

A COLOR-MAGNITUDE DIAGRAM FOR THE SCULPTOR DWARF GALAXY

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ABSTRACT

Photoelectric and photographic observations of stars in the Sculptor system provide colors and magnitudes of 523 stars. The resulting color-magnitude diagram, which reaches only the giant branch, is very similar to that of galactic globular clusters. In the slope of the giant branch and in the mean period of the RR Lyrae variables, Sculptor closely resembles M3. A distance of 88 kpc is derived from the luminosities of the giant-branch stars, the short-period W Virginis variables, and the RR Lyrae variables.

I. INTRODUCTION

After its discovery in 1938 (Shapley 1939), the Sculptor dwarf galaxy was soon recognized by Baade and Hubble (1939) to be a system very similar, except for size and distance, to globular clusters. Its brightest stars were seen to be red, it was rich with RR Lyrae variables, and it contained no young stars, clusters, or gas clouds. The present paper further explores this similarity by presenting a color-magnitude diagram for the system's brightest stars, and comparing it with those of globular clusters. The only elliptical galaxy for which this has been done heretofore is the Draco system (Baade and Swope 1961).

No photometric work on the Sculptor system has been published since Baade and Hubble's 1939 paper. From their magnitude estimates for the maxima of several RR Lyrae variables, they estimated the distance to the system to be 84 kpc. However, this was based on photographic transfers of shaky magnitude standards to an object that had an extremely large zenith distance at Mount Wilson, and therefore the quoted figures could not be taken as very accurate.

Only two other papers dealing with the Sculptor system have been published since 1939. Thackeray (1950) described a photographic program of discovery of RR Lyrae variables, in which he reported 350 discoveries and an estimate of a total variable star population of 700. The structure of the galaxy as determined from star counts has also been discussed in the literature (Hodge 1961).

II. OBSERVATIONS

A photoelectric sequence of fourteen stars within the boundaries of the Sculptor system was measured at the Mount Stromlo Observatory, Australia (see Table 1). All measures are in the *UBV* system and were established by comparison with equatorial Yerkes *UBV* standards and with a photoelectric sequence of Bok and Bok (1961). Each star of the sequence was measured at least four times and during two different runs. Probable errors range from ± 0.01 mag. at the bright end of the sequence to ± 0.08 at the faint end. For the fainter stars, the Johnson offset photometer was used on the 50-inch reflector, and many deflections were necessary for each measurement.

A series of photographic plates was obtained with the ADH Schmidt at the Boyden Observatory, South Africa, in 1957; the best of these were used for the color-magnitude diagram. The yellow plates were taken with Kodak 103a-D emulsion with a Schott GG11 filter and the blue with 103a-O emulsion and a GG13 filter. These plates were found to be closely in agreement with the *UBV* system.

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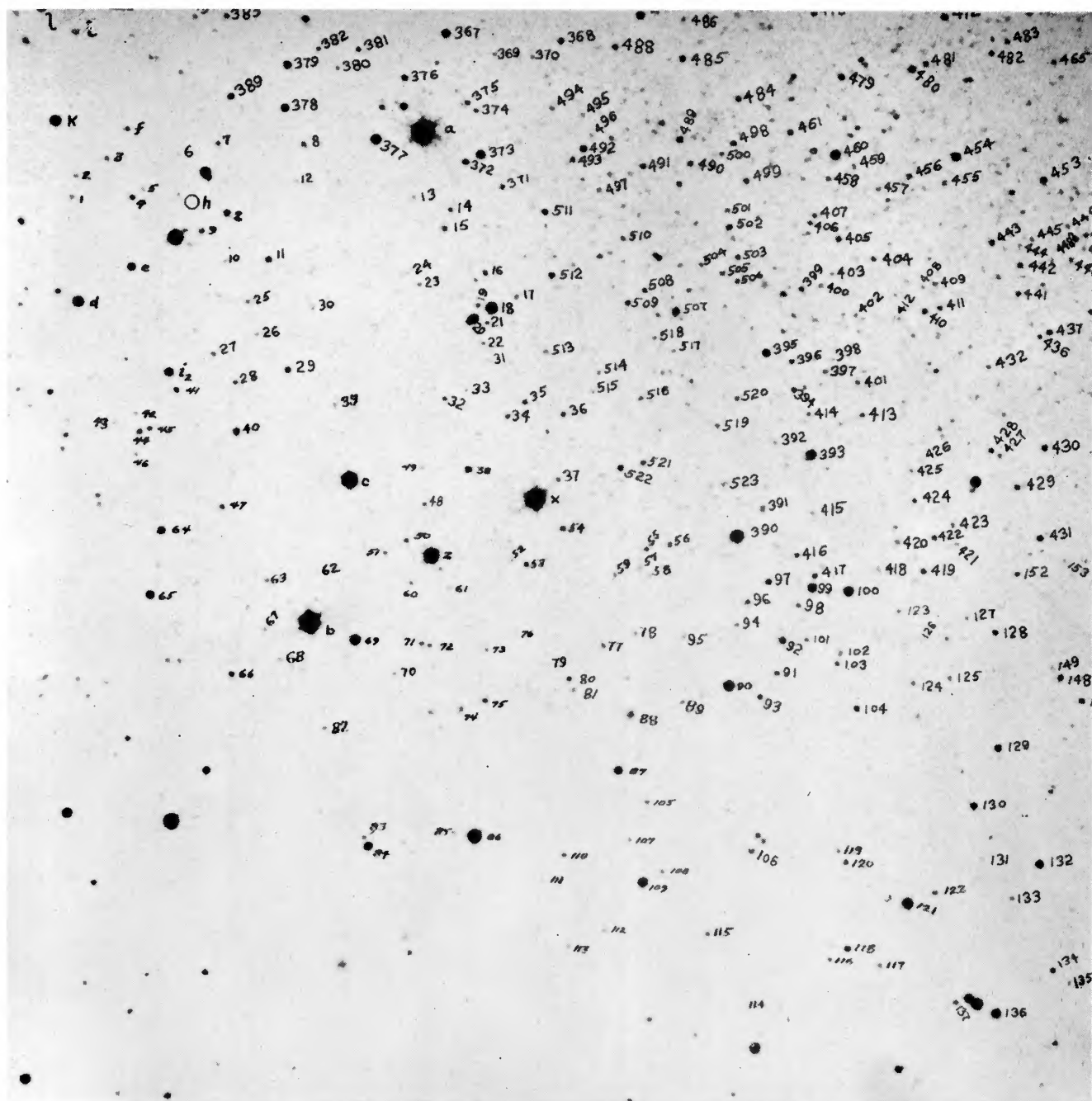


