed to some of the similarities described above. Their discussion of systems with anomalous color-magnitude diagrams includes the Draco and Leo II dwarf galaxies. Since these clusters and dwarf galaxies are widely distributed in the sky, it is tempting to conclude that Reticulum is another of the so-called intergalactic globular clusters.

On the other hand, the proximity of Reticulum to the Large Magellanic Cloud implies that a close relation may have existed between them at one time. The present separation of 10 kpc from the Large Cloud is similar to that of other outlying clusters associated with the Cloud: NGC 1466, NGC 1841, and NGC 2257 (Gascoigne 1966). Also, the mass of Reticulum is of the same order as obtained for both young and older clusters of the Large Cloud (Freeman and Gascoigne 1971; Freeman and Munsuk 1972; Freeman 1974).

It has been suggested that about 5×10^8 years ago orbital motion may have carried the Large Cloud to within 20 kpc of the Galaxy (Hunter and Toomre 1969). At such a close approach it seems unlikely that all of the outlying halo clusters will continue bound to the Large Cloud. From von Hoerner's formula (King 1962) a limiting radius may be calculated beyond which some loss of matter will occur. Taking for the masses of the Galaxy and the Large Cloud 1.8×10^{11} and $5 \times 10^9 \mathfrak{M}_\odot$ (Thackeray 1971), one finds that $r_{\text{lim}}/R \approx 0.2$, so that loss of matter may be expected for separations greater than 4 kpc. At the present separation of 10 kpc from the Large Cloud, Reticulum may well be in the process of ejection from the Cloud, along with others of the outlying halo globular clusters.

IX. SUMMARY

The color-magnitude diagram of the Reticulum cluster resembles that of the Draco dwarf galaxy in most details, particularly in the steepness of its giant branch and the deficiency of blue horizontal-branch stars. The data suggest the existence of an "anomalous" group of stellar systems that share several characteristics which distinguish them from halo globular clusters of the Galaxy. The Reticulum cluster belongs to this class. The principal distinguishing features of the group members are a galactocentric

distance greater than 25 kpc, a horizontal branch deficient in blue stars, and often a low central concentration and a large core radius.

The proximity of Reticulum to the Large Magellanic Cloud, as well as a mass comparable to that of clusters of the Large Cloud, and similar mean period for the RRab variables suggests a common origin. The present separation from the Large Cloud of 10 kpc is double the limiting radius at which mass loss due to tidal interaction set in, if the perigalactic distance of the Large Cloud from the Galaxy was as low as 25 kpc. The possibility exists that the Reticulum cluster, and others ascribed to the halo of the Magel-

lanic Clouds, are no longer gravitationally bound to the Clouds, and are in the process of detaching.

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APPENDIX

PHOTOMETRY WITH THE IIIa-J EMULSION

The IIIa-J emulsion was used on four occasions, together with a Schott GG-385 2 mm filter. Since our photoelectric sequence contains only 16 stars, we found that a more satisfactory calibration of the transformation relation for the IIIa-J emulsion could be obtained by comparing the photographic photometries directly. Writing

$$B_{aO} = b_{aO} + \alpha_{aO}(B - V) + \text{const.}$$

and

$$B_{aJ} = b_{aJ} + \alpha_{aJ}(B - V) + \text{const.},$$

one would expect the difference $B_{aJ} - B_{aO}$ to lie along a straight line of zero slope, for the proper choice of α_{aJ} and α_{aO} . Figure 8 shows the difference found from 74 stars of this investigation, for values $\alpha_{aO} = -0.09$ and $\alpha_{aJ} = 0.25$. It should be noted that it is the difference $\alpha_{aJ} - \alpha_{aO}$ that has been determined with the greater precision. Our photoelectric sequence was not strong enough to determine the value of α_{aJ} alone with high precision.

