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THE REDSHIFT-DISTANCE RELATION. VI. THE HUBBLE DIAGRAM FROM S20 PHOTOMETRY FOR RICH CLUSTERS AND SPARSE GROUPS: A STUDY OF RESIDUALS

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ABSTRACT

Magnitudes, corrected for aperture effect (to a standard metric diameter), for K dimming, and for galactic absorption are given in B, V, and R for 33 clusters, 20 HMS groups, and 45 galaxies associated with radio sources. The Hubble diagram for the first-ranked E or S0 galaxy in the smallest groups (population as sparse as five members) is the same as that for the great clusters to within 0.3 mag, which is $\sim 1\ \sigma$ of the distribution of absolute magnitude of the cluster galaxies themselves.

The absolute magnitudes of first-ranked galaxies in *compact* groups, where the ratio of projected separation to angular diameter of the dominant galaxy is small (of order unity), are fainter, indicating some type of interaction between group members.

A few clusters are abnormally bright in the Hubble diagram, and these are of Bautz-Morgan cluster types I and II. The magnitudes are not strongly correlated with richness, but the Bautz-Morgan effect is dominant and must be removed before a proper richness correlation can be made.

The mean absolute magnitude of first-ranked cluster galaxies is $\langle (M_V)_C \rangle_1 = -23.30 \pm 0.38\ (\sigma)$ if $H_0 = 50$ km s^{-1} Mpc^{-1}. If the mean mass-to-light ratio is 30 visual solar units, the mean mass of such galaxies will be $\langle \mathfrak{M} \rangle = 5 \times 10^{12}\ \mathfrak{M}_\odot \pm 40$ percent.

Subject headings: galaxies, clusters of — galaxies, photometry of

I. INTRODUCTION

An unexpected result from Paper II (Sandage 1972*b*) was that the absolute magnitude of first-ranked cluster galaxies in that particular sample had no strong dependence on cluster richness. However, the sample did not contain sparse groups, and the result could not be claimed over a wide range of cluster population.

To investigate the absolute magnitudes of the brightest E galaxies in small aggregates, the photometry reported in Paper V (Sandage 1973, table 3) for members of the groups listed by Humason, Mayall, and Sandage (HMS 1956, table 11) was corrected for aperture effect. Preliminary to a more extended analysis than that given in Paper II of the various causes of scatter in the Hubble diagram (Paper VII), we present in § II of this paper the corrected magnitudes for these groups, and for all other galaxies listed in Paper V. A new reduction of the cluster data of Paper II, using the absorption corrections of Paper V, is given in § III. New corrections to Peterson's (1970) V and R data are also made in § III to conform with the system of corrections used here. A discussion of the resulting Hubble diagram in R_C and V_C magnitudes, together with histograms of the distribution of residuals from the Hubble lines, is given in §§ III and IV.

The special emphasis is on the Hubble diagram for members of the small HMS groups, and on analysis of the external errors of the cluster photometry, done by comparing results listed here with those given in Paper II. The comparison will be useful in later papers of this series to form a judgment of the error in q_0 due to errors in the photometry alone.

II. CORRECTED APPARENT MAGNITUDES AND THE PHOTOMETRIC ERRORS FOR GALAXIES IN CLUSTERS, GROUPS, AND RADIO SOURCES

Galaxies in tables 2, 3, and 4 of Paper V were corrected for aperture effect by the method of Paper I (Sandage 1972*a*). The results are listed in table 1 for the cluster galaxies, in table 2 for HMS groups, and in table 3 for the radio sources, all observed with an S20 photometer.

Because the system of aperture correction gives the intensity within a standard metric diameter (eq. [23] of Paper I), the notation $(\mathrm{mag})_{26}$ used previously for these *metric* magnitudes is misleading since it applies to an isophotal level of ~26 mag per square arc sec only in the $z \rightarrow 0$ limit. (The magnitudes are not isophotal except in this limit.) To eliminate the potential confusion of the previous notation, we now designate the metrically corrected magnitudes as B_{SM} and R_{SM}, where SM denotes *standard metric*.

TABLE 1

REDUCED S20 PHOTOMETRY OF FIRST RANKED CLUSTER GALAXIES

Cluster (1)	b^{II} (2)	z (3)	V_{SM} (4)	B_{SM} (5)	R_{SM} (6)	V_C (7)	B_C (8)	R_C (9)	log cz (10)	$(B-V)_C$ (11)	$(V-R)_C$ (12)	Remarks (13)
Virgo..........	+70	0.00381	8.44	9.47	7.60	8.44	9.47	7.60	3.058	1.03	0.84	N4472
Peg I..........	-48	0.01279	11.34	12.42	10.39	11.30	12.33	10.37	3.584	1.03	0.93	N7619
N507...........	+29	0.0170	11.85	12.90	10.98	11.72	12.68	10.90	3.710	0.96	0.82	N507
Perseus........	-13	0.01811	11.87	12.62	10.99	11.50	12.08	10.74	3.735	0.58	0.76	N1275
Abell 1213......	+69	0.0287	13.77	14.87	12.89	13.72	14.73	12.87	3.935	1.01	0.85	N2
Abell 119.......	-64	0.0387	13.80	14.91	12.90	13.74	14.72	12.87	4.065	0.98	0.87	N2
Peg II.........	-48	0.0428	13.94	15.14	13.02	13.85	14.89	12.97	4.109	1.04	0.88	N7503
2322 + 1425.....	-43	0.0439	14.23	15.32	13.34	14.12	15.04	13.29	4.120	0.92	0.83	N7649
0106 - 1536.....	-78	0.0526	14.29	15.42	13.39	14.21	15.15	13.35	4.198	0.94	0.86	Haufen A
1239 + 1852.....	+81	0.0718	14.60	15.84	13.69	14.48	15.47	13.63	4.333	0.99	0.85	Virgo 2
1520 + 2754.....	+57	0.0722	15.37	16.56	14.42	15.25	16.19	14.36	4.334	0.94	0.89	Cor Bor
Abell 2670......	-69	0.0775	14.90	16.13	13.98	14.77	15.74	13.92	4.366	0.97	0.85	
Abell 2029......	+50	0.0777	14.18	15.41	13.26	14.05	15.01	13.19	4.367	0.96	0.86	
0705 + 3506.....	+18	0.0779	15.14	16.45	14.23	14.79	15.76	14.01	4.369	0.97	0.78	Gemini
1513 + 0433.....	+49	0.0944	15.60	16.86	14.70	15.44	16.37	14.62	4.452	0.93	0.82	
Abell 98........	-42	0.10282	15.76	17.10	14.79	15.55	16.51	14.68	4.489	0.96	0.87	
Abell 274.......	-64	0.1289	16.29	17.72	15.29	16.08	17.06	15.17	4.587	0.98	0.91	
Abell 2224......	+34	0.1499	17.03	18.61	...	16.70	17.73	...	4.653	1.03	...	
0025 + 2223.....	-40	0.1594	17.03	18.52	16.06	16.71	17.63	15.87	4.680	0.92	0.84	
0138 + 1832.....	-43	0.1730	17.84	19.42	16.83	17.49	18.47	16.63	4.714	0.98	0.86	
0925 + 2044.....	+43	0.1917	16.84	18.41	15.73	16.44	17.37	15.50	4.760	0.93	0.94	
0855 + 0321.....	+29	0.2018	17.70	19.39	16.64	17.20	18.22	16.35	4.782	1.02	0.85	Hydra
1447 + 2617.....	+63	0.36	19.87	21.36	18.27	18.79	(19.77)	17.84	5.033	(0.98)	0.95	
3C31...........	-30	0.01755	12.19	13.28	11.28	12.06	13.05	11.20	3.706	0.99	0.86	N383
3C40...........	-63	0.0180	12.36	13.44	11.48	12.33	13.35	11.47	3.732	1.02	0.86	N545
3C66...........	-16	0.0215	12.82	13.82	11.92	12.53	13.38	11.72	3.810	0.85	0.81	
3C465..........	-33	0.0301	13.28	14.38	12.36	13.15	14.10	12.28	3.956	0.95	0.87	N7720
3C338..........	+44	0.0303	12.58	13.64	11.73	12.49	13.43	11.69	3.958	0.94	0.80	N6166
3C317..........	+50	0.0351	13.47	14.57	12.56	13.41	14.39	12.53	4.022	0.98	0.88	
M23 - 112......	-64	0.0825	15.56	16.62	14.63	15.42	16.20	14.56	4.394	0.78	0.86	
3C219..........	+45	0.1745	17.21	18.59	16.27	16.87	17.65	16.07	4.719	0.78	0.80	
3C28...........	-37	0.1959	17.61	19.03	16.47	17.17	17.94	16.22	4.769	0.77	0.95	
3C295..........	+61	0.461	20.13	21.55	18.40	18.65	(19.63)	17.79	5.141	(0.98)	0.86	