FIG. 1.—Identification chart of measured stars. From a yellow plate taken by the ADH Baker-Schmidt

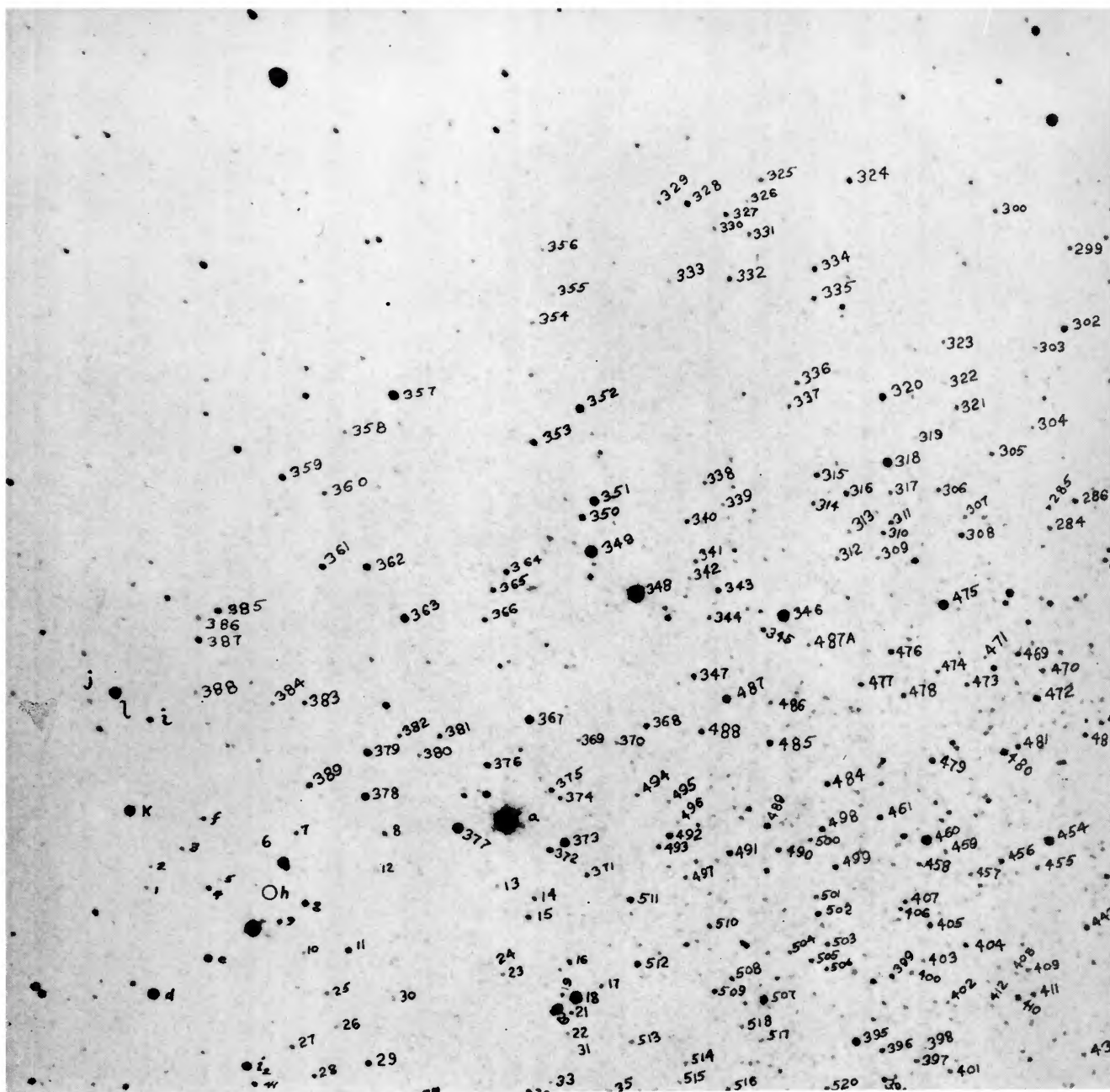


FIG. 1.—Continued

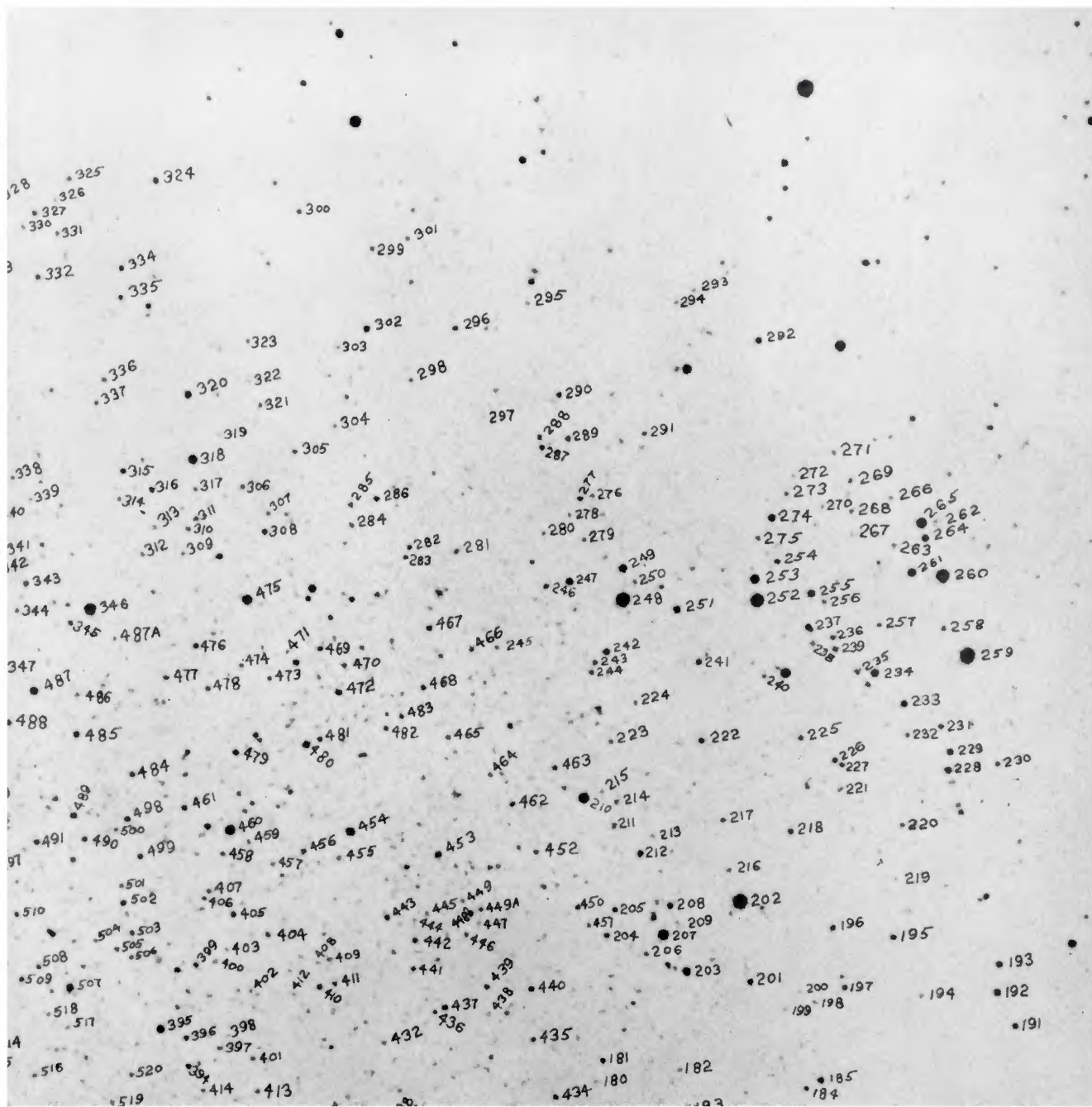


FIG. 1.—Continued

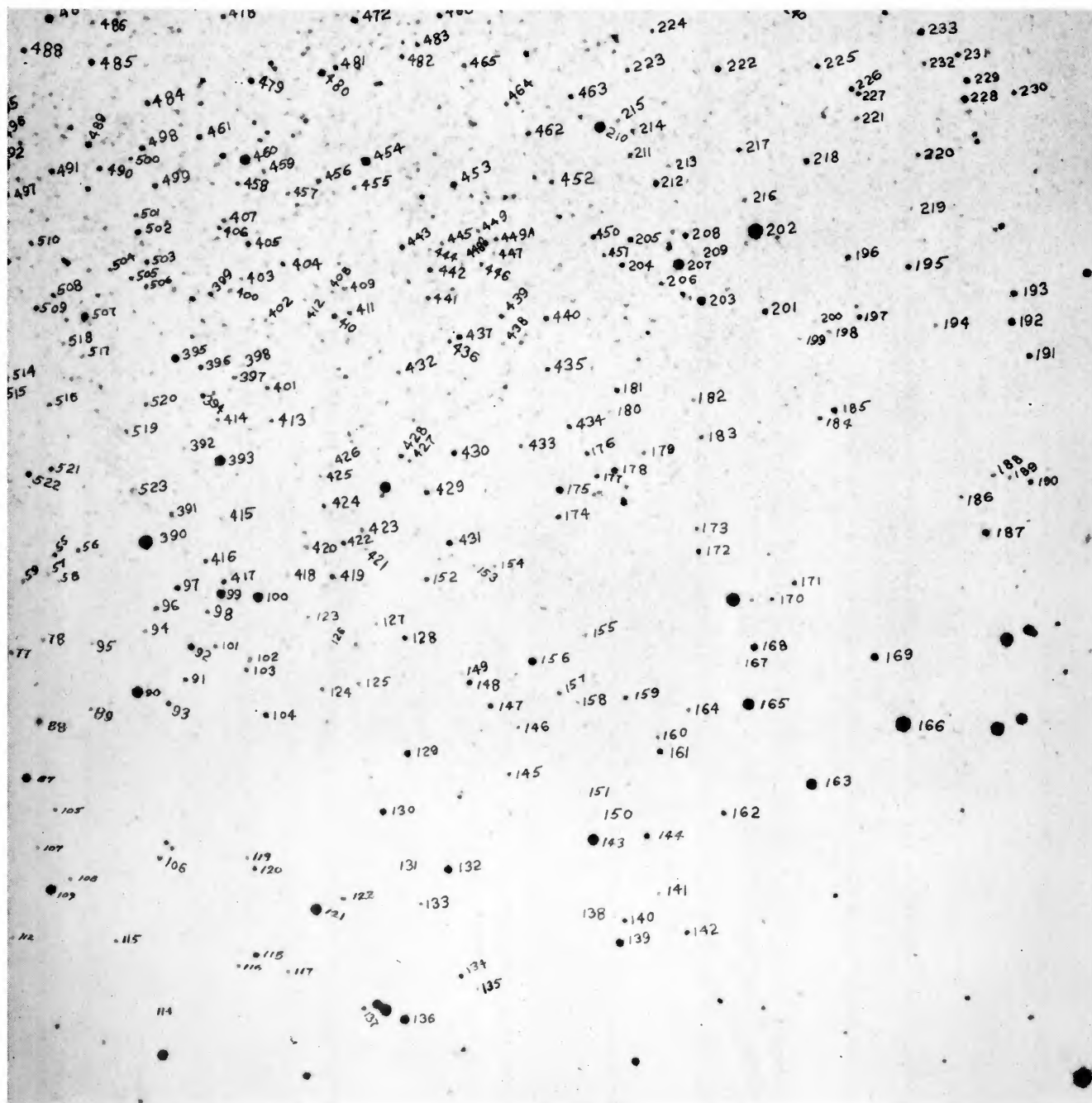


FIG. 1.—Continued

A total of 523 stars in (and in front of) the Sculptor system was chosen for measurement (Fig. 1). These extend out to a radius of $15'$ from the center of the system, the semimajor axis of which is $46'$. Only the central part of the galaxy is sampled by these measures, but the stars do extend out to distances where the projected density is only 0.2 that at the center (Hodge 1961). The 523 stars plus the 14 standards were measured on four V plates and three B plates using a Cuffey iris astrophotometer. The probable errors in the photographic measures averaged ± 0.10 mag. per plate.

III. REDDENING AND ABSORPTION

