

THE GLOBULAR CLUSTER M107: MEMBERSHIP AND KINEMATICS

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ABSTRACT

We present photographic photometry and proper motions for approximately 400 stars in the field of the globular cluster M107 (NGC 6171). Membership via proper motions is used to produce a clean color-magnitude diagram for this cluster. We find a reddening $E(B - V) = 0.34 \pm 0.03$ and a distance of 6.2 ± 0.9 kpc, in good agreement with previous work. We also confirm membership for most, but not all, previously known variables. In addition, the space velocity for M107 is derived: $(U, V, W) = (20 \pm 12, 144 \pm 31, -44 \pm 26)$ km s⁻¹ in the Galactic rest frame. Thus, the kinematics of this cluster do not allow us to unambiguously assign it to either the disk or the halo.

1. INTRODUCTION

M107 (NGC 6171) is a relatively sparse globular cluster at $(l, b) = (3^\circ 5', +23^\circ 0')$. Van Agt (1961) published a color-magnitude diagram (CMD) indicating that the cluster is relatively metal rich. Sandage & Katem (1964), hereafter referred to as SK, obtained photographic photometry for 293 stars within a radius of approximately 6' around the cluster center, resulting in a CMD reaching to $V \sim 16.5$, approximately 0.8 mag fainter than the horizontal branch (HB). From this, SK suggested that the cluster is intermediate in both metallicity and spatial position within the galaxy. With additional observations by Sandage, Dickens (1970) examined the cluster RR Lyrae variables photometrically and discovered a systematic error in the photometry of SK due to the neglect of color terms. (SK had been aware of the potential importance of the color term but did not, at the time, have photoelectric standards blue enough to include the correction.) Dickens & Rolland (1972, hereafter referred to as DR), used additional observations to produce a CMD of the cluster to $V \sim 16.9$, and in a much more limited area to $V = 18.8$, confirming the relatively high metallicity of the cluster.

Sandage & Roques (1984, hereafter referred to as SR), and DaCosta *et al.* (1984, hereafter referred to as DMO), produced deep CMDs which found the main sequence turn-off at $V = 19.35$. SR's color-magnitude diagram has a HB length of 0.4 mag, along with a well-populated red giant branch (RGB). As expected for a relatively metal-rich cluster, the HB stars are concentrated on the redward side of the instability strip. Given the metallicity and age determined from their CMD's, both SR and DMO found that there exists no large age difference among globular clusters of different metallicities. Thus, they concluded that chemical enrichment of the Galactic system occurred over a period of at most a few billion years.

Armandroff (1989, hereafter, referred to as Af), in his treatment of the properties of the disk globular system, categorized M107 as a halo cluster based on its metallicity which he listed as $[Fe/H] = -0.99$. But, this cluster has the second highest metallicity in Af's halo group and is suspected of having a relatively low value for its maximum height above the disk ($z_{\max} < 5$ kpc), which places it within the stellar

thick disk (Majewski 1992). DaCosta & Seitzer (1989) drew specific attention to M107 because it is one of the most metal-rich halo clusters and cannot be ruled out from being a disk object by either its position in the Galaxy or its radial velocity. Furthermore, recent studies have shown that the globular cluster system may be more complex than simply a metal-poor halo and a metal-rich thick disk with a division at $[Fe/H] = -0.8$. M28, e.g., has been shown by Rees & Cudworth (1991) to be kinematically associated with the disk while probably having a metallicity below $[Fe/H] = -1.3$. Since M107 apparently lies near the borderline between the thick disk and the halo in its metallicity and location in the Galaxy, a proper motion study leading to a space velocity may prove valuable toward understanding the Galactic globular cluster system.

This study examines approximately 400 stars in the field of the globular cluster M107. Using plates from several epochs, we will determine the relative proper motions of these stars and use these motions to determine membership probabilities for each. This membership information will allow us to construct a *clean* CMD from which cluster parameters such as reddening, distance modulus, and metallicity can be determined. In addition, the space velocity for the cluster itself will be derived to determine if M107 is kinematically associated with the disk or with the halo.

2. OBSERVATIONS AND MEASUREMENTS

The plates used for this study are listed in Table 1 along with their epochs, passbands, and relative depths. The prefix before each plate number indicates the telescope used. LC indicates the Lick 36 in. refractor, CD represents the Las Campanas Dupont 100 in. reflector, π corresponds to the Yerkes 40 in. refractor, and Y41 denotes the Yerkes 41 in. reflector. These plates have varying depths; weak plates, denoted by (w), have an extreme magnitude limit of about 15 (16 in B), moderate plates, denoted by (m), have a limit of about 17 (18 in B), and deep plates, denoted by (d), have a limit of about 19 (20 in B). Measurement limits, of course, were somewhat brighter than these extreme limits. Stars were chosen for inclusion from the best Lick plate to ensure that the longest possible epoch difference could be used. The CD plates are by far the deepest and provide the best data for

TABLE 1. M107 plate material.

Plate Number	Epoch	Color	Depth
LC-2705	1965.54	V	m
LC-5790	1971.32	V	m
LC-5795	1971.33	V	m
π -25877	1979.40	V	w
π -25891	1979.46	V	w
π -25900	1979.50	V	w
π -28209	1989.34	V	m
π -28210	1989.34	V	m
π -28211	1989.34	V	m
π -28212	1989.36	V	m
π -28213	1989.42	V	m
π -28220	1989.48	V	m
π -28224	1989.51	V	m
CD-2869	1990.18	B	d
CD-2870	1990.18	B	d
CD-2871	1990.18	B	d
CD-2872	1990.18	B	d
CD-2873	1990.18	B	d
Y41-1427	1989.29	B	m
Y41-1434	1989.35	B	m
Y41-1438	1989.41	B	w
Y41-1439	1989.42	B	m
Y41-1440	1989.42	B	w
Y41-1448	1989.42	B	m

the faintest stars in the sample, and their generally good seeing also allowed resolution of crowded or blended images which otherwise could have contaminated the astrometric and photometric fitting. The Lick and CD plate sets dominated the proper motion solution, while the poorer seeing π plates added weight for the brighter stars. The Y41 plates were not used in the astrometry at all and only provided added weight in the photometry for the brighter stars.

All acceptable images out to a radius of approximately 12' were measured with the addition of a few outer bright-blue stars for which photoelectric photometry was available. This radius was close to the edge of the useful field of the π and Lick plates and coma may have had some effect on the astrometric fitting for some of the brighter stars near the edge of the field (see Sec. 4.1). Crowding prevented the measurement of the innermost stars in the field, most significantly inside a radius of approximately 30", but a few were measurable to about 20". For comparison, Webbink (1985) listed a core radius of 43" and a tidal radius of 23'.