TABLE 2

REDUCED S20 PHOTOMETRY FOR HMS GROUPS

Object (1)	b (2)	z (3)	V_{SM} (4)	B_{SM} (5)	R_{SM} (6)	V_C (7)	B_C (8)	R_C (9)	log cz (10)	$(B-V)_C$ (11)	$(V-R)_C$ (12)	Remarks (13)
NGC 68.......	-32	0.0226	13.28	14.35	12.44	13.16	14.12	12.36	3.831	0.96	0.80	
NGC 80.......	-40	0.0209	12.47	13.56	11.60	12.38	13.38	11.55	3.797	1.00	0.83	
NGC 128......	-60	0.0155	11.69	12.64	10.82	11.67	12.57	10.81	3.667	0.90	0.86	
NGC 194......	-60	0.0177	12.24	13.19	11.36	12.21	13.11	11.35	3.725	0.90	0.86	
NGC 383......	-30	0.0176	12.19	13.28	11.28	12.06	13.06	11.20	3.723	1.00	0.86	In Table 1
NGC 507......	-29	0.0155	11.80	12.82	10.92	11.68	12.60	10.84	3.668	0.92	0.84	In Table 1
NGC 547......	-63	0.0180	12.38	13.44	11.48	12.35	13.35	11.47	3.732	1.00	0.88	Comp to 3C40 Table 1,3
NGC 741......	-54	0.0188	12.02	13.11	11.23	11.99	13.02	11.22	3.751	1.03	0.77	
NGC 1600.....	-33	0.0160	11.57	12.58	10.67	11.46	12.38	10.60	3.681	0.92	0.86	
NGC 2563.....	+29	0.0159	12.22	13.27	11.33	12.10	13.05	11.25	3.677	0.95	0.85	
NGC 2832.....	+44	0.0200	12.23	13.29	11.36	12.16	13.14	11.32	3.778	0.98	0.84	
NGC 3158.....	+55	0.0234	12.27	13.30	11.39	12.23	13.19	11.37	3.846	0.96	0.86	
NGC 5044.....	+46	0.0087	10.95	11.99	10.06	10.92	11.91	10.11	3.415	0.99	0.87	
NGC 5077.....	+50	0.0084	10.94	11.98	10.09	10.93	11.94	10.09	3.401	1.01	0.84	
NGC 5353.....	+71	0.0076	10.52	11.56	9.66	10.51	11.53	9.66	3.359	1.02	0.85	
NGC 5846.....	+49	0.0060	10.14	11.20	9.30	10.12	11.16	9.29	3.257	1.04	0.83	
NGC 6027*....	+47	0.0146	12.42	13.30	11.58	12.38	13.20	11.56	3.640	0.82	0.82	
NGC 7242.....	-16	0.0204	12.75:	13.90:	11.81:	12.46:	13.46:	11.61:	3.787	1.00	0.85	
NGC 7385.....	-41	0.0258	12.87	13.97	11.94	12.78	13.78	11.90	3.889	1.00	0.88	
NGC 7619.....	-48	0.0128	11.31	12.50	10.49	11.28	12.30	10.38	3.584	1.02	0.90	In Table 1

*Magnitudes are for all six members of this very compact group. For brightest component alone, $V_C \simeq 13.1$, $B_C \simeq 14.1$, $R_C \simeq 12.3$ as bright limits.