The three-color measurements for the six brightest stars provide a means to determine the galactic reddening in the direction of the Sculptor system (Fig. 2). The data agree well with the unreddened main sequence of Johnson and Morgan (1953), and lead to an upper limit for the reddening of ~ 0.02 mag. in $B - V$, under the assumption that all six stars are foreground main-sequence stars. This implies that the upper limit to the galactic absorption in front of the Sculptor system is ~ 0.06 mag. in V . The galactic latitude of Sculptor is 83° .

TABLE 1
PHOTOELECTRIC STANDARDS

Star	V	$B - V$	$U - B$
A	10 08	+0 52	+0 08
B	10 68	+0 72	+ 31
C	12 33	+0 40	- 03
X	10 78	+0 89	+ 49
Z	12 40	+0 46	+ 01
D	14 80	+0 81	+0 44
E	16 21	+0 57	
F	15 92	+0 80	
G	17 07	+1 22	
H	19 08	-0 24	
I	17 80	+1 18	
J	18 61	+1 12	
K	15 10	+1 29	
L	14 99		

IV. THE COLOR-MAGNITUDE DIAGRAM

Table 2 lists the average magnitudes and colors determined for the 523 measured stars. These are plotted in Figure 3. It is seen that only the top of the giant branch was reached in this study, the horizontal branch being fainter than the photometric limits. A few stars fainter than the photoelectric limits are included in Table 2 but not plotted in the figure. These are extrapolated measures, used only for rough comparisons with some faint variable stars.

The top of the giant branch reaches colors of $B - V = +1.8$, the usual red limit for globular clusters. Its slope over the limited portion where it can be measured averages approximately 0.6 mag. in $B - V$ per V magnitude over the interval $V = 17.3$ to $V = 18.7$. Fainter than this the B limit cuts out the red stars and may influence the apparent slope. For a similar interval, the slope of the giant branch of the globular cluster M3 is also 0.6 in $B - V$ per V magnitude.

These two similarities reinforce the early conclusion that Sculptor is very similar in stellar composition to typical halo globular clusters. It is also very similar to Draco, the color-magnitude diagram for which (Baade and Swope 1961) is more poorly defined at the bright end.