The plates were scanned on the PDS microdensitometer at the Midwest Astronomical Data Reduction and Analysis Facility (MADRAF) in Madison, WI. Measurement and reduction procedures followed closely those described by Cudworth (1985, 1986).

3. REDUCTIONS AND RESULTS

3.1 Photometry

The PDS data were used to derive photographic values for V and $B - V$ using software described by Cudworth (1985, 1986). Both color-dependent and radial-dependent terms were used as needed in the plate reductions. The reduction to V and $B - V$ was based on the most recent catalog of photoelectric observations by SR, with a total of 67 stars used to tie the photographic photometry to the standard photoelectric system.

We find the typical uncertainty in our (V , $B - V$) photometry to range from 0.01 to 0.02 mag for the brightest stars at 0.04 to 0.06 mag at $V \sim 16.0$, and somewhat poorer for the faintest stars. Comparing our photographic photometry with the photographic photometry of SK, we confirm the systematic radial dependence of SK's iris photometry mentioned by previous authors. As discussed by Cudworth (1988), PDS photographic photometry is much less sensitive to background light near the cluster center than is iris photometry.

3.2 Astrometry

Proper motions were derived from PDS measures using the central-overlap software described by Cudworth (1985, 1986). As previously mentioned, the Y41 plates were not used in the astrometry due to the small scale of the plates. Eighteen plates were used over a time period of 24.6 yr to obtain a common solution. Twelve plate constants were used, including linear and quadratic terms in magnitude and coordinates, a coma term, linear terms in color and color magnification, and a distortion term.

The resulting proper motions are relative to the mean cluster motion. This mean motion was found to lie well within the distribution of proper motions of the field stars in the sample. Cluster membership probabilities were derived using software described by Cudworth (1985). Table 2 lists the parameters describing the Gaussian fits to the field and cluster stars. This table contains the numbers of stars (N), the centers of the distributions (μ_{x0} and μ_{y0}), as well as the standard deviations of each distribution (σ_x and σ_y). Despite the similar mean motions of the cluster and the field stars, the segregation between cluster members and non-members is good, with approximately 90% of the stars having unambiguous membership status.

The results of the analysis are listed in Table 3. Column one gives the star identification. When no previous identification was found the star was assigned our Y number. In one case, two stars were found which shared the same SK number (SK 267), an ambiguity not noted in the previous litera-

TABLE 2. Probability parameters for M107.

Parameter	Cluster	Field
N	216	140
μ_{x0}	-0.010 cent ⁻¹	0.200 cent ⁻¹
μ_{y0}	0.010	0.000
σ_x	0.090	0.550
σ_y	0.130	0.600

TABLE 3. M107 positions, proper motions, photometry, and membership probabilities.

