

Remote halo globular cluster Palomar 5

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The color-magnitude diagram for the sparse, remote globular cluster Palomar 5 ($\alpha_{50} = 15^{\text{h}}13^{\text{m}}5$, $\delta_{50} = +00^{\circ}05'$; $l = 1^{\circ}$, $b = +45^{\circ}$) is obtained from a *UBV* photoelectric sequence of 29 stars that covers the interval $13.4 \leq V \leq 18.6$. The horizontal branch occurs at $V = 17.35$ which, with $E(B - V) = 0.03$ and $M_v(\text{RR}) = +0.6$, gives $(m - M)_0 = 16.66$, or $D = 21.5$ kpc. The cluster is on the other side of the Galactic center, at $X \simeq 5$ kpc, and is 15 kpc above the plane. The horizontal branch is concentrated toward the red side of the RR Lyrae star gap, and appears to have the NGC 7006 anomaly. The shape of the luminosity function is normal for giants and subgiants, but is ~ 34 times less populous than $\varphi(V)$ for M3, giving an absolute magnitude of $M_v = -5.0$, which is at the extreme faint end of the known luminosity distribution for Galactic globular clusters (compare $M_v = -6.2$ for NGC 5053, -5.7 for Palomar 4, and -5.3 for Palomar 3). Palomar 5, with five RR Lyraes, all of type c, is variable rich for its luminosity. The unreddened color of the subgiant branch at the level of the HB is $(B - V)_{0,g} = 0.82 \pm 0.02$, which corresponds to a metal abundance of $[\text{Fe}/\text{H}] \simeq -1.5$, intermediate between that for the weak-lined clusters M15, M30, M92, and NGC 5053 and the metal-rich clusters 47 Tuc, NGC 6171. The conclusion agrees with the stronger prior determination of $[\text{Fe}/\text{H}]$ by Hesser, Hartwick, and McClure (1977), and by Zinn and Searle, from different methods. The intermediate metallicity of this distant halo cluster, compared with the lower metal abundance of less remote clusters, suggests that the chemical enrichment of the halo was spotty, caused by random enrichment events with inefficient stirring on the free-fall time scale of $< 10^9$ yrs, so that the halo was not mixed with much spatial uniformity during the Galactic collapse.

INTRODUCTION

AS part of a continuing program to map the variations of chemical composition within Galactic halo, we report here on the color-magnitude (CM) diagram of the sparse, remote globular cluster Palomar 5 (the Serpens system at $\alpha_{50} = 15^{\text{h}}13^{\text{m}}5$, $\delta_{50} = +00^{\circ}05'$; $l = 1^{\circ}$, $b = +45^{\circ}$). The cluster is important because it has a large linear diameter (the tidal radius is ~ 18 arcmin, or $D_t = 225$ pc), from which we can be certain that it has never been closer to the Galactic center than $R_p \simeq 15$ kpc. Otherwise the diameter would be smaller due to the stripping action of the Galactic tidal force (von Hoerner 1955; Peterson 1974). Hence, the chemical composition of Palomar 5 must reflect that of the halo at this particular distance, or beyond, at the time the cluster was formed.

Palomar 5 was found by Baade on 1.2-m Schmidt plates taken before the National Geographic-Palomar Sky Survey was begun. It was rediscovered by Wilson (1955) during the course of the survey, and is included in a list of other new faint clusters given by Abell (1955).

This present report concerns the CM diagram, based

on a *UBVR* photoelectric sequence of 29 stars observed with the Mount Wilson and Palomar 2.5- and 5-m reflectors, and a set of two plates in each color taken with the Hale telescope.

I. PHOTOMETRY

The first photoelectric observations were made in April 1968. A skeleton sequence of ten stars was measured, from which we obtained a preliminary color-magnitude diagram by iris photometry of the photographic plates. The diagram was interesting enough that a longer, more secure sequence of 19 additional photoelectric standards was measured in June 1974. The photometry was done with S20 ITT FW 130 photomultipliers, using the usual filters for *UBVR* photometry (Sandage and Smith 1963).

The final photoelectric sequence, listed in Table I, covers the interval $13.4 < V < 18.6$. The errors should generally be less than $\sim \pm 0.03$ mag in each color. Also listed are the smoothed photographic values obtained by reading the standards back through the iris photometer calibrations for the plates, and adjusted by a small color

TABLE I. Photoelectric standards for the Serpens system (Palomar 5).