The bright stars of intermediate color, lying between magnitudes of $V = 12$ and $V = 17$ and colors of $B - V = +0.4$ and $B - V = +1.6$, are undoubtedly foreground stars. The two blue stars, at $V = 17.44$ and $V = 18.74$, are possibly members, however. If so, they are examples of the unexplained main-sequence stars occasionally found in globular clusters.

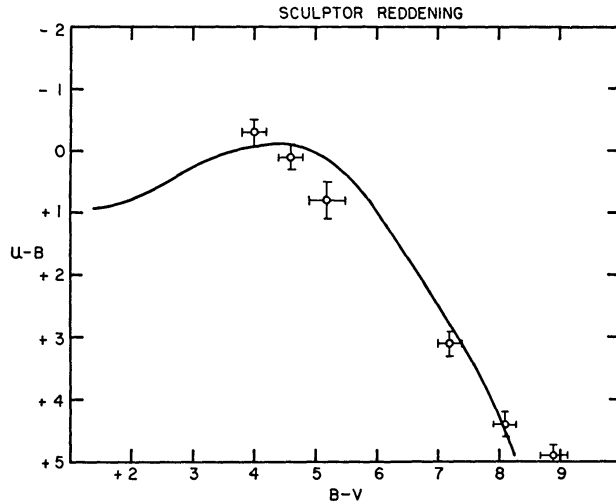


FIG. 2.—Two-color diagram for foreground stars in the direction of the Sculptor system compared with the unreddened main-sequence two-color diagram.

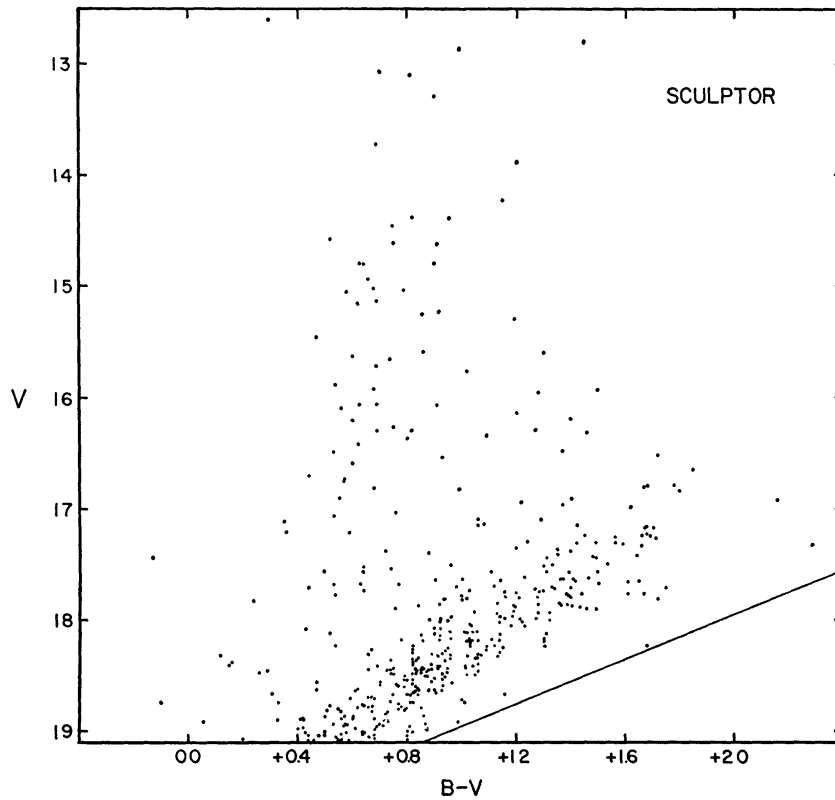


FIG. 3.—Color-magnitude diagram for measured stars in and in front of the Sculptor system