Names	X	Y	μ_α	ϵ_α	μ_δ	ϵ_δ	V	B-V	P	Names	X	Y	μ_α	ϵ_α	μ_δ	ϵ_δ	V	B-V	P
	arcsec		milliarcsec	cent-1	milliarcsec	cent-1			%		arcsec		milliarcsec	cent-1	milliarcsec	cent-1			%
A	-244.9	71.3	780	15	-1051	49	10.70	1.42	0	SK140	102.1	-3.3	-132	38	60	31	15.21	1.28	94
D01	90.7	568.1	677	29	302	53	10.88	1.86	0	Y392	-555.6	170.5	849	53	210	34	15.21	1.02	0
D02	80.1	376.4	-541	23	2062	19	11.19	1.46	0	Y350	72.6	-610.5	-356	25	-20	35	15.21	1.21	6
B	-48.4	-152.7	186	20	2121	29	11.67	0.77	0	SK005	-254.0	-120.9	86	42	-261	34	15.22	1.25	71
C	177.6	-49.2	-77	16	-153	27	11.79	1.17	94	SK203	25.1	212.2	58	27	-90	28	15.22	1.32	96
D26	-223.0	-528.8	13	37	65	45	11.87	0.75	97	SK116	296.4	138.1	-192	27	925	32	15.22	1.14	0
D25	-391.9	-582.1	91	31	-510	50	11.96	0.74	2	SK061A	40.1	-61.5	-4	39	17	41	15.22	1.15	97
D27, V1	-109.7	-528.0	-126	61	997	69	12.53	0.29	0	Y348	32.7	356.7	-396	44	-163	38	15.22	1.38	1
D15	-760.8	-221.7	-1319	39	-1067	23	12.82	0.97	0	SK008	-179.3	-78.8	-63	30	-37	31	15.23	1.11	97
D	-236.7	-97.7	-1192	15	-839	19	12.88	1.24	0	SK044	-12.9	-226.1	633	32	964	44	15.24	0.77	0
D23	-711.9	-495.0	-86	20	-1329	42	12.94	0.71	0	Y346	105.5	-527.1	-142	29	341	39	15.25	1.34	44
D28	125.8	-366.3	-2752	20	-2056	17	13.19	1.10	0	SK010	-165.9	-32.5	-13	42	-74	47	15.25	1.25	97
SK273	-115.4	63.1	139	32	78	21	13.23	1.81	89	SK129	264.8	15.3	82	36	-48	35	15.26	1.07	95
E	-103.7	22.1	47	17	89	14	13.29	1.88	97	Y401	-439.9	546.1	643	39	242	46	15.27	1.33	0
D10	-693.6	228.9	114	31	51	26	13.31	1.41	93	Y348	73.6	-553.3	667	34	-488	27	15.32	1.02	0
F	-158.1	22.3	-13	30	-3	32	13.39	1.70	98	SK125	201.9	61.8	790	42	-471	42	15.32	0.92	0
D30	-703.7	-103.9	984	25	622	27	13.42	1.40	0	Y387	-657.9	-168.8	-2949	47	-2498	41	15.33	1.26	0
D20	-279.5	-340.5	286	28	-483	30	13.46	1.33	0	Y336	431.7	-533.7	1070	39	412	43	15.36	0.85	0
G	113.3	-101.1	12	22	43	25	13.50	1.66	97	Y288	-446.0	-166.2	1135	46	-443	45	15.37	0.89	0
D21	-626.2	-439.5	-86	22	-47	29	13.53	1.04	97	SK025	-58.0	-75.6	-127	25	208	31	15.42	1.10	86
Y342	209.4	-719.7	23	28	141	30	13.55	1.53	96	V	-165.7	41.7	176	51	-30	34	15.42	1.08	76
D14	-753.3	-92.5	167	35	-421	21	13.74	1.73	4	Y282	-223.3	-189.6	-551	46	385	40	15.43	0.70	0
H	-113.4	123.1	-51	23	50	16	13.84	1.61	97	SK043	-0.6	-191.7	-29	25	-73	26	15.44	1.02	97
I	139.2	-82.4	-24	20	91	17	13.89	1.46	97	SK019	-63.2	-23.6	-52	33	25	34	15.45	1.07	0
D31	395.0	-4.9	139	26	-77	26	13.95	1.44	88	DR344	314.5	309.6	-1513	20	-1682	25	15.45	1.02	97
SK062	16.1	-65.8	-63	24	17	40	13.97	1.62	97	V08	12.5	-46.7	-40	43	-149	48	15.46	0.72	94
J	-262.5	125.7	83	29	-92	36	13.97	1.58	94	SK001	-338.6	-164.5	-70	37	5	27	15.46	0.51	97
SK035	-7.0	-30.2	-76	40	62	31	14.01	1.56	97	Y349	50.8	-578.8	-501	34	-391	33	15.48	0.97	0
K	130.0	-169.4	-12	20	18	30	14.04	1.48	98	SK044	-98.8	131.9	-1102	26	590	30	15.49	1.05	0
L	-20.5	-196.9	-15	18	-31	17	14.04	1.47	98	SK261	-96.9	6.0	111	29	97	17	15.50	0.97	92
Y343	143.8	-718.4	-185	52	-93	32	14.04	0.78	79	SK264	-79.2	55.3	-112	33	-257	40	15.51	1.23	74
SK127	211.3	-11.1	1	23	65	18	14.05	1.48	97	SK080	31.1	-87.6	55	44	80	53	15.51	1.22	95
SK162	49.0	-4.7	-30	28	-16	32	14.09	1.59	98	SK004	-217.9	-68.2	-96	26	10	33	15.51	0.81	96
SK278	-146.8	-20.3	-16	26	19	27	14.14	1.48	98	V05	232.1	-165.0	-5	41	198	38	15.52	0.77	93
SK111	332.4	-71.8	-277	22	562	36	14.19	0.95	0	Y402	-80.5	-275.0	-71	42	-235	58	15.53	0.98	82
M	-244.4	-134.1	266	23	-37	30	14.21	1.07	28	Y408	-98.8	632.8	-949	23	-535	46	15.53	1.09	0
SK100	103.3	-90.4	-64	35	-15	36	14.21	1.40	97	V06	-9.7	-72.3	-159	46	112	52	15.53	0.52	86
N	221.4	-92.6	28	35	-55	38	14.26	1.53	97	SK084	51.2	-26.8	-16	49	-17	51	15.54	1.29	97
SK016	-146.4	-131.8	37	30	-107	26	14.29	1.43	96	V04	-98.1	-161.8	-104	35	63	35	15.55	0.49	96
SK166	18.4	-13.5	-118	54	-115	41	14.34	1.73	91	SK109	299.0	-128.6	-392	21	-124	33	15.55	1.48	1
SK090	84.3	-22.4	-744	26	-417	20	14.37	1.01	0	V17	-99.0	66.5	-26	63	186	41	15.56	0.68	93
O	47.7	-235.0	-109	26	-99	30	14.38	1.44	94	SK249	-31.6	34.9	185	56	131	29	15.56	0.83	64
P	67.9	-138.4	-580	35	-1016	30	14.39	1.03	4	SK142	109.1	63.1	-59	26	-41	45	15.57	1.24	97
Y373	-239.9	-701.1	86	21	99	23	14.40	0.70	95	W	-125.6	-153.1	16	35	-37	35	15.57	0.99	97
SK236	-29.4	-15.3	-50	27	81	35	14.41	1.46	97	SK268	-92.6	129.6	13	60	79	33	15.59	1.02	96
SK200	72.0	238.6	20	34	-463	26	14.41	0.97	8	SK014	-131.3	-77.4	-72	39	75	49	15.59	0.90	96
Q	140.5	68.9	-52	23	-69	36	14.48	1.54	97	SK075	126.0	-178.2	-38	37	16	40	15.59	1.10	97
D29	168.5	-427.7	-473	24	-643	28	14.49	1.03	0	Y245	448.4	-109.8	979	49	743	59	15.59	0.89	0
Y321	456.6	290.0	-64	30	-62	22	14.49	1.53	97	SK143	91.2	88.1	-102	39	67	54	15.60	0.85	95
SK110	354.9	-99.8	-379	32	185	41	14.53	1.24	2	DR465	383.0	72.0	-1289	46	326	38	15.60	1.18	0
Y326	647.5	321.2	-74	32	173	34	14.53	1.48	94	SK138	125.8	-3.2	-20	38	0	40	15.61	1.01	97
SK205	-37.5	221.7	-27	26	-135	28	14.56	1.45	96	SK096	116.3	-41.3	-91	41	53	38	15.61	1.27	96
SK108	324.3	-161.9	-1006	25	-298	23	14.58	1.03	0	SK082	50.7	-48.9	-146	34	-19	40	15.61	1.36	93
Y319	410.9	499.4	535	22	231	34	14.58	1.42	0	SK120	235.0	187.0	-111	47	-52	54	15.61	0.96	94
Y287	-394.9	-187.8	-250	22	-912	36	14.59	1.08	0	Y328	669.7	-32.9	1329	50	369	48	15.61	1.01	0
SK147	82.1	39.5	34	25	-72	30	14.60	1.51	97	SK188	27.5	50.8	-52	48	55	61	15.61	1.09	96
SK141	-513.3	24.1	-942	24	-141	61	14.61	1.04	0	SK250	-22.2	46.5	-3	37	-172	50	15.61	1.34	93
SK157	42.9	20.0	-108	28	-73	43	14.62	1.41	95	SK150	76.5	3.8	-94	46	18	50	15.62	1.23	96
SK259	-58.8	37.4	0	31	-36	32	14.64	1.30	97	SK164	28.7	-9.5	64	24	58	44	15.62	1.10	96
SK262	-89.7	15.6	9	53	-17	61	14.64	1.18	97	V15	18.6	115.6	100	53	258	49	15.62	0.53	71
R	67.8	-175.3	-47	28	-55	21	14.66	1.28	97	SK282	-262.7	12.9	-64	37	125	45	15.62	0.58	96
SK072	112.9	-256.4	-51	20	-117	25	14.66	1.39	96	SK124	178.7	97.9	-100	34	15	63	15.63	1.29	93
I339	248.9	-45.0	-45	35	-13	31	14.71	0.81	44	SK263	-83.8	30.2	-16	45	113	50	15.63	0.44	96
SK020	-66.9	-48.5	-31	15	17	40	14.72	1.33	98	SK136	140.0	19.5	-20	56	74	51	15.63	0.83	97
SK023	-70.2	-81.4	-41	26	-79	24	14.74	1.38	97	SK106	198.9	-186.1	86	34	1355	42	15.63	0.85	0
SK063	7.0	-64.1	-99	25	-15	36	14.74	1.35	96	V02	151.6	-393.2	-82	52	225	31	15.64	0.72	88
U	-178.3	114.4	8	28	-52	39	14.78	1.28	97	SK211	-16.0	72.6	61	40	-1	57	15.64	1.03	96
Y275	-7.8	-495.5	-44	31	203	28	14.78	0.86	93	Y279	-376.2	-285.0	-174	31	161	39	15.64	1.26	81
SK123	165.9	152.2	-363	27	1784	28	14.78	0.95	0	SK098	134.1	-66.9	-142	35	179	48	15.64	0.76	85
S	-139.1	79.5	69	22	-232	36	14.79	1.40	83	V14	17.5	77.7	-47	45	9	30	15.64	0.67	97
Y395	-600.2	321.3	-773	41	-873	59	14.80	1											