TABLE 3

REDUCED S20 PHOTOMETRY OF RADIO GALAXIES

Source (1)	ℓ^{II} (2)	b^{II} (3)	z (4)	V_{SM} (5)	B_{SM} (6)	R_{SM} (7)	V_C (8)	B_C (9)	R_C (10)	log cz (11)	$(B-V)_C$ (12)	$(V-R)_C$ (13)	S_6 (14)	Remarks (15)
3C15............	115	-64	0.0733	15.43	16.57	14.54	15.31	16.20	14.48	4.342	0.89	0.83	~ 1	Group
3C17............	115	-65	0.2201	17.83	18.58	16.98	17.37	17.46	16.73	4.820	0.09	0.64	7	Isolated
3C26............	125	-67	0.2106	18.03	19.17	17.17	17.60	18.09	16.94	4.800	0.49	0.66	11	Isolated
3C28............	124	-37	0.1959	17.60	19.02	16.46	17.16	17.93	16.21	4.769	0.77	0.95	2	ClA115
3C29............	127	-64	0.0450	14.06	15.13	13.17	13.99	14.90	13.13	4.130	0.91	0.86	0	ClA119?
3C33............	129	-49	0.0600	15.20	16.36	14.36	15.10	16.08	14.31	4.255	0.98	0.79	12	Isolated
3C40............	142	-63	0.0180	12.41	13.46	11.52	12.38	13.37	11.51	3.732	0.99	0.87	?	N545
3C66............	140	-17	0.0215	12.80	13.80	11.90	12.53	13.37	11.71	3.810	0.84	0.82	?	
3C75N	170	-45	0.0241	13.47	14.71	12.44	13.40	14.55	12.40	3.859	1.15	1.00	?	North, DB
3C75S...........	170	-45	0.0241	13.80	15.02	12.77	13.72	14.84	12.72	3.859	1.12	1.00	?	South, DB
3C76.1..........	163	-36	0.0328	14.79	15.89	13.86	14.67	15.63	13.79	3.993	0.96	0.88	0	Isolated
3C78............	175	-45	0.0289	12.98	14.13	12.00	12.90	13.94	11.96	3.938	1.04	0.94	1:	N1218
3C83.1..........	151	-13	0.0181	(13.09)	(14.24)	(12.12)	(12.72)	(13.71)	(11.87)	3.735	(0.99)	(0.85)	?	N1265
3C84............	151	-13	0.0181	11.87	12.62	10.99	11.50	12.08	10.74	3.735	0.58	0.76	Hi	N1275
3C88............	181	-42	0.0302	14.12	15.21	13.17	14.02	14.99	13.13	3.957	0.97	0.89	2	Isolated
3C98............	180	-31	0.0306	14.42	15.62	13.44	14.26	15.33	13.36	3.963	1.07	0.90	8	Isolated
3C192...........	198	+26	0.0596	15.37	16.58	14.51	15.15	16.11	14.37	4.252	0.96	0.78	~ 5?	Group
3C198...........	218	+23	0.0809	16.60	17.50	15.82	16.31	16.88	15.64	4.385	0.57	0.67	7	Group?
3C219...........	174	+45	0.1745	(17.21)	(18.59)	(16.27)	(16.87)	(17.65)	(16.07)	4.719	0.78	0.80	8	Rich Cl
3C223.1.........	183	+49	0.1075	(16.36)	(17.65)	(15.44)	(16.18)	(17.09)	(15.35)	4.508	0.91	0.83	~ 6:	
3C264...........	236	+73	0.0206	12.76	13.79	11.88	12.72	13.69	11.86	3.791	0.97	0.86	0	N3862
3C270...........	282	+67	0.0070	10.40	11.37	9.56	10.40	11.37	9.56	3.322	0.97	0.84	0	N4261
3C272.1.........	278	+74	0.0029	9.36	10.38	8.52	9.36	10.38	8.52	3.058	1.02	0.84	?	N4374
3C278...........	273	+50	0.0143	11.50	12.59	10.58	11.48	12.52	10.57	3.632	1.04	0.91	0	N4782, DB
3C278a..........	273	+50	0.0143	11.78	12.79	10.92	11.76	12.72	10.91	3.632	0.96	0.85	0	N4783, DB
3C293...........	54	+76	0.0454	14.31	15.31	13.48	14.24	15.08	13.44	4.134	0.84	0.80	~ 2	Isolated
3C295...........	98	+61	0.461	20.13	21.55	18.40	18.65	(19.63)	17.79	5.141	(0.98)	0.86	~ 1	Rich Cl
3C296...........	354	+62	0.0237	12.11	13.18	11.26	12.07	13.07	11.24	3.852	1.00	0.83	0	IC 5532
3C317...........	9	+50	0.0351	13.47	14.57	12.55	13.41	14.39	12.52	4.022	0.98	0.89	3	ClA2052
3C318.1.........	11	+49	0.0440	14.29:	15.41:	13.33:	14.22:	15.17:	13.29:	4.121	0.95	0.93	0	Group
3C338...........	63	+44	0.0303	12.58	13.64	11.74	12.49	13.43	11.70	3.959	0.94	0.79	0	N6166
3C381...........	76	+23	0.1614	17.45	18.87	16.53	17.01	17.86	16.26	4.685	0.85	0.75	> 8	Group
3C382...........	61	+17	0.0586	14.72	15.87	13.79	14.38	15.25	13.57	4.245	0.87	0.81	5	Isolated
3C388...........	75	+20	0.0917	15.63	17.04	14.67	15.29	16.31	14.45	4.439	1.02	0.84	1	N1, DB
3C402...........	83	+13	0.0263	12.89	14.02	11.87	12.51	13.44	11.61	3.897	0.93	0.89	0	G1
3C436...........	80	-19	0.2154	(18.11)	(19.56)	(16.94)	(17.47)	(18.18)	(16.56)	4.810	0.71	0.91	5	
3C442...........	75	-34	0.0270	13.68	14.75	12.83	13.56	14.51	12.76	3.908	0.95	0.80	~ 1	N4237, DB
3C442a..........	80	-19	0.0270	13.42	14.48	12.58	13.30	14.24	12.51	3.908	0.94	0.79	0	N4236, DB
3C449...........	95	-16	0.0181	13.10	14.20	12.18	12.81	13.77	11.98	3.735	0.96	0.83	0	Group
3C452...........	98	-17	0.0820	16.06	17.36	15.14	15.69	16.62	14.90	4.391	0.93	0.79	5	Group?
3C455...........	85	-41	0.0331	14.03	15.06	13.16	13.93	14.82	13.11	3.997	0.89	0.82	0	Isolated
3C456...........	86	-46	0.2337	18.67	19.46	17.54	18.14	18.24	17.27	4.846	0.10	0.87	7:	
MSH 23-112.....	66	-64	0.0825	15.56	16.62	14.63	15.43	16.19	14.56	4.394	0.76	0.87	7	
3C465 N1........	104	-33	0.0301	13.29	14.41	12.37	13.16	14.13	12.29	3.956	0.97	0.87	1	
3C465 N2........	104	-33	0.0301	14.02	15.00	13.09	13.89	14.74	13.01	3.956	0.85	0.88	?	

( ) means that only one measure at a single aperture is involved.

: denotes that tabulated value is uncertain.

The magnitudes corrected for metric aperture effect are listed in columns (4)–(6) of table 1, (4)–(6) of table 2, and (5)–(7) of table 3. In the following columns of each table are the V_C, B_C, and R_C magnitudes, which are the B_{SM}, V_{SM}, and R_{SM} values corrected for K dimming by table 5 of Paper V and for galactic reddening by equations (4) and (5) of the same paper. The other columns of each table are largely self-explanatory.