TABLE 2
PHOTOGRAPHIC MEASURES

Star	V	B-V	Star	V	B-V	Star	V	B-V
1	19 08	0 59	59	18 69	0 93	117	18 49	1 05
2	19 10	0 64	60	18 87	0 60	118	17 12	0 35
3	18 60	0 83	61	19 53	. . .	119	18 67	0 80
4	17 92	1 05	62	19 68	0 13	120	17 99	0 92
5	19 03	0 64	63	18 75	0 92	121	14 58	0 52
6	19 56	0 29	64	16 27	0 75	122	18 08	0 99
7	18 28	0 94	65	15 93	1 50	123	18 62	0 62
8	18 12	0 90	66	17 74	0 64	124	18 23	0 90
9	18 00	0 95	67	19 01	0 58	125	18 62	0 90
10	19 34	0 23	68	19 01	0 82	126	19 46	0 20
11	17 51	1 30	69	14 79	0 64	127	19 00	0 80
12	19 28	0 79	70	18 97	0 61	128	17 56	1 16
13	19 09	0 59	71	18 60	0 79	129	16 80	1 67
14	18 34	1 05	72	18 58	0 76	130	16 81	0 68
15	18 23	1 03	73	18 74	0 81	131	19 15	0 44
16	18 01	0 92	74	18 31	0 96	132	16 06	0 69
17	18 74	0 82	75	17 94	1 10	133	18 85	0 72
18	14 23	1 15	76	19 60	-0 14	134	17 67	1 50
19	18 47	1 06	77	18 49	0 82	135	19 00	0 50
20	14 80	0 90	78	18 90	0 42	136	15 22	0 92
21	18 54	0 82	79	19 64	0 24	137	17 87	1 40
22	19 09	0 58	80	17 96	1 19	138	19 13	0 23
23	19 03	0 48	81	18 86	0 75	139	15 93	0 68
24	19 59	0 23	82	18 94	0 58	140	17 56	1 11
25	18 82	0 67	83	18 74	-0 10	141	18 63	0 93
26	18 90	0 33	84	15 65	0 74	142	17 61	1 23
27	18 48	0 93	85	18 89	0 56	143	14 62	0 75
28	18 31	1 06	86	13 08	0 70	144	17 30	1 56
29	17 42	1 48	87	15 89	0 54	145	18 56	0 70
30	18 95	0 58	88	17 73	1 13	146	19 11	0 09
31	19 55	0 61	89	18 78	0 67	147	17 51	1 47
32	18 50	1 02	90	14 63	0 91	148	17 65	1 65
33	19 29	0 47	91	18 09	0 43	149	19 09	0 44
34	18 39	1 06	92	16 84	1 80	150	19 10	0 56
35	18 13	1 08	93	17 93	1 34	151	. . .	. . .
36	18 23	0 54	94	18 80	0 55	152	18 11	1 02
37	18 35	0 82	95	18 89	0 83	153	19 38	0 40
38	16 98	1 62	96	17 89	0 76	154	18 74	1 01
39	19 03	0 56	97	17 27	1 71	155	18 78	0 78
40	17 04	0 76	98	18 28	0 85	156	16 19	1 40
41	17 78	1 28	99	15 60	0 86	157	18 10	1 32
42	19 03	0 68	100	15 13	0 69	158	18 96	0 57
43	19 26	0 51	101	18 54	0 93	159	18 23	0 82
44	17 81	1 02	102	18 45	0 66	160	18 54	0 79
45	18 27	0 82	103	18 13	0 52	161	17 35	1 20
46	19 01	0 64	104	17 50	1 33	162	17 95	1 12
47	18 37	0 83	105	18 46	0 85	163	14 79	0 63
48	18 67	0 81	106	17 95	1 24	164	18 74	0 33
49	19 46	0 36	107	18 79	0 62	165	14 46	0 75
50	18 41	1 04	108	18 68	0 72	166	12 79	1 45
51	18 96	0 69	109	15 16	0 62	167	19 36	0 65
52	19 31	0 34	110	18 40	0 15	168	16 48	0 53
53	17 87	1 15	111	19 29	0 45	169	16 29	1 27
54	17 65	1 41	112	18 90	0 06	170	18 49	0 83
55	18 17	1 30	113	18 92	0 99	171	18 24	1 15
56	18 14	1 21	114	19 21	0 66	172	17 79	1 28
57	19 09	0 55	115	18 63	0 47	173	18 42	1 01
58	19 92	0 01	116	18 57	0 47	174	17 96	1 14

TABLE 2—Continued

Star	V	B-V	Star	V	B-V	Star	V	B-V
175	16 43	0 62	233	17 16	1 70	291	18 32	1 07
176	18 19	1 14	234	16 14	1 20	292	17 44	-0 13
177	18 18	1 06	235	18 19	1 02	293	18 88	0 68
178	17 07	0 53	236	17 85	1 36	294	19 05	0 54
179	18 67	0 75	237	16 99	1 78	295	18 65	0 91
180	19 12	0 54	238	18 24	1 30	296	17 98	1 16
181	17 85	0 92	239	17 71	1 40	297	19 23	0 50
182	18 43	1 01	240	18 51	0 87	298	18 92	0 79
183	18 49	0 85	241	17 31	1 42	299	18 32	0 12
184	18 33	1 13	242	16 90	0 55	300	18 17	0 72
185	17 31	1 59	243	18 11	1 01	301	18 45	0 86
186	18 55	1 08	244	17 92	1 19	302	17 14	1 08
187	16 96	1 37	245	18 52	1 14	303	19 46	0 01
188	18 63	0 88	246	17 86	1 28	304	19 03	0 80
189	18 76	0 77	247	16 53	0 93	305	18 47	0 87
190	17 70	0 98	248	13 28	0 90	306	18 32	1 02
191	17 54	0 74	249	16 31	1 46	307	18 86	0 86
192	16 65	1 85	250	18 65	0 64	308	17 80	1 21
193	17.10	1 29	251	16 75	0 57	309	19 01	0 43
194	18 69	0 96	252	13 72	0 69	310	18 43	0 77
195	17 63	1 36	253	15 46	0 47	311	18 33	0 91
196	17 62	1 46	254	17 75	1 20	312	18 71	0 68
197	17 68	0 53	255	16 47	1 37	313	18 82	0 39
198	18 77	0 64	256	18 40	1 06	314	18 61	0 84
199	19 20	.. . . .	257	18 24	1 09	315	17 83	0 24
200	18 77	1 37	258	18 34	0 96	316	17 57	0 50
201	17 32	1 66	259	12 86	0 99	317	18 78	0 85
202	13 10	0 81	260	13 89	1 20	318	15 72	0 69
203	16 10	0 46	261	16 03	0 58	319	19 30	0 43
204	17 74	1 28	262	19 24	0 17	320	16 70	0 44
205	17 72	1 30	263	18 65	0 82	321	18 22	1 68
206	18 46	0 29	264	17 15	1 42	322	19 25	0 52
207	14 93	0 66	265	15 25	0 86	323	18 95	0 75
208	17 21	0 59	266	18 82	0 56	324	17 68	0 77
209	18 96	0 81	267	19 05	1 10	325	18 38	0 16
210	15 10	0 72	268	18 44	0 99	326	19 25	0 61
211	18 23	1 12	269	18 18	1 30	327	18 05	1 23
212	17 24	1 69	270	18 99	0 68	328	17 58	0 64
213	18 97	0 40	271	18 82	0 79	329	18 88	0 60
214	18 26	0 67	272	19 01	0 64	330	19 04	0 44
215	18 73	0 93	273	18 44	0 75	331	18 80	0 80
216	18 55	0 89	274	16 73	0 57	332	18 13	1 14
217	17 88	1 29	275	18 44	0 85	333	19 16	0 47
218	17 41	1 42	276	18 72	0 71	334	17 70	1 75
219	19 34	0 63	277	17 87	1 39	335	18 17	1 22
220	18 29	0 82	278	18 91	0 73	336	18 56	0 97
221	18 55	0 80	279	18 48	0 26	337	18 71	1 00
222	17 05	2 29	280	18 68	0 84	338	18 66	0 31
223	18 27	1 09	281	18 17	0 78	339	19 13	0 67
224	18 51	0 94	282	18 18	1 04	340	18 17	0 92
225	17 88	1 43	283	18 08	1 07	341	18 49	0 93
226	17 65	1 61	284	18 45	1 10	342	19 28	0 29
227	17 94	1 13	285	18 21	1 03	343	17 71	1 34
229	16 82	0 99	286	17 71	1 27	344	18 77	0 52
229	17 09	1.06	287	17 78	1 39	345	18 00	1 32
230	18 44	0 83	288	17 89	1 07	346	14 39	0 82
231	17.76	1 61	289	17 80	1 36	347	17 76	1 67
232...	18 43	0 91	290	11.80	1 39	348	12 33	0 49