TABLE 3. (continued)

Names	X	Y	μ_α	ϵ_α	μ_δ	ϵ_δ	V	B-V	P	Names	X	Y	μ_α	ϵ_α	μ_δ	ϵ_δ	V	B-V	P
	arcsec		milliarcsec	cent-1					%		arcsec		milliarcsec	cent-1					%
SK078	63.0	-102.5	-94	45	82	34	15.73	0.97	95	Y361	-78.2	-642.8	-110	46	-169	46	16.13	1.01	88
Y313	-52.8	459.4	127	43	41	48	15.73	0.92	90	Y403	-321.1	410.0	-54	42	161	42	16.13	1.04	95
SK281	-182.5	140.6	-19	63	32	52	15.73	0.92	97	Y332	600.8	-172.4	53	58	-29	36	16.13	1.19	95
SK079	45.6	-91.2	93	51	46	43	15.74	1.05	93	Y399	-509.0	463.1	137	66	112	25	16.14	0.84	81
V18	76.5	211.1	57	38	355	34	15.74	0.73	52	Y091	-63.0	13.8	38	47	386	48	16.15	0.42	40
SK114	335.0	-5.7	7	36	58	36	15.74	0.92	97	SK027	-55.6	-46.7	181	60	306	57	16.17	0.46	31
SK265	-74.5	65.6	110	40	2	40	15.74	1.01	93	SK274	-120.3	82.9	88	67	19	68	16.18	1.15	92
SK195	25.1	94.0	40	33	30	29	15.75	1.03	97	SK018	-105.3	-183.6	144	35	-148	73	16.19	1.17	76
V19	232.0	159.7	-94	25	0	29	15.75	0.56	97	Y224	196.2	306.7	-92	46	-177	60	16.21	1.34	88
DR341	-23.6	319.3	39	48	-179	57	15.75	1.07	90	Y407	-140.8	501.0	-486	53	219	97	16.21	1.11	0
SK149	84.3	11.2	-23	61	36	43	15.75	0.97	97	Y382	-376.4	-415.1	1032	67	-821	38	16.21	1.08	0
DR340	-98.6	285.0	104	61	819	56	15.75	1.23	0	SK038	-27.6	-59.1	-58	42	65	36	16.22	1.11	97
SK187	13.3	65.3	62	48	-100	27	15.76	1.04	94	DR383	-264.3	258.6	339	59	948	84	16.23	0.94	0
Y405	-228.2	538.7	120	47	673	51	15.76	0.98	0	SK134	144.1	87.5	24	45	-171	24	16.23	1.31	93
SK131	241.3	17.4	-46	27	121	55	15.76	0.90	96	SK103	157.2	-85.7	-73	43	-30	68	16.25	1.15	96
Y258	213.9	-355.3	-28	38	7	29	15.76	1.02	97	Y345	141.0	-568.2	292	83	863	72	16.26	0.95	0
Y311	-70.0	410.9	82	37	-58	40	15.77	0.96	95	SK102	129.2	-99.0	106	37	462	42	16.26	1.10	8
V13	-26.8	67.3	-1	46	-80	44	15.77	0.70	97	Y398	-409.9	404.6	687	64	-315	66	16.26	1.33	0
SK089	84.7	-32.9	-146	42	200	50	15.77	0.96	81	SK113	335.3	-12.6	343	45	395	55	16.26	0.91	0
Y322	462.3	244.5	86	54	-231	95	15.77	1.00	71	SK130	246.8	20.2	408	72	881	61	16.27	0.96	0
SK275	-123.8	90.1	113	39	-45	53	15.77	0.95	92	Y289	-405.4	73.1	-1090	60	682	62	16.29	1.25	0
Y365	-177.5	-532.1	50	39	-678	27	15.78	1.40	0	SK039	-24.0	-130.0	67	33	112	56	16.29	1.14	95
SK197	53.8	102.7	-100	63	172	39	15.79	0.90	89	Y358	-7.7	-705.5	-27	43	-899	79	16.30	1.32	80
SK256	-53.3	82.6	-22	36	188	24	15.79	0.87	94	SK015	-151.2	-126.9	153	29	-143	58	16.30	1.19	76
SK101	103.0	-101.0	-58	20	-39	31	15.80	1.24	97	Y396	-444.1	315.6	-220	42	-370	37	16.31	0.95	9
SK212	-12.8	57.7	-29	53	47	49	15.80	0.95	97	Y388	-663.1	-71.5	-696	26	9	54	16.31	1.02	0
SK126	202.7	23.7	32	40	-901	60	15.80	0.89	0	SK128	214.9	-15.4	105	35	0	49	16.32	1.20	93
SK186	5.9	58.8	34	29	52	32	15.80	0.95	97	Y278	-290.3	-322.7	442	54	-1419	66	16.33	1.42	0
Y377	-255.9	-501.3	472	40	-104	29	15.80	0.90	0	Y261	103.4	-391.6	-78	62	-184	57	16.33	1.26	88
SK121	190.3	180.3	38	29	-69	24	15.80	1.03	97	Y364	-164.1	-530.8	-235	36	-374	65	16.33	1.05	8
SK206	-23.9	186.5	124	37	-94	58	15.80	1.03	88	Y383	-434.5	-355.7	283	53	-265	49	16.34	0.93	7
SK180	17.7	36.8	13	30	16	60	15.81	0.98	97	Y315	61.6	492.7	72	31	367	35	16.34	1.06	44
SK022	-66.4	-65.8	-134	36	76	52	15.81	1.14	93	Y318	253.2	551.8	249	79	377	52	16.35	0.90	7
SK028	-52.0	-43.4	-38	45	-4	47	15.82	1.07	97	SK013	-106.1	-59.7	102	21	34	33	16.36	1.22	95
Y357	64.9	-733.5	-297	39	-848	46	15.82	1.18	0	Y274	24.5	-452.0	538	38	257	87	16.36	0.98	0
Z	-12	166.3	49	28	12	39	15.82	1.03	97	Y346	-412.1	-303.8	311	89	-695	65	16.36	1.25	0
SK112	354.5	-21.0	-83	37	-425	41	15.84	1.03	17	Y397	-371.9	299.1	717	88	618	53	16.39	0.99	0
Y344	124.3	-653.9	-622	42	571	30	15.84	1.24	0	SK041	-32.9	-92.0	155	43	60	45	16.40	1.20	83
SK280	-156.9	93.4	103	44	-183	30	15.84	1.18	84	Y21	82.0	-149.1	-314	138	-574	155	16.42	0.74	2
SK051	21.5	-25.8	-66	42	-60	41	15.84	1.28	96	DR415	18.0	-319.5	-58	22	-164	50	16.42	1.27	93
SK045	-6.9	-227.3	718	24	832	59	15.84	0.88	0	Y371	-122.5	-717.2	569	81	135	107	16.42	0.91	0