Star	Photoelectric				<i>n</i>	Photographic	
	<i>V</i>	<i>B</i> - <i>V</i>	<i>U</i> - <i>B</i>	<i>V</i> - <i>R</i>		<i>V</i>	<i>B</i> - <i>V</i>
A	13.40	0.76	0.29	0.64	7 (200)	...	...
B	15.11	0.96	...	...	1 (100)	15.12	1.05
C	15.16	0.74	0.21	0.64	1 (200)	15.04	0.74
D	15.22	0.37	-0.02	0.42	3 (200)	15.19	0.42
E	15.64	1.11	0.73	...	1 (200)	15.73	1.03
F	15.92	1.08	0.81	...	1 (200)	15.96	1.07
G	16.02	1.08	0.83	0.87	1 (200)	15.95	1.02
H	16.24	0.83	...	...	1 (100)	16.28	0.98
I	16.24	0.98	0.70	0.79	1 (200)	16.16	0.97
J	16.42	0.82	...	...	1 (100)	16.48	0.87
K	16.46	1.05	0.63	0.81	1 (200)	16.51	0.96
L	16.53	1.05	0.53	0.81	1 (200)	16.44	1.03
M	16.71	0.81	0.20	0.72	1 (200)	16.73	0.79
N	16.75	0.98	0.60	0.77	1 (200)	16.78	0.96
O	16.79	0.80	0.38	0.70	1 (200)	16.78	0.82
P	17.21	0.67	0.00	0.60	1 (200)	17.25	0.65
Q	17.32	0.61	0.08	0.63	1 (200)	17.33	0.67
R	17.35	0.48	-0.01	0.71	1 (200)	17.31	0.48
S	17.37	0.29	0.09	0.38	1 (200)	17.28	0.43
T	17.38	0.17	0.12	0.23	1 (200)	17.40	0.14
U	17.39	0.78	0.44	...	1 (200)	17.37	0.87
V	17.44	0.50	0.05	0.47	1 (200)	17.42	0.51
W	17.53	0.56	-0.06	0.53	1 (200)	17.56	0.54
X	17.53	0.68	0.04	0.62	1 (200)	17.57	0.62
Y	17.56	0.10	0.03	0.15	1 (200)	17.52	0.11
Z	17.61	0.87	0.49	0.66	1 (200)	17.61	0.80
AA	17.73	0.14	-0.11	0.17	1 (200)	17.79	0.12
AB	18.39	0.79	0.19	0.71	1 (200)	18.35	0.86
AC	18.61	0.81	0.08	...	1 (200)	18.63	0.82

TABLE II. Additional photographic data for Palomar 5.

Star	<i>V</i>	<i>B</i> - <i>V</i>	Star	<i>V</i>	<i>B</i> - <i>V</i>
1	17.15	1.35	19	17.81	0.84
2	15.54	0.60	20	18.71	0.85
3	17.53	0.45	21	18.21	0.80
4	17.25	0.30	22	18.52	0.79
5	18.09	0.89	23	15.68	0.44
6	17.62	0.85	24	17.72	0.72
7	15.85	0.43	25	17.44	0.51
8	16.50	0.72	26	18.00	0.86
9	17.78	1.23	27	17.78	0.84
10	18.16	1.00	28	17.71	0.55
11	18.67	1.60	29	17.34	0.49
12	17.88	0.85	30	18.64	0.82
13	17.47	0.53	31	18.16	0.78
14	17.35	0.88	32	18.22	1.75
15	18.18	1.65	33	17.59	0.82
16	18.45	0.82	34	17.37	0.83
17	18.46	1.75	35	17.92	0.88
18	16.82	1.24			

and magnitude equation to the system of the photoelectric values. The photographically measured *V* and *B* - *V* values for additional program stars that are listed in Table II should, therefore, be on the standard *BV* system systematically to within $\sim \pm 0.02$ mag, as judged from the scatter of differences between the photographic and photoelectric values of Table I.

The photoelectric sequence stars (letters, Table I) and the other program stars (numbers, Table II) are identified in Plate I (p. 525), which is from a 25-min exposure on 103a-D emulsion plus GG11 filter, taken with the Hale reflector. [Inspection of the photograph shows that the photometric field is abnormally small on this plate, only ~ 6 arcmin in diameter rather than the usual 15 arcmin. On this night, the Ross prime-focus corrector lens had not been positioned correctly, and its distance from the emulsion plane was about 15 cm smaller than normal. Although a proper focus was obtained at the center of the plate, the field breaks into coma abruptly at $r \approx 3$ arcmin. A few of the program stars are affected, but enough photoelectric standards are available near the edge of the field (e.g., stars I, M, O, P, Q, R, W, X, Z) to show that the photographic photometry near the edge is, unexpectedly, reliable.]

Also marked in Plate I are three of the five known RR Lyrae variables (V1, V3, and V5) discovered by Rosino (1951). Their periods have been determined by Pietra (1956) and Mannino (1956), and improved by Kinman and Rosino (1962), with the unusual circumstance that all five are of Bailey type c with mean period of $\langle P \rangle_c =$

0.299 ± 0.016 day. The result puts the cluster in the short-mean-period Oosterhoff group I, which is generally associated with *intermediate* to *rich* metal clusters. Hence, the CM diagram of Palomar 5 is of particular interest to test if other evidence on the metallicity exists for this remote halo cluster.