TABLE 4

MASTER LIST OF CLUSTER PHOTOMETRY OBTAINED BY AVERAGING TABLE 2 OF PAPER II WITH TABLE 1 HERE

Cluster (1)	l^{II} (2)	b^{II} (3)	z (4)	Richness (5)	V_C (6)	B_C (7)	R_C (8)	log cz (9)	ΔV_C (10)	ΔB_C (11)	ΔR_C (12)	Remarks (13)
					Clusters							
Virgo	287	+70	0.00381	(1)	8.44	9.44	7.60	3.058	-0.05	+0.02	-0.08	N4472, 4486
Fornax	240	-57	0.00509	(1)	8.90	9.90	...	3.184	-0.22	-0.15	...	N1316
Peg I	88	-48	0.0128	(0)	11.25	12.26	10.37	3.584	+0.13	+0.21	+0.06	N7619
0122 + 3305	131	-29	0.0170	(1)	11.77	12.72	10.90	3.710	+0.02	+0.04	-0.04	N507
Perseus	151	-13	0.0181	2	11.50	12.08	10.74	3.735	-0.38	-0.73	-0.33	N1275
Coma	57	+88	0.0222	2	(11.51)	(12.50)	...	3.824	-0.81	-0.75	...	N4489
Abell 1213	201	+69	0.0287	1	13.72	14.73	12.87	3.935	+0.84	+0.93	+0.81	N2
Hercules	32	+44	0.0341	2	13.12	13.90	...	4.017	-0.16	-0.31	...	
Abell 119	126	-64	0.0387	1	13.74	14.72	12.87	4.065	+0.22	+0.27	+0.15	N2
2308 + 0720	84	-48	0.0428	(0)	13.66	14.56	12.97	4.109	-0.08	-0.11	+0.03	N7503: PII wt 2
2322 + 1425	93	-43	0.0440	0	14.11	15.00	13.29	4.120	+0.31	+0.27	+0.30	N7649
1145 + 5559	141	+59	0.0516	1	14.39	15.33	...	4.191	+0.24	+0.25	...	UMa #1
0106 - 1537	143	-78	0.0526	1	14.12	15.03	13.35	4.198	-0.07	-0.09	-0.03	Haufen A
1024 + 1039	233	+52	0.0649	1	14.81	15.78	...	4.290	+0.16	+0.20	...	Leo
1239 + 1852	287	+81	0.0718	0	14.50	15.47	13.63	4.333	-0.36	-0.33	-0.43	Virgo 2
1520 + 2754	43	+57	0.0722	2	15.25	16.19	14.36	4.334	+0.38	+0.39	+0.30	Cor Bor
Abell 2670	81	-69	0.0775	3	14.77	15.74	13.92	4.366	-0.26	-0.22	-0.30	
Abell 2029	7	+50	0.0777	2	14.05	15.01	13.19	4.367	-0.98	-0.95	-1.04	
0705 + 3506	182	+18	0.0779	0	14.96	15.90	14.01	4.369	-0.08	-0.07	-0.23	Gemini
1513 + 0433	5	+49	0.0944	1	15.47	16.36	14.62	4.452	+0.01	-0.03	-0.03	
Abell 98	121	-42	0.1028	3	15.55	16.51	14.68	4.489	-0.09	-0.06	-0.15	
Abell 274	161	-64	0.1289	3	16.08	17.06	15.17	4.587	-0.05	0.00	-0.15	
1431 + 3146	51	+67	0.1312	1	16.06	16.91	...	4.595	-0.11	-0.20	...	Bootis
1055 + 5702	149	+54	0.1345	1	15.93	16.86	...	4.606	-0.30	-0.30	...	UMa #2
1153 + 2341	225	+77	0.1426	3	(15.46)	(16.40)	...	4.631	-0.89	-0.89	...	
1641 + 1327	358	+34	0.1499	3	16.69	17.72	...	4.653	+0.22	+0.33	...	
1534 + 3749	61	+54	0.1532	3	16.55	17.51	...	4.662	+0.04	+0.07	...	
0025 + 2223	115	-40	0.1594	2	16.66	17.59	15.87	4.680	+0.06	+0.06	+0.08	
1228 + 1050	285	+73	0.1651	2	16.90	17.84	...	4.695	+0.22	+0.23	...	Virgo 3
0138 + 1832	139	-43	0.1730	1	17.34	18.33	16.63	4.714	+0.57	+0.63	+0.67	
1309 - 0105	313	+61	0.1745	4	16.93	17.73	...	4.719	+0.14	0.00	...	
1304 + 3110	82	+85	0.1831	2	(16.90)	(17.85)	...	4.740	0.00	+0.02	...	
0925 + 2044	209	+43	0.1917	2	16.50	17.49	15.50	4.760	-0.50	-0.44	-0.69	
1253 + 4422	121	+73	0.1979	1	17.66	18.63	...	4.774	+0.59	+0.63	...	
0855 + 0321	226	+29	0.2018	1	17.20	18.16	16.35	4.782	+0.09	+0.12	+0.05	Hydra
1447 + 2617	37	+63	0.36	(2)	18.78	19.78	17.84	5.033	+0.42	+0.49	+0.29	
0024 + 1654	115	-45	0.38	(2)	18.35	19.32	...	5.057	-0.13	-0.09	...	
					Radio Source Clusters							
3C31	127	-30	0.0169	(0)	12.03	13.08	11.20	3.706	+0.30	+0.42	+0.28	N383
3C40	142	-63	0.0180	0	12.29	13.28	11.47	3.732	+0.43	+0.49	+0.42	N545
3C66	140	-17	0.0215	0	12.58	13.41	11.72	3.810	+0.33	+0.23	+0.28	
3C465	104	-33	0.0301	1	13.15	14.12	12.28	3.956	+0.17	+0.21	+0.11	N7720
3C338	63	+44	0.0303	2	12.52	13.34	11.69	3.958	-0.47	-0.58	-0.49	N6166, A2199
3C317	9	+50	0.0351	0	13.40	14.36	12.53	4.022	+0.09	+0.12	+0.03	
M23 - 122	66	-64	0.0825	2	15.38	16.17	14.56	4.394	+0.21	+0.07	+0.20	
3C219	174	+45	0.1745	(2)	16.90	17.74	16.07	4.719	+0.10	+0.01	+0.09	
3C28	124	-37	0.1959	3	17.16	17.94	16.22	4.769	+0.12	-0.03	-0.01	
3C295	97	+61	0.461	(1)	18.64	19.63	17.79	5.141	-0.26	-0.21	-0.31	
					Westerlund and Wall Not In HMS Groups							
0131 - 36	261	-77	0.0298	(0)	13.19	14.11	...	3.951	+0.24	+0.23	...	
0915 - 11	243	+25	0.0522	(0)	13.73	14.58	...	4.194	-0.44	-0.52	...	Hydra A
1245 - 41	302	+22	0.0113	(2)	10.89	11.85	...	3.498	+0.20	+0.23	...	N4696
1332 - 33	313	+28	0.0114	(0)	10.77	11.73	...	3.535	-0.10	-0.07	...	IC4296
1400 - 33	320	+27	0.0138	(0)	11.04	12.01	...	3.617	-0.24	-0.21	...	N5419
2152 - 69	322	-41	0.0266	(0)	13.23	14.10	...	3.902	+0.52	+0.46	...	
					HMS Groups Not Previously Used							
N68	114	-32	0.0226	(0)	13.16	14.12	12.36	3.831	+0.80	+0.83	+0.81	
N80	114	-40	0.0209	(0)	12.38	13.38	11.55	3.797	+0.20	+0.27	+0.17	
N128	112	-60	0.0155	(0)	11.67	12.57	10.81	3.667	+0.14	+0.11	+0.09	
N194	117	-60	0.0177	(0)	12.21	13.11	11.35	3.725	+0.38	+0.35	+0.33	
N741	151	-54	0.0188	(0)	11.99	13.02	11.22	3.751	+0.04	+0.13	+0.07	
N1600	200	-33	0.0160	(0)	11.46	12.38	10.60	3.681	-0.14	-0.15	-0.19	
N2563	203	+29	0.0159	(0)	12.10	13.05	11.25	3.677	+0.52	+0.53	+0.47	
N2832	191	+44	0.0200	(0)	12.16	13.14	11.32	3.778	+0.07	+0.12	+0.04	
N3158	183	+55	0.0234	(0)	12.23	13.19	11.37	3.846	-0.20	-0.17	-0.25	
N5044	311	+46	0.0087	(0)	10.92	11.91	10.11	3.415	+0.64	+0.71	+0.65	
N5077*	314	+50	0.0084	(0)	10.93	11.94	10.09	3.401	+0.72	+0.81	+0.69	
N5353	83	+71	0.0076	(0)	10.51	11.53	9.66	3.359	+0.52	+0.61	+0.47	
N5846	0	+49	0.0060	(0)	10.12	11.16	9.29	3.257	+0.64	+0.74	+0.62	
N7242	92	-16	0.0204	(0)	12.46:	13.46:	11.61:	3.787	+0.32	+0.39	+0.29	
N7385	82	-41	0.0258	(0)	12.78	13.78	11.90	3.889	+0.14	+0.21	+0.07	

*NGC 5077 has very low surface brightness.