SK190	52.2	50.7	33	35	-70	44	15.84	1.26	96	BB	-97.3	-130.0	76	139	-32	60	16.42	1.10	81
SK070	13.6	-215.3	-45	42	-104	58	15.85	1.18	96	DR373	-321.7	57.6	-328	43	-899	79	16.43	1.15	0
Y257	158.8	-401.1	-788	42	178	47	15.85	1.02	0	Y320	402.4	387.8	513	89	-543	78	16.44	1.05	0
Y380	-282.2	-424.7	302	43	-120	46	15.85	0.87	12	Y276	-89.4	-453.4	146	144	-634	69	16.44	0.96	0
Y304	-316.4	321.2	587	63	344	28	15.86	1.32	0	Y259	281.4	-331.7	-820	65	854	48	16.44	0.89	0
SK092	103.8	-25.3	-533	18	736	52	15.87	1.25	0	SK011	-131.5	-37.8	-604	56	-64	76	16.45	0.72	0
Y391	-537.8	92.2	-120	51	-458	42	15.88	1.02	7	Y359	25.6	-616.6	44	38	-836	50	16.47	1.36	0
SK282	-334.4	47.7	163	33	-322	48	15.88	1.25	26	Y285	-262.4	-62.9	283	82	47	141	16.49	1.20	25
SK069	6.6	-166.8	95	36	-38	37	15.88	1.17	94	SK024	-67.1	-102.9	167	79	463	44	16.50	1.08	5
SK007	-175.0	-128.1	191	45	-237	27	15.89	1.20	39	SK199	56.7	110.6	41	57	-94	61	16.51	1.27	94
SK094	96.1	-37.4	-175	69	-99	121	15.90	1.22	72	DR461	346.3	198.2	153	55	-83	28	16.52	1.25	80
SK196	50.0	107.5	-22	61	17	77	15.91	1.22	97	Y171	-96.6	-220.7	70	116	-13	106	16.55	1.26	84
SK277	-133.8	35.1	15	29	-81	69	15.91	1.21	96	SK105	232.9	-80.0	121	90	273	61	16.56	1.01	56
SK135	137.9	79.8	-56	40	111	59	15.92	1.06	96	DR464	386.8	92.8	213	223	-493	207	16.56	1.36	10
Y273	-26.8	-453.5	214	35	-600	41	15.92	0.90	86	Y337	434.2	-430.2	1153	82	-559	172	16.58	1.22	0
SK068	8.0	-150.5	37	53	-218	36	15.93	1.24	86	SK046	-14.9	-256.2	142	53	79	47	16.58	1.19	84
Y367	-210.7	-511.6	1145	42	-690	55	15.94	0.98	0	DR408	186.7	-242.0	-891	44	952	89	16.59	1.17	0
AA	-161.8	60.8	67	47	-109	62	15.94	1.17	93	DR399	11.9	-111.5	190	81	155	83	16.60	1.11	55
SK074	109.4	-183.5	406	47	287	71	15.94	1.02	0	Y375	-285.2	-557.8	-1901	71	110	88	16.60	0.94	0
Y400	-519.2	475.4	-108	57	-130	80	15.95	1.02	89	Y223	73.5	429.8	436	109	301	86	16.60	0.99	1
Y356	70.0	-715.9	-7	23	-1141	56	15.96	1.07	0	Y369	-118.1	-659.5	48	73	266	57	16.60	1.12	75
Y393	-662.1	128.2	200	53	184	50	15.96	1.12	51	Y314	-14.1	494.2	367	48	58	55	16.60	1.15	3
Y381	-287.5	-421.9	-89	46	208	39	15.97	1.02	89	Y360	3.5	-624.6	328	46	-775	44	16.62	1.15	0
SK267N	-98.6	143.1	151	56	-99	54	15.97	1.20	78	Y272	-31.0	-406.4	364	46	449	96	16.63	1.24	0
SK198	59.4	102.9	60	30	25	56	15.98	1.14	96	Y376	-330.8	-532.2	1041	58	-873	69	16.65	1.34	0
Y372	-155.8	-712.4	-1930	27	-1049	33	15.98	0.73	0	Y312	-64.4	425.0	-3	84	381	103	16.68	1.24	42
Y378	-276.6	-480.7	37	42	-350	39	16.00	0.87	47	DR322	50.3	122.0	64	51	203	44	16.72	1.12	88
SK213	-2.3	51.0	70	43	-41	65	16.00	1.33	95	Y110	37.5	194.7	260	73	-50	61	16.73	1.26	36
SK076	121.1	-171.9	50	39	62	56	16.02	1.25	96	DR303	57.6	78.6	96						

ture. These stars were given an additional letter N and S (north and south) to aid in their identification. Columns two and three list the offsets in arcseconds (epoch 1975) from the cluster center determined by Shawl & White (1986). The coordinate system is oriented along right ascension and declination for equinox 1950. (The orientation of this system and the position of the center were established by measuring the positions of several cluster members and 11 stars from the SAO catalog on three wide-field plates from the Yerkes 18 cm $f/4$ Schmidt telescope.) Figure 1 [Plate 87] is provided as an identification chart with the offset coordinates marked. Columns four through seven contain the proper motion and the uncertainty in this motion, respectively, with units of milliarcseconds per century (10^{-5} arcsec yr $^{-1}$). The V magnitude is listed in column eight and the $B - V$ color in column nine. The V and $B - V$ values shown in this table are from this study, except in the case for the RR Lyrae variable stars where these values have been taken from DR. Column 10 has the membership probability P for each of the stars.