TABLE 2—Continued

Star	V	B-V	Star	V	B-V	Star	V	B-V
349	14 38	0 96	408	19 08	0 46	466	18 02	1 14
350	17 37	1 40	409	18 42	0 91	467	17 44	1 31
351	15 95	1 28	410	17 69	1 22	468	17 73	1 03
352	17 57	1 39	411	18 26	0 95	469	17 73	1 13
353	16 40	0 51	412	18 87	0 48	470	18 05	1 18
354	18 93	0 87	413	18 32	0 66	471	17 29	1 49
355	19 08	0 55	414	18 61	0 84	472	16 93	1 22
356	19 05	0 66	415	19 08	0 93	473	18 45	0 88
357	15 60	1 30	416	18 19	1 03	474	18 49	0 75
358	18 97	0 42	417	17 78	1 00	475	15 30	1 19
359	17 08	1 72	418	19 23	0 57	476	17 69	1 12
360	18 42	0 92	419	17 90	1 49	477	18 00	1 21
361	17 51	1 35	420	18 34	1 05	478	18 07	1 16
362	16 79	1 68	421	19 24	0 54	479	17 29	1 24
363	16 33	1 09	422	17 85	1 13	480	16 59	0 60
364	17 63	1 28	423	18 51	0 79	481	17 35	1 35
365	17 87	1 19	424	18 11	1 04	482	18 03	1 03
366	18 08	0 92	425	19 07	0 20	483	17 97	0 96
367	16 07	0 91	426	19 38	-0 02	484	17 71	0 44
368	17 68	0 63	427	18 69	0 66	485	17 15	1 68
369	19 13	0 60	428	17 94	1 32	486	18 76	0 64
370	18 82	0 73	429	17 81	1 00	487	16 20	0 60
371	18 52	0 90	430	17 50	0 96	488	17 63	1 00
372	17 17	1 67	431	17 38	0 72	489	17 20	0 36
373	15 63	0 60	432	18 64	0 83	490	17 81	0 94
374	18 64	0 61	433	18 56	0 82	491	17 64	1 14
375	18 06	1 04	434	18 02	1 22	492	16 91	1 40
376	17 24	1 66	435	18 16	1 11	493	18 13	0 85
377	15 03	0 79	536	18 47	0 95	494	18 58	0 70
378	16 36	0 80	437	17 63	0 90	495	18 93	0 70
379	16 30	0 69	438	18 94	0 53	496	19 18	0 27
380	19 06	0 68	439	18 07	0 90	497	18 69	0 67
381	18 32	1 02	440	17 76	1 44	498	17 44	1 49
382	18 49	0 74	441	11 99	1 27	499	17 77	1 38
383	18 40	0 82	442	17 90	1 46	500	18 44	0 95
384	19 03	0 50	443	17 73	1 09	501	18 35	0 84
385	17 15	1 06	444	18 88	0 42	502	17 41	1 64
386	18 80	0 51	445	18 86	0 57	503	17 99	0 88
387	17 52	0 64	446	18 45	0 74	504	18 52	0 87
388	19 16	0 60	447	19 13	0 06	505	18 33	0 79
389	17 39	0 88	448	17 56	1 50	506	18 30	0 93
390	13 60	0 30	449	18 70	0 59	507	16 51	1 72
391	18 45	0 83	449A	18 39	0 82	508	18 14	0 92
392	19 03	.. . . .	450	18 10	0 96	509	17 75	1 16
393	15 06	0 58	451	18 66	1 16	510	18 48	0 67
394	17 70	1 33	452	18 17	1 03	511	17 23	1 45
395	16 06	0 63	453	16 92	2 16	512	17 50	1 53
396	17 77	0 54	454	15 76	1 02	513	18 80	0 77
397	18 36	0 94	455	18 17	0 96	514	18 95	0 71
398	19 32	0 11	456	17 87	0 84	515	18 86	0 50
399	17 79	1 16	457	18 42	0 69	516	18 30	0 89
400	18 60	0 77	458	18 29	1 14	517	18 78	0 66
401	18 39	0 89	459	18 45	0 73	518	18 57	0 68
402	18 89	0 41	460	15 02	0 68	519	18 59	0 66
403	19 12	0 52	461	17 57	1 31	520	18 35	0 90
404	18 10	1 06	462	17 94	1 28	521	17 87	1 19
405	17 63	1 37	463	17 99	1 31	522	17 42	1 35
406	18 36	0 74	464	18 11	1 31	523	18 74	0 74
407	18 30	0 98	465	18 19	0 86			