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The photometry in tables 1–3 here is independent of that of Papers II and III (Sandage 1972*c*). Comparison permits a determination of the combined external errors of both sets of data. The errors test not only the measuring accuracy, but the total reduction to standard metric magnitudes as well.

There are 52 galaxies common to the two studies. All data in Papers II and III were reduced anew using the revised latitude-absorption corrections of Paper V. The distributions of the differences of the final B_C and V_C magnitudes, in the sense of this paper minus Papers II and III, are shown in figure 1. The distributions are roughly Gaussian, are centered closely on zero, and have dispersions of $\sigma(\Delta V) = 0.13$ mag and $\sigma(\Delta B) = 0.18$ mag with no exclusions. If both sets of data are of equal weight, the photometric errors in Papers II and III and in tables 1–3 here will be separately distributed as $\sigma(\Delta V) \simeq 0.09$ mag and $\sigma(\Delta B) \simeq 0.12$ mag, which are satisfactorily small compared with other sources of scatter in the Hubble diagram. The reasons for the few large differences in figure 1 have not been investigated.

III. THE HUBBLE DIAGRAM IN V_C AND R_C MAGNITUDES

The new S20 photometric data have been combined with the S4 data of Papers II and III (newly reduced for the reason mentioned before), and the results are listed in table 4. The magnitudes V_C, B_C, and R_C in columns (6)–(8) mean the same as those in tables 1–3. Table 4 is the summary of all photoelectric magnitudes that have now been determined in the current programs. It, and table 5 to be described, form the basis for the discussion in this paper and the one that follows (Sandage and Hardy 1973, Paper VII).

The Hubble diagram in R_C magnitudes (from table 4) is shown in figure 2, given primarily to illustrate the agreement of the magnitudes for most brightest members of HMS *groups* (*open circles*) with those of the brightest galaxy of great clusters (*dots*). None of the open circles deviates from the distribution of dots (relative to the line of slope 5) by more than 2 σ. Because some of these groups have only 10 members or less (G128, G741, G1600, G5077, G5353), the approximate agreement (to within 2 σ) of the dots and circles shows that there is not a strong dependence, if any, of the absolute

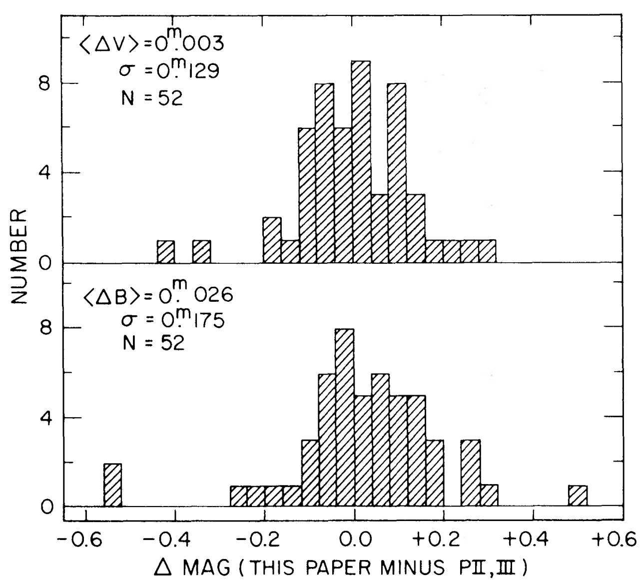

FIG. 1.—Distribution of the differences in the B_C and V_C magnitudes (corrected for aperture effect, K dimming, and galactic absorption) between this paper and the reanalyzed data from Papers II and III for 52 galaxies in common.

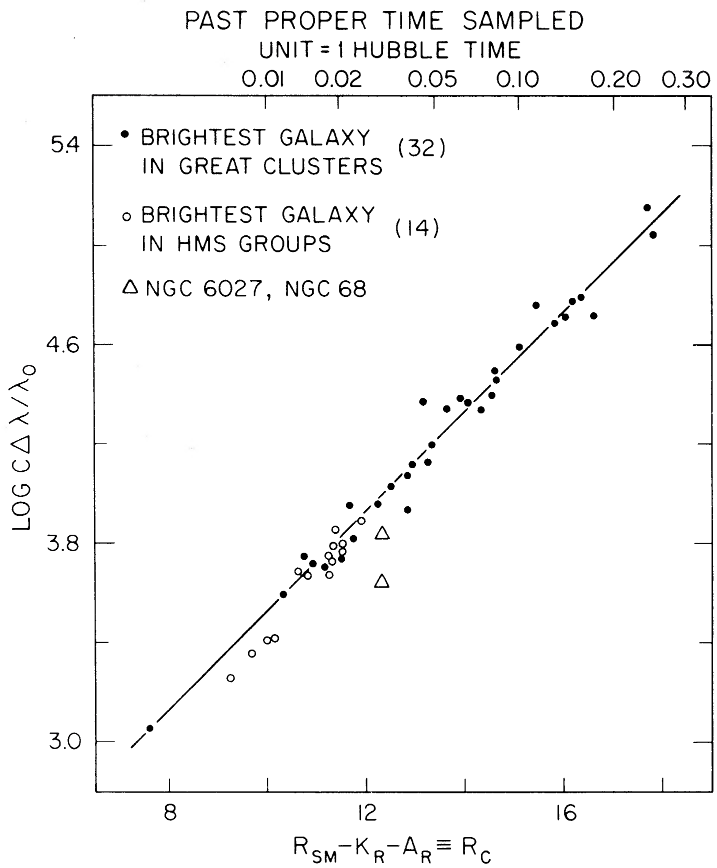

FIG. 2.—The Hubble diagram in R_C magnitudes for galaxies in table 4. The line is equation (1) of the text. The look-back time for a particular redshift, read from the drawn line, is given along the top in units of the Hubble time for a $q_0 = +1$ model from results given elsewhere (Sandage 1961, table 3). Two compact groups are plotted as open triangles. Sixteen groups are plotted as open circles from the data in table 4 (last section) plus NGC 6027 from table 2.

magnitude of the brightest member on the cluster population—the same result as in Paper II, but now extended.