4. DISCUSSION

4.1 The Color-Magnitude Diagram

Figure 2(a) illustrates the CMD of all stars measured without consideration of membership. Figure 2(b) plots all stars having membership probabilities $P \geq 85\%$ with filled circles and stars with $30\% \leq P < 85\%$ with open circles. Known RR Lyrae variables are included in the diagram with the phase-averaged colors and magnitudes from DR. Based on the derived probabilities, about seven field stars are expected to be included in the most probable, $P \geq 85\%$, category while about 20 field stars are expected in the $30\% \leq P < 85\%$ category.

Our CMD appears very similar to the CMDs published by previous authors. The HB is dominated by stars on the red side of the RR Lyrae instability strip, although we do find a few stars on the blue side. As noted by Green (1979, 1981), the RGB is rather sparsely populated at higher luminosities compared to similar clusters. Our CMD reaches to approximately $V = 16.8$, about 1 mag below the HB. Below $V = 16.4$, the number of highly probable members falls dramatically, due to the increase in uncertainty of the proper motions for fainter stars.

An examination of Table 3 and the CMD in Fig. 2(b) shows that five very probable members ($P \geq 85\%$) fall off the principal sequences in the CMD (though two of these are not displayed on the figure since they are brighter than $V = 12$). In addition, three of the intermediate probability stars fall in the same region, above the HB to the far left of the RGB. An examination of these stars found that six of the eight stars were within $3'$ of the edge of the field and that these stars suffered from coma on the Lick and Yerkes refractor plates. Both astrometry and photometry may be less reliable for these stars. In addition to these six stars near the edge, the bright star—C—has a noncircular image on the Lick plates and some of the Yerkes plates for reasons not entirely clear. The remaining star Y275 has a good image on all plates. Nonetheless, as stated at the beginning of this discussion, because of the overlap of the proper motion distributions of the field stars and cluster members, we must expect that approximately seven of the most probable members are field stars. The fact that the majority of the probable members off the principle sequences in the CMD lie far from

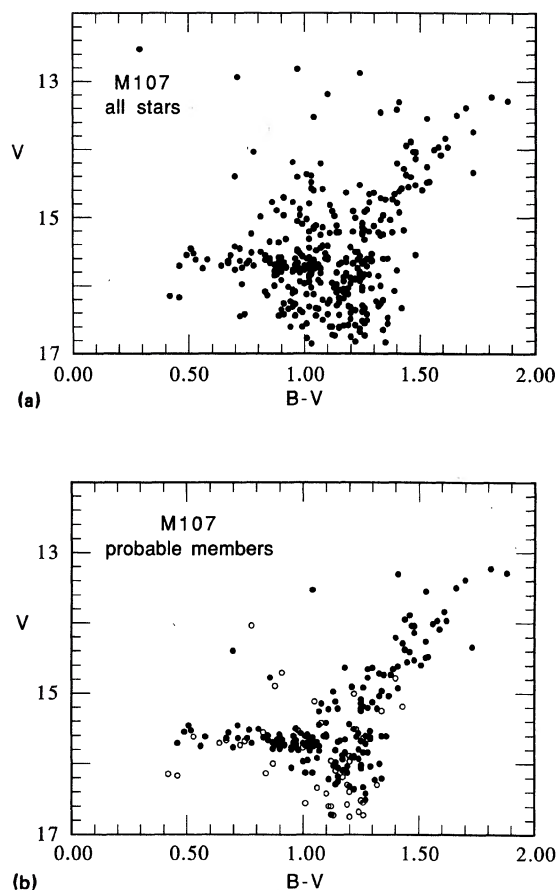


FIG. 2. (a) Color-magnitude diagram of all stars with $V > 12$ measured in the region of M107, regardless of membership probability. (b) Color-magnitude diagram of probable members of M107. Stars with astrometric membership probability $P \geq 85\%$ are indicated by filled circles while those with $30\% \leq P < 85\%$ are shown as open circles.

the cluster center leads us to suspect they are mostly non-members, though some, of course, could be UV-bright members of the cluster.

The probable member redder than the RGB at $V \sim 14.3$ is SK 166. This star lies very near the center of the cluster and is significantly more crowded on the deeper B plates than on any of the V plates. This situation is likely to have yielded a spurious color for this star.

4.2 Reddening and Distance

The mean $E(B - V)$ reddening of the cluster was determined using the red and blue edges of the instability strip as determined from the nonvariable stars. We find the instability strip to be 0.28 ± 0.06 mag wide with the red edge at $(B - V) = 0.78$ and the blue edge at $(B - V) = 0.50$, with an estimated uncertainty of ± 0.04 at each edge. With these values we infer a reddening of $E(B - V) = 0.34 \pm 0.03$. This value is between, and in agreement with, the values obtained by SR [$E(B - V) = 0.32$] and DMO [$E(B - V) = 0.38$]. Taking $R_V = 3.2$, $M_V(\text{HB}) = +0.70 \pm 0.15$, and $V(\text{HB}) = 15.75$ the distance modu-

lus to the cluster is calculated to be $(m - M)_0 = 13.96 \pm 0.18$, corresponding to a distance of 6.2 ± 0.9 kpc.

Because this cluster, like M4, lies behind the Sco-Oph dust complex, it is plausible that M107 may suffer from differential reddening as Cudworth & Rees (1990) found for M4. Indeed, wide-angle plates show patchy reddening in this region of the sky, with considerable filamentary structure. Furthermore, the subgiant and giant branches in our CMD are marginally broader than we would have expected from the photometric uncertainties. Following the procedure of Cudworth & Rees (1990), we have looked at the colors of subgiants as a function of position in the cluster. We find only a hint of a reddening gradient across the central few arcminutes of M107, in the sense that reddening is larger to the east. Our data show no clearly significant reddening gradient in any orientation across a larger region of the cluster. It is possible, of course, that any differential reddening that is present may be too patchy to be described as a simple gradient. Since M107 has fewer subgiants available for this test than M4 (due to the magnitude limit of this study and the distance modulus to M107), a deeper study of M107 with excellent photometry may yield a clear observation of differential reddening.