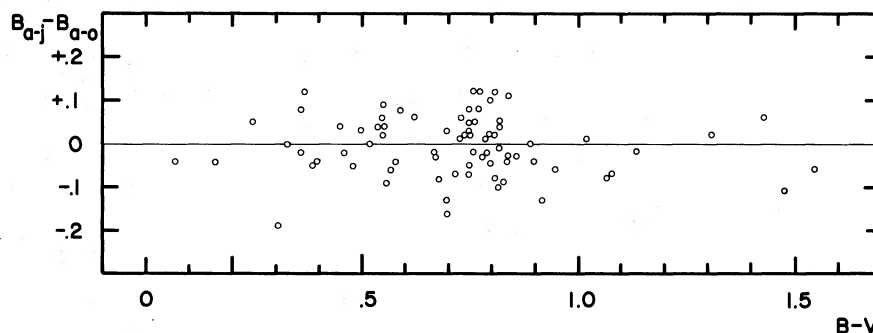


FIG. 8.—Differences in photographic B -magnitudes determined from IIIa-J, baked at 65° C for 4.5 hours in dry N_2 , and IIIa-O as a function of color ($B - V$).

REFERENCES

- Abell, G. O. 1955, *Pub. A.S.P.*, **67**, 258.
 Baade, W., and Swope, H. H. 1961, *A.J.*, **66**, 300.
 Böhm-Vitense, E. 1970, *Astr. and Ap.*, **8**, 283.
 Böhm-Vitense, E., and Szkody, P. 1974, *Ap. J.*, **193**, 607.
 Burbidge, E. M., and Sandage, A. R. 1958, *Ap. J.*, **127**, 527.
 Caputo, F., and Castellani, V. 1971, *Ap. and Space Sci.*, **14**, 323.
 Ciatti, F., Rosino, L., and Sussi, M. G. 1965, *Padova Comm.*, No. 44.
 Cristy, R. F. 1966, *Ap. J.*, **144**, 108.
 Dickens, R. J., 1972, *M.N.R.A.S.*, **157**, 281.
 Freeman, K. C. 1974, *ESO/SCR/CERN Conference on Research Programs for the New Large Telescopes*, ed. A. Reiz, p. 177.
 Freeman, K. C., and Gascoigne, S. C. B. 1971, *Bull. AAS*, **3**, 26.
 Freeman, K. C., and Munsuk, C. 1972, *Proc. Astr. Soc. Australia*, **2**, 151.
 Gascoigne, S. C. B. 1966, *M.N.R.A.S.*, **134**, 59.
 Graham, J. A. 1973, *IAU Colloquium No. 21: Variable Stars in Globular Clusters and Related Systems*, ed. J. D. Fernie (Dordrecht: Reidel), p. 120.
 Harris, W. E. 1974, (unpublished) Ph.D. thesis, University of Toronto.
 Hesser, J. E. 1975, private communication.
 Hunter, C., and Toomre, A. 1969, *Ap. J.*, **155**, 101.
 Iben, I., Jr., Rood, R. T., Strom, K. M., and Strom, S. E. 1969, *Nature*, **224**, 1006.
 Illingworth, G. D. 1973, Ph.D. thesis, Australian National University.
 Johnson, H. L. 1964, *Ap. J.*, **141**, 923.
 ———, 1966, *Comm. Lunar and Planet. Lab.*, **4**, 99.

- King, I. R. 1962, *A.J.*, **67**, 471.
———. 1966, *ibid.*, **71**, 64.
King, I. R., Hedemann, E., Jr., Hodge, S. M., and White, R. E. 1968, *A.J.*, **73**, 456.
Landolt, A. U. 1973, *A.J.*, **78**, 959.
Peterson, C. J., and King, I. R. 1975, *A.J.*, **80**, 427.
Sandage, A. R. 1954, *A.J.*, **59**, 162.
———. 1969, *Ap. J.*, **157**, 515.
———. 1970, *ibid.*, **162**, 841.
Sandage, A. R. 1973, *Ap. J.*, **183**, 711.
Sandage, A. R., and Smith, L. L. 1963, *Ap. J.*, **137**, 1057.
Sandage, A. R., and Wildey, R. 1967, *Ap. J.*, **150**, 469.
Sandage, A. R., and Tammann, G. A. 1971, *Ap. J.*, **167**, 293.
Sérsic, J. L. 1974, *Ap. and Space Sci.*, **28**, 365.
Thackeray, A. D. 1971, *The Magellanic Clouds*, ed. A. B. Muller (Dordrecht: Reidel), p. 6.
Walker, M. F. 1971, *Ap. J.*, **167**, 1.

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