Two groups, NGC 68 and NGC 6027, do deviate from the mean Hubble line by large amounts ($\Delta R_C = 0.81$ mag for NGC 68, and $\Delta R_C = 1.71$ mag for NGC 6027). Inspection of photographs of these groups shows that they differ from the others of table 2 by differences in the ratio of the *projected separation* of the galaxies from one another, in units of the angular diameter of the largest galaxy. This ratio is much *smaller* for G68 and G6027 than for any of the other groups in the sample (see the *Palomar Sky Survey* prints). The compactness of the group implied by the small ratio has apparently either (1) prevented any galaxy in the group from forming at the characteristic maximum size attained in looser groups and in the great clusters, or (2) caused the outer envelopes of the members to be stripped by tidal action. A more extensive investigation of this phenomenon promises to provide varied empirical data on galaxy interactions.[1]

[1] Is the deviation from the Hubble diagram of first (or *n*th) ranked members a continuous function of the ratio of *separation* to galaxy *diameter*, or is there a cutoff? Is the functional dependence characteristic of tidal interaction as the inverse third power, or a more general relation? Many compact groups and "nests" exist (e.g., the catalog of Vorontsov-Velyaminov 1959), and the investigation of such questions with present methods is clearly feasible.

The sample of table 4, shown in figure 2, can be increased by adding the clusters studied by Peterson (1970), if his data are corrected to the present system. It was shown in Paper II that V_{SM} for the metric diameter of equation (23) of Paper I differs by 0.39 mag from the mean aperture correction adopted by Peterson. With the new absorption corrections of Paper V (eqs. [4] and [5]), this can be shown to change to 0.44 mag in V_C so as to make the zero points of Peterson's magnitudes agree with those of table 4. Such magnitudes, corrected also by the K_V and A_V values listed in columns (5) and (6) of table 5, are given in column (7) of that table as $V_C(0.44)$.

However, the corresponding R_C magnitude of Peterson, corrected to the present system is not $V_C(0.44) - (V - r)$, as might be expected, because the $V - r$ colors of Peterson's system are inexplicably systematically bluer in zero point than $V - R$.[2]

TABLE 5

PETERSON'S DATA CORRECTED TO THE PHOTOMETRIC SYSTEM OF THIS PAPER

Cluster (1)	Richness (2)	l^{II} (3)	b^{II} (4)	A_V (5)	K_V (6)	$V_C(0.44)$* (7)	$R_C(0.44)$* (8)	log cz (9)	ΔV_C† (10)	ΔR_C† (11)
A76.......	0	117	-56	0.00	0.06	13.33	12.48	4.053	-0.14	-0.18
A147......	0	131	-60	0.00	0.07	14.23	13.39	4.122	+0.42	+0.39
A262......	0	137	-25	0.13	0.03	11.94	11.12	3.702	+0.22	+0.22
A278......	0	139	-29	0.10	0.15	15.26	14.44	4.433	-0.11	-0.12
A376......	0	147	-21	0.18	0.08	14.02	13.20	4.165	-0.01	-0.02
A505......	0	132	+22	0.16	0.09	13.74	12.90	4.212	-0.52	-0.55
A539......	1	196	-18	0.22	0.04	13.04	12.21	3.904	+0.32	+0.30
A548......	1	230	-24	0.14	0.06	13.49	12.67	4.069	-0.06	-0.06
A553......	0	165	+14	0.31	0.11	14.58	13.77	4.303	-0.14	-0.14
A569......	0	169	+23	0.16	0.03	12.08	11.23	3.763	+0.06	+0.02
A576......	1	161	+26	0.12	0.07	13.74	12.91	4.084	+0.12	+0.10
A592......	1	210	+16	0.26	0.10	14.40	13.70	4.270	-0.16	-0.04
A634......	0	159	+34	0.08	0.04	13.05	12.20	3.902	+0.34	+0.30
A671......	0	193	+33	0.08	0.08	13.63	12.80	4.173	-0.44	-0.46
A754......	2	239	+25	0.13	0.09	13.68	12.88	4.207	-0.56	-0.54
A993......	0	249	+42	0.04	0.09	13.91	13.09	4.201	-0.30	-0.30
A1060.....	1	270	+27	0.12	0.02	11.02	10.19	3.538	+0.12	+0.11
A1139.....	0	251	+53	0.00	0.06	13.70	12.90	4.052	+0.24	+0.25
A1228.....	1	187	+69	0.00	0.06	13.60	12.81	4.014	+0.32	+0.35
A1257.....	0	183	+70	0.00	0.05	14.03	13.19	4.007	+0.79	+0.76
A1314.....	0	152	+64	0.00	0.05	13.16	12.34	4.002	-0.06	-0.06
A1318.....	1	144	+59	0.00	0.03	12.28	11.51	3.753	+0.31	+0.36
A1367.....	2	234	+73	0.00	0.03	12.09	11.30	3.787	-0.05	-0.02
A1736.....	0	313	+35	0.08	0.07	13.74	12.87	4.112	-0.02	-0.08
A2147.....	1	29	+45	0.03	0.06	13.33	12.52	4.022	+0.02	+0.02
A2152.....	1	30	+44	0.04	0.07	13.85	13.06	4.121	+0.04	+0.06
A2162.....	0	49	+46	0.02	0.05	12.97	12.17	3.980	-0.14	-0.12
A2197.....	1	65	+44	0.04	0.05	12.67	11.85	3.985	-0.46	-0.46
A2319.....	1	76	+14	0.31	0.09	13.94	13.15	4.217	-0.35	-0.32
A2657.....	1	97	-50	0.00	0.07	14.26	13.39	4.094	+0.58	+0.53
A2666.....	0	107	-34	0.08	0.04	12.39	11.61	3.913	-0.38	10.34

*$V_C(0.44) \equiv V_{PET} - 0.44 - A_V - K_V$

*$R_C(0.44) \equiv V_C(0.44) + C^P_{V-r} + 0.05 - 0.026 (\csc b - 1)$.

†Sense of Δ mag is observed minus calculated. Brighter than average galaxies have negative Δ mag.

[2] The $V - R$ colors for five of Peterson standards listed in table 1 of Paper V are systematically redder by 0.07 mag than the values listed by Peterson, and this has carried over to $V - R$ of the galaxies themselves.

To transform Peterson's colors to the present system, it was found that $R_C(0.44) = V_C(0.44) + C_{v-r}{}^P + 0.05 - 0.026(\csc b - 1)$ is the necessary relation, where $C_{v-r}{}^P$ is Peterson's (1970, table 1) measured $V - r$ color uncorrected for galactic reddening. These adopted magnitudes are listed in column (8) of table 5.