4.3 The Red Giant Branch and Metallicity

With the value of the reddening taken to be 0.34 mag, we find $(B - V)_{0,g}$, the color of the RGB at the HB, to be 0.91 ± 0.08 , essentially identical to the value obtained for NGC 6712 (Cudworth 1988) which has $(B - V)_{0,g} = 0.92 \pm 0.09$ and $[\text{Fe}/\text{H}] = -1.01$ (Af). Using Webbink's (1985) empirical relation $[\text{Fe}/\text{H}] = -4.94 + 4.23(B - V)_{0,g}$, we find a metallicity of $[\text{Fe}/\text{H}] = -1.09 \pm 0.43$ dex in agreement with values determined via other methods. Searle & Zinn (1978) found $[\text{Fe}/\text{H}] = -0.55 \pm 0.19$ dex. The four giants used in their study (SK 017, SK 117, SK 205, J) all have $P < 94\%$. Zinn & West (1984) derived $[\text{Fe}/\text{H}] = -0.99$ dex with a spread of approximately 0.1 dex between different methods. Smith & Manduca (1983) using the ΔS method for RR Lyrae variables in the cluster derived $[\text{Fe}/\text{H}] = -0.84 \pm 0.25$ dex. The two variables used for this determination (V13 and V14) both have $P = 97\%$.

Other metallicity-dependent parameters measured from the CMD include ΔV (Sandage & Wallerstein 1960), defined as $V(\text{HB}) - V[(B - V)_0 = 1.4]$, and S , the slope of the RGB measured from the HB to a point 2.5 mag brighter (Hartwick 1968). The values derived are $\Delta V = 2.35 \pm 0.14$ and $S = 4.5 \pm 0.6$. Because of the sparse population of giants at the bright tip of the RGB, S may be more uncertain. The value obtained for ΔV is approximately 0.3 mag larger than the value quoted in SK, who used $E(B - V) = 0.3$ mag.

Comparing these observed parameters with values obtained for M5 and 47 Tuc confirms that, indeed, M107 is intermediate between the two. For M5, $\Delta V = 2.6$ and $(B - V)_{0,g} = 0.80$, while for 47 Tuc the observed values are $\Delta V = 2.1$ and $(B - V)_{0,g} = 0.95$ (Madore 1980). The slope of the RGB for M107, $S = 4.5 \pm 0.6$, is similar to the value obtained for M4 (Cudworth & Rees 1990), M5 (Madore 1980) and NGC 6712 (Cudworth 1988) but much greater than the value of 3.4 obtained for 47 Tuc (Madore 1980). The observed abnormalities in M107's RGB luminosity function, i.e., the lack of more luminous giants near the tip of

the RGB, may have an effect on some or all of these parameters.

4.4 Variable Stars

Of the 23 known RR Lyrae variables in the cluster, 17 were included in our sample. Of these stars, 8 are found to be very probable members and seven more have $30\% < P < 90\%$. V21 was labeled a probable field RR Lyrae by DR based on its photometry and has $P = 1\%$ here. This membership value is nonzero only because of the large uncertainty in the proper motion caused by the faintness of the star. The photometry for this variable puts it below the cluster's HB, and this represents a bright limit to the variable's position on the CMD, since only in the star's most favorable phase were reliable measurements able to be obtained. Thus, we agree that this variable is most likely a field RR Lyrae behind the cluster.

The variable V3 ($P = 0\%$) lies slightly above the HB on our CMD and has the brightest average magnitude of the RR Lyraes in the sample both according to our photometry and the more accurate DR analysis. V3 was not measurable on the four weakest Yerkes 40 in. plates but has a good image on the other 12 plates and, hence, a reliable proper motion. Thus, it is possible that this star is a field RR Lyrae passing near the cluster but not gravitationally associated.

As mentioned in Sec. 4.3, Smith & Manduca (1983) derived a value for $[\text{Fe}/\text{H}] = -0.84 \pm 0.25$ using the ΔS method for RR Lyrae variables V13 and V14, both having $P = 97\%$. Smith & Perkins (1982) determined a heliocentric radial velocity ($V_r = 48 \pm 17$ km s⁻¹) measured with respect to V14, V16, and V17. The membership probabilities for V16 and V17 are 63% and 92%, respectively.

The only known variable examined in this study not classified as an RR Lyrae is V1 (= V720 Oph). This star is a long-period variable with a period of 332 d and an amplitude of 3 mag. Previous work has classified V1 as a Mira variable (Kukarkin 1970) not associated with the cluster, but with $P = 10\%$ for this star we cannot rule out membership. Although this star has low membership probability, its mean magnitude may be consistent with the tip of the cluster's RGB. We suspect that the large amplitude variability may have degraded the astrometry of this star, leading to a low membership probability. Further study of this potentially interesting star may be warranted. V25, a red variable, was not included in our sample because of crowding close to the cluster center.

A search was conducted for additional variables in the field. Stars with large residuals in a photometric plate reduction were examined with special attention to stars in potentially interesting positions on the CMD, such as the HB and the tip of the RGB. No stars in our sample were identified as possible variables which were not already known to vary, though all previously known variables measured in this study were rediscovered.

4.5 Space Velocity

In order to determine the cluster's space velocity, the relative proper motion with respect to 69 field stars, $P < 30\%$, with V magnitudes between 14.0 and 16.0 ($\langle V \rangle = 15.31$, $\langle B - V \rangle = 1.05$) was determined. The stars were weighted by their probability of being nonmembers. The relative motion was found to be $\mu_{\text{rel}}(\alpha, \delta) = (0''.11 \pm 0''.09, 0''.01 \pm 0''.10)$ cent⁻¹. Converting from relative to absolute

proper motion using the method described in Cudworth & Hanson (1992) gives an absolute proper motion for the cluster of $\mu_{\text{abs}}(\alpha, \delta) = (-0.07 \pm 0.09, -0.31 \pm 0.10)$ cent^{-1} . Combining this absolute proper motion with the radial velocity of the cluster $-35 \pm 2 \text{ km s}^{-1}$ (DaCosta & Seitzer 1989), a heliocentric space velocity of $(U, V, W) = (3 \pm 11, -75 \pm 31, -44 \pm 26) \text{ km s}^{-1}$ is obtained, with U measured toward $l = 180^\circ$, V measured toward $l = 90^\circ$, and W measured toward $b = +90^\circ$. Removing the basic solar motion and converting to the Galactic rest frame (assuming $\odot_0 = 220 \text{ km s}^{-1}$) the space velocity of the cluster is $(\Pi, \Theta, Z) = (20 \pm 12, 144 \pm 31, -44 \pm 26) \text{ km s}^{-1}$. Here, Π is outward in the Galaxy, and Θ is in the direction of Galactic rotation, at the cluster's position.

This space velocity may be intermediate between the disk cluster system and the halo system. Although the cluster's Z velocity is greater than that of M28 or the disk cluster M71 (Cudworth 1985), it has a Z velocity much less than that of NGC 6712, a more typical halo cluster of similar metallicity to M107. Furthermore, the cluster's Θ velocity shows that it lags behind local circular Galactic rotation by an amount that may be consistent with the thick disk. Consideration of the Π and Θ components shows the cluster is currently near apogalacticon.