V. VARIABLE STARS

All but two of the variable stars of the system were generally fainter in V than the limit of this study. One of those bright enough to be measured is star A, identified as No. 303 in Figure 1. This star was noted by Baade and Hubble (1939) and studied by Shapley (1939) and Thackeray (1950). Thackeray found it to have a period of 0.925 days. On measurable plates, I find star A to have an average B magnitude of 19.47 and to reach a maximum of $B \sim 18.8$. There are too few plates to measure color. This star is definitely brighter than most of the RR Lyrae variables and is no doubt similar to those four W Virginis variables with periods near 1 day found in Draco (Baade and Swope 1961). A similar star, star B, with a period of 1.35 days (Shapley 1939) was found to have an average brightness of $B = 19.36$.

In order to gauge the brightness of the normal RR Lyrae variables, measurements were made of a few that seemed to be near maximum light, and which therefore were bright enough to be detected in B . The only published finding chart of variables is that of Baade and Hubble (1939), which had only eight RR Lyrae stars marked. Of these only three were bright enough to be seen. They are stars 11, 21, and 27, with magnitudes of $B = 19.81, 19.77, \text{ and } 19.82$, respectively, on the plates where they were brightest. As the B photoelectric limit was 19.73, all three of these measures necessitated a small extrapolation, an unreliable procedure which means that they must be considered only as rough estimates.

VI. DISTANCE

The photoelectric measurements of stars in the Sculptor system allow a determination of a photometric distance to the system. The distance can be determined in three ways: from the luminosity of the giant-branch stars, from the W Virginis stars, or from the estimated magnitudes of the RR Lyrae variables. For the first method, an assumption must be made about V_{GB} , the over-all slope of the giant branch (Sandage and Wallerstein 1960), which varies from 2.5 to 3.1 for globular clusters. The mean period of the ab type RR Lyrae variables in Sculptor is ~ 0.55 days (Thackeray 1950), suggesting that Sculptor is most likely to be similar to M3 in chemical composition, as this mean period is correlated with V_{GB} and chemical composition (Sandage and Wallerstein 1960). For M3, $V_{\text{GB}} = 2.6$, and adopting this for Sculptor leads to the conclusion that its horizontal branch lies at $V = 20.2$ (the giant branch at $B - V = +1.4$ averages $V = 17.6$). If the horizontal branch has an absolute magnitude of $M_v = +0.5$, then the apparent distance modulus for Sculptor is 19.7.

The two bright variables, A and B, can be used to estimate Sculptor's distance by comparing them with similar stars in Draco and globular clusters (Baade and Swope 1961). Taking the average magnitudes found on my very few plates to be roughly the true average for these stars, I find that they fit Baade and Swope's curve (taking RR Lyrae to have $M_v = +0.5$) at $M_B = -0.2$ and -0.1 , leading to a distance modulus of $m - M = 19.6$, apparent.

Finally, the distance can be estimated from the measurements of the three RR Lyrae variables caught near maximum. Their mean magnitude was 19.80. Assuming them to have been 0.4 mag. brighter than their individual mean luminosities, the horizontal branch is placed at 20.2. On the assumption of $+0.5$ as the absolute magnitude for these RR Lyrae stars, a distance modulus of 19.7 is calculated.

These three methods of estimating the distance to the Sculptor galaxy have given essentially identical results, and it is therefore concluded that the apparent distance modulus is approximately 19.7 with a probable error of about 0.1. The amount of galactic absorption estimated in § III, $A \leq 0.06$ mag. in V , places the true modulus between 19.7 and 19.6. From the cosecant law of absorption with a constant of 0.25, the absorption is expected to be 0.25 mag. in B . The adopted true distance modulus, there-

fore, will be 19.70 ± 0.15 . The linear distance to Sculptor, then, is 88 ± 7 kpc. This is a good agreement with Baade and Hubble's original estimate, because their magnitude scale error exactly balances the difference in our assumed luminosity for RR Lyrae variables.

I am indebted to the Mount Stromlo Observatory for helping me to obtain the photoelectric measures and to the Harvard College Observatory for access to the facilities of the Boyden Observatory, where the plates were obtained. The research was partially supported by a grant from the National Science Foundation.

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