The resulting Hubble diagram is shown in figure 3, where all R_C magnitudes from tables 4 and 5 are plotted. The theoretical line of slope 5 with q_0(apparent) = +1 is shown. The equation of the line in both figures 2 and 3 is

$$R_C = 5 \log cz - 7.61 . \quad (1)$$

The V_C values in table 4 alone have been plotted in the Hubble diagram of figure 4, where again the separation into great clusters, HMS groups, and the two compact groups of G68 and NGC 6027 is made. The conclusions from this diagram are essentially the same as those from figure 2. The equation of the line is

$$V_C = 5 \log cz - 6.80 . \quad (2)$$

A similar solution for the B_C magnitudes from table 4 is

$$B_C = 5 \log cz - 5.87 . \quad (3)$$

Equations (1)–(3) define the mean values from which the magnitude residuals ΔB_C, ΔV_C, and ΔR_C have been obtained, in the sense of observed minus calculated, as listed

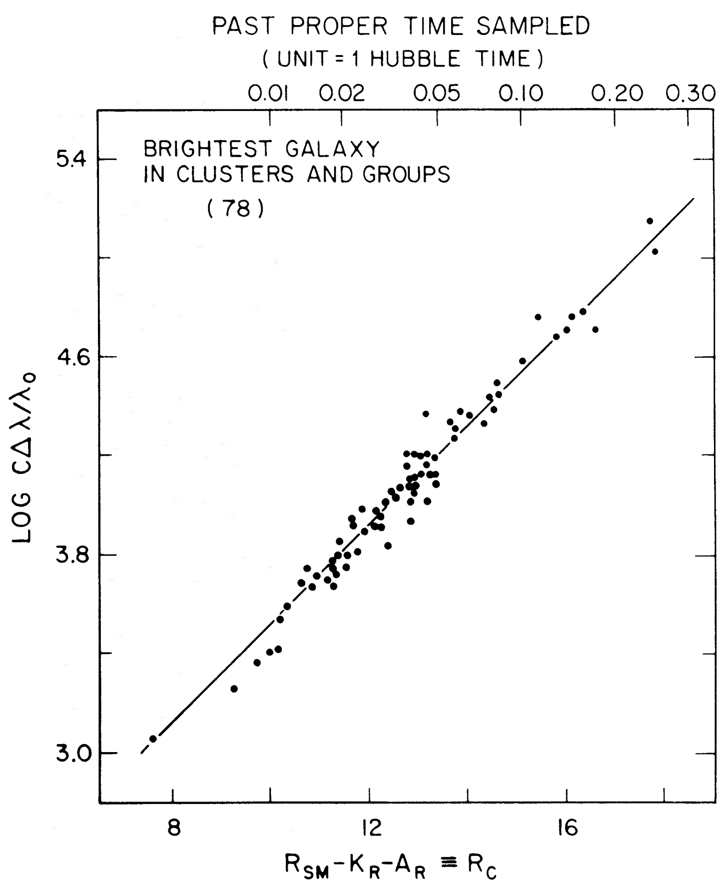

FIG. 3.—Same as fig. 2, but with Peterson's data of table 5 added. Where crowded, a few points have been omitted to avoid confusion.

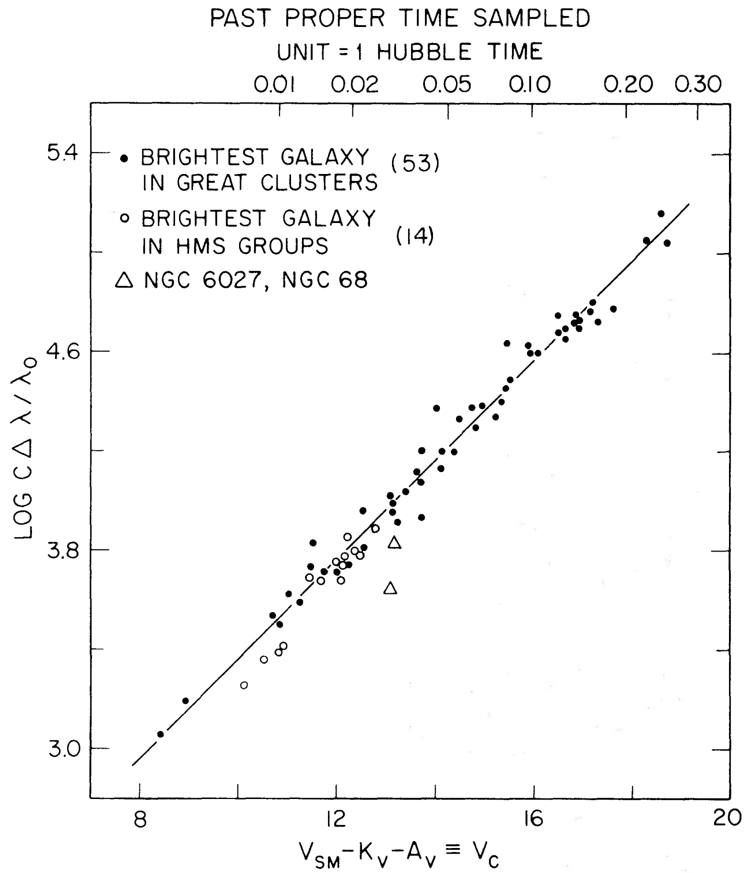

FIG. 4.—Same as fig. 2 for V_C magnitudes, using the data of table 4 alone, plus NGC 6027 from table 2. The line is equation 2 of the text.

in tables 4 and 5, columns (10)–(12). Brighter than average galaxies have negative residuals. None of the HMS groups was included in the solutions for equations (1)–(3).

IV. DISTRIBUTION OF RESIDUALS FROM THE MEAN HUBBLE LINE IN B_C, V_C, AND R_C

The histograms of the residuals in each of the three colors from the data of table 4 are shown in figure 5. The hatched part of each diagram is for the cluster data alone, and the open bars are for the HMS groups. The mean values in the upper left of each panel include both the groups and the clusters. The nonzero values of $\langle \Delta R_C \rangle = +0.076$, $\langle \Delta V_C \rangle = +0.075$, and $\langle \Delta B_C \rangle = +0.081$ show that the mean residuals of the HMS group members alone are not zero, but are fainter than the bulk of the cluster members. (The mean residuals for the clusters themselves are accurately zero). However, the first-ranked group galaxy is fainter than the cluster mean *by less than 2 sigma of the distribution in each case*. That there may be a very weak correlation with richness is therefore suggested by this slight faintward shift, but the shift is hardly significant at 1 sigma in the mean.

There is, however, another effect that is shown in Paper VII to dominate the systematics within the distribution of residuals. The three clusters with the largest negative residuals in figure 5 are Coma with $\Delta V_C = -0.81$ mag, Abell 2029 ($\Delta V_C = -0.98$ mag), and 1153+2341($\Delta V_C = -0.89$ mag). The brightest galaxies in each of these clusters is a Morgan-Lesh (1965) "supergiant cD" system; more importantly,