We have attempted some fairly simple dynamical calculations to determine how far from the plane, $|z_{\text{max}}|$, M107 can reach, given its current position ($z = 2.4 \text{ kpc}$) and space velocity. The conclusions depend rather strongly on details of the assumed density distribution for the bulge and halo as well as for the disk at distances $\sim 3\text{--}4 \text{ kpc}$ from the Galactic center. With reasonable assumptions it appears that $|z_{\text{max}}| \lesssim 5 \text{ kpc}$ for our derived Z velocity of -44 km s^{-1} . A one sigma change to $Z = -70 \text{ km s}^{-1}$, however, would allow the cluster to reach considerably larger z distances. With the space velocity we derive, M107 thus cannot, at present, be categorized unambiguously as either a halo or disk globular. A one sigma deviation in either direction, especially in the Z component, will put the cluster within the bounds of either system. Thus in kinematics, as well as metallicity, the cluster cannot be conclusively categorized as a disk or halo cluster.

5. CONCLUSIONS

This study has obtained photographic photometry and proper motions for approximately 400 stars in the field of the globular cluster M107. This information has been used to produce a CMD for the cluster to $V \sim 17$, which is significantly cleaner than those by previous authors. From this CMD, we have determined the reddening to M107 to be $E(B - V) = 0.34 \pm 0.03$ and the distance to be $6.2 \pm 0.9 \text{ kpc}$, in agreement with previous work. The metallicity inferred from the CMD, $[\text{Fe}/\text{H}] = -1.09 \pm 0.45 \text{ dex}$, is consistent with spectroscopic determinations of $[\text{Fe}/\text{H}]$.

We have confirmed membership for 15 of the 17 RR Lyrae variables that we measured in the field of M107. V21, shown by previous studies to be significantly fainter than the HB, has very low membership probability, but V3, photometrically near the HB, also has a low membership probability. The Mira variable V1 ($= \text{V720 Oph}$) is found to have low but nonzero membership probability and may be photometrically consistent with the tip of the RGB.

The space velocity for M107 was also derived and found to be inconclusive in distinguishing this cluster as either a disk cluster or a halo cluster: $(\Pi, \Theta, Z) = (20 \pm 12, 144 \pm 31, -44 \pm 26) \text{ km s}^{-1}$ in the Galactic rest frame. Although a one sigma deviation in either direction will place this cluster within the bounds of the halo clusters or the disk clusters, it is interesting to note that M107 cannot be conclusively identified with the disk or the halo based on either kinematics or metallicity. If more clusters are found in this regime, this may imply a smoother distribution between the disk clusters' kinematics and the halo clusters' kinematics than was found by Af, who had only radial velocities, not space velocities.

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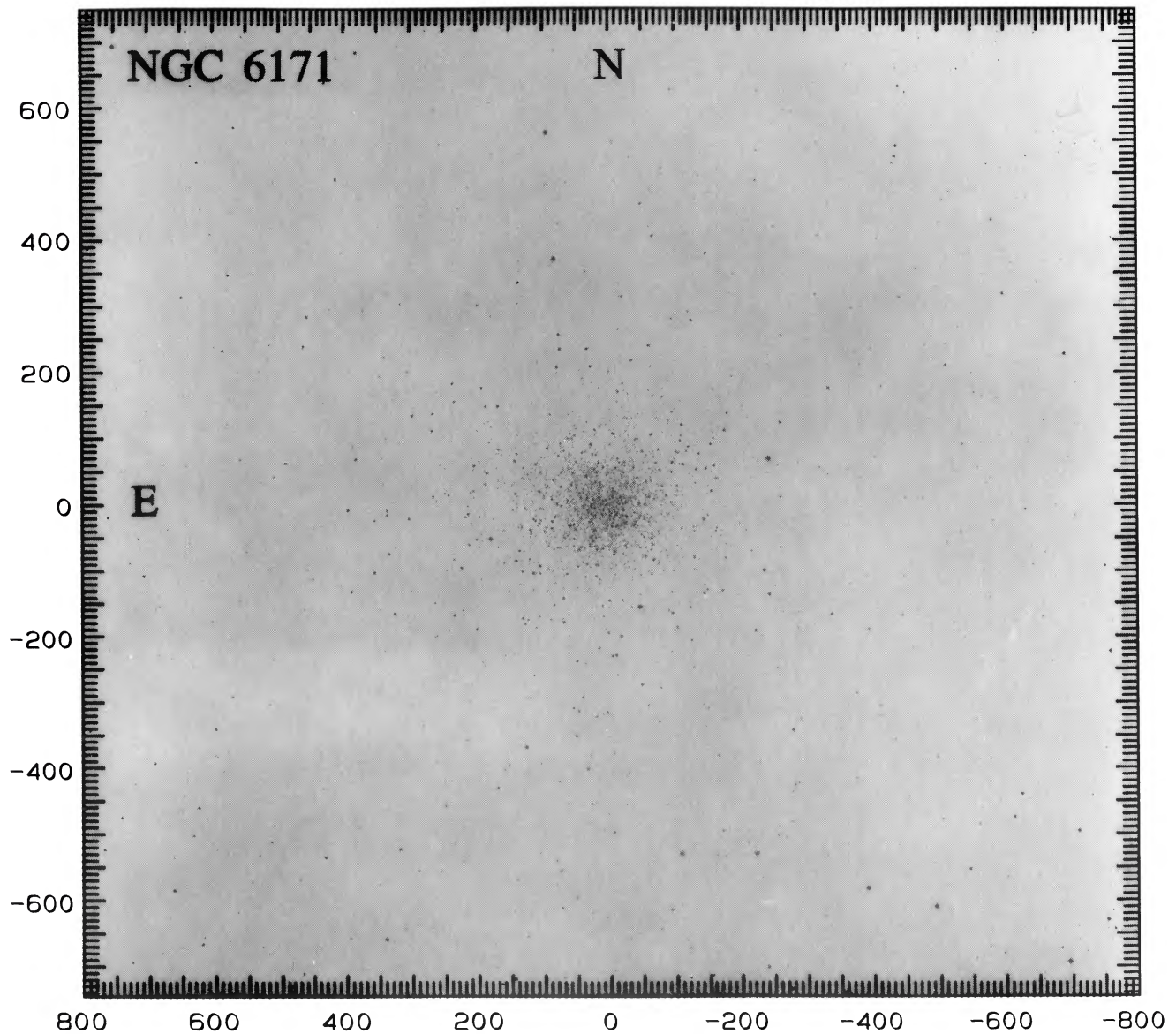


FIG. 1. Identification chart for stars measured in the region of M107 (NGC 6171). North is at the top, and east to the left. The offset coordinates in arcseconds correspond to the coordinates listed in Table 3.

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