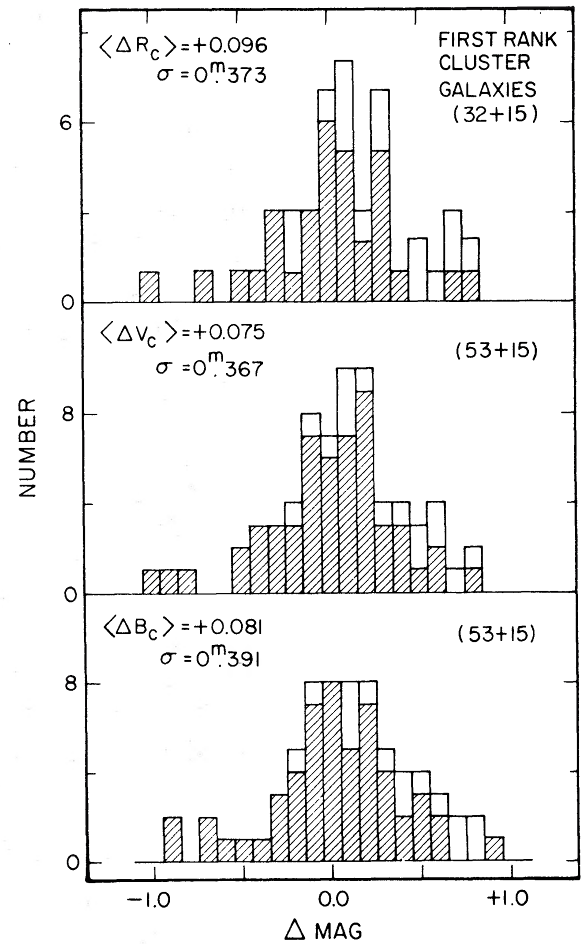

FIG. 5.—Histogram of the magnitude residuals from the Hubble line, listed in columns (10)–(12) of table 4. *Hatched areas*, cluster data. *Open bars*, HMS groups. The residuals are from equations (1)–(3) of the text, defined by cluster galaxies alone. The positive values of $\langle \Delta R_C \rangle$, $\langle \Delta V_C \rangle$, and $\langle \Delta B_C \rangle$ show that the first-ranked HMS group galaxy is slightly fainter than the mean of the cluster data.

two of the three clusters are of Bautz-Morgan (1970) cluster type I. We show in Paper VII that the mean place within the residual distribution is, in fact, correlated monotonically with Bautz-Morgan cluster type, in agreement with the prior results of Bautz and Abell (1972). The effect is large and must be removed before the much weaker correlation with cluster richness can be properly evaluated.

Finally, the distribution of residuals for all data in tables 4 and 5 are shown for R_C and V_C in figure 6. Again the hatched areas represent the cluster data, and open bars are the HMS groups. These groups, although placed with nearly the same distribution as the clusters, are again skewed slightly toward fainter magnitudes, as shown by the small positive values of $\langle \Delta R_C \rangle$ and $\langle \Delta V_C \rangle$.

Equations (1)–(3), together with the distributions of figures 5 and 6, give the mean absolute magnitudes of first-ranked cluster galaxies as

$$\langle (M_V)_C \rangle = -23.30 \pm 0.38 \, (1 \, \sigma) \, , \qquad (4)$$

$$\langle (M_B)_C \rangle = -22.37 \pm 0.39 \, (1 \, \sigma) \qquad (5)$$

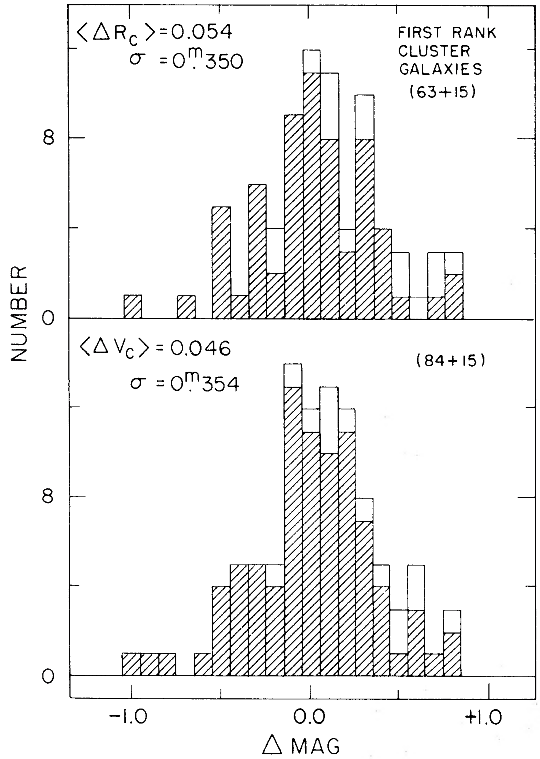

FIG. 6.—Same as fig. 5, with the data of table 5 added

and

$$\langle (M_R)_C \rangle = -24.11 \pm 0.37\,(1\,\sigma) \tag{6}$$

if the Hubble constant is $H_0 = 50$ km s^{-1} Mpc^{-1}.

V. SUMMARY

1. The measuring errors of the final aperture-corrected magnitudes in table 4 here, and in Papers II and III, are distributed with $\sigma \simeq 0.1$ mag, which is small compared with the sources of cosmic scatter in the absolute magnitudes and, therefore, in the Hubble diagram.

2. *Groups* of E and S0 galaxies that contain as few as 10 members follow the Hubble diagram defined by first-ranked galaxies in the great clusters to within about 1 sigma of the distribution of residuals about the Hubble line. The exceptions appear to be the very compact groups where the mean separation of galaxy centers is less than twice the apparent angular diameter of the first-ranked member (e.g., G68 and G6027). The possibility that the systematic faintness of the first-ranked member of such compact groups is due to some type of tidal interaction remains to be investigated.

3. Galaxies with the largest negative residuals in figures 5 and 6 are, for the most part, Morgan-Lesh supergiant cD systems that appear in Bautz-Morgan early cluster types (I or II). The correlation of residuals with Bautz-Morgan type (Paper VII) is strong, and must be removed before a proper study of a possible richness correlation can be made.

4. If $H_0 = 50$ km s^{-1} Mpc^{-1}, then the mean absolute magnitude of the first-ranked galaxy in great clusters of our sample (no account taken of Bautz-Morgan cluster

type) is $\langle (M_V)_C \rangle_1 = -23.30 \pm 0.38(\sigma)$. If the mass-to-light ratio of such galaxies is $\mathfrak{M}/L = 30$ in visual solar units, the mean mass of these systems would be $\langle \mathfrak{M} \rangle = 5 \times 10^{12} \mathfrak{M}_\odot \pm 40$ percent.

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REFERENCES

Bautz, L. P., and Abell, G. O. 1972, preprint.
Bautz, L. P., and Morgan, W. W. 1970, *Ap. J.* (*Letters*), **162**, L149.
Humason, M. L., Mayall, N. U., and Sandage, A. 1956, *A.J.*, **61**, 97.
Morgan, W. W., and Lesh, J. R. 1965, *Ap. J.*, **142**, 1364.
Peterson, B. A. 1970, *A.J.*, **75**, 695.
Sandage, A. 1961, *Ap. J.*, **134**, 916.
———. 1972*a*, *ibid.*, **173**, 485 (Paper I).
———. 1972*b*, *ibid.*, **178**, 1 (Paper II).
———. 1972*c*, *ibid.*, **178**, 25 (Paper III).
———. 1973, *ibid.*, **183**, 711 (Paper V).
Sandage, A., and Hardy, E. 1973, *Ap. J.*, **183**, 743 (Paper VII).
Vorontsov-Velyaminov, B. A. 1959, *Atlas and Catalog of Interacting Galaxies* (Moscow: Sternberg Institute, Moscow State University).