II. CM DIAGRAM, TWO-COLOR DIAGRAM, REDDENING, AND DISTANCE

The CM diagram, plotted from Tables I and II, is shown in Fig. 1. The few stars off the principal sequences are arbitrarily drawn as small circles. Four of the five variables are put as open circles at their mean measured values from the available plates, hence the plotted colors and magnitudes are not proper averages over complete light curves.

The CM diagram is unusual. There are very few giants brighter than the horizontal branch, but this is expected from the small number of cluster stars. What is not ex-

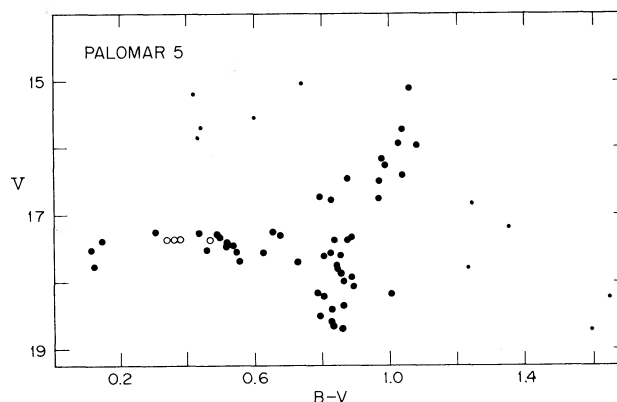


FIG. 1. The CM diagram for Palomar 5, using photographic values from Tables I and II. Stars off the principal sequences are arbitrarily shown as small dots. Four of the RR Lyrae stars are plotted as open circles at the mean colors and magnitudes of our incomplete measurements.

pected is the heavy strength of the horizontal branch (HB) relative to the number of giants. The ratio of HB stars to giants is so large as to make Palomar 5 unusual compared with most other clusters (Demarque, unpublished).

Furthermore, the distribution of stars along the HB is also unusual for a halo cluster because it favors the red side of the RR Lyrae gap, characteristic of many metal-rich clusters (47 Tuc, NGC 6712, NGC 6171, etc.), but also of those clusters with the NGC 7006 anomaly (Sandage and Wildey 1967) where the HB morphology evidently does not follow a one-parameter family. Figure 1 indeed does suggest that Palomar 5 has the NGC 7006 second-parameter strength, but the number of stars is somewhat too small to make a definite case.

The metal abundance can be found from the color of the subgiant branch, $(B - V)_{0,g}$, at the level of the HB (Sandage and Smith 1966; Butler 1975a), since it is known that this color is a strong function of the abundance of those elements that control the envelope opacity (low first-ionization potential metals such as Ca and Fe) along the Hayashi track. But to determine this color requires knowledge of the reddening, which we have estimated in four standard ways, and one new method.

(a) The $U - B$, $B - V$ two-color diagram, plotted from Table I, is shown in Fig. 2. The three obvious field stars A, C, and D are given as open circles. A reddening of $E(B - V) \lesssim 0.08$ is suggested from A and C. (b) The four RR Lyrae type-c variables have $\langle B - V \rangle \simeq 0.38$ at the arbitrary phases we have obtained, suggesting $E(B - V) \simeq 0.10$, but this clearly has low weight. (c) The neutral-hydrogen column density at $l = 1^\circ$, $b = +45^\circ$, averaged over the 0.6 -diameter beamwidth of the Hat Creek radio telescope, is $5 \times 10^{20} \text{ cm}^{-2}$ (Heiles 1975), which, with the calibration by Knapp and Kerr (1974) of $E(B - V) = N_{\text{HI}}/5 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1}$, gives

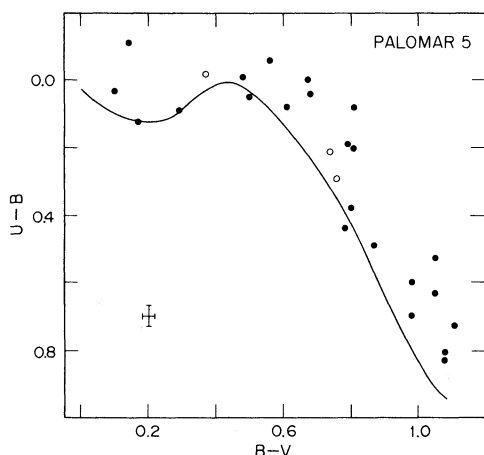


FIG. 2. The two-color diagram from the photoelectric data of Table I. The field stars A, C, and D are shown as open circles. Typical errors are shown by the cross.

$E(B - V) \simeq 0.10$ —but again the error is large because of the intrinsic scatter of the N_{HI} color relation itself. (d) Palomar 5 is only 2.5° from M5, for which the reddening of $E(B - V) = 0.01 \pm 0.01$ is well determined (Arp 1962). As there is no obvious gradient or spottiness in the H I column density between Palomar 5 and M5, nor is there evidence from the Sky Survey prints for high-latitude reflection nebulosities within 5° of M5, we believe that the M5 reddening should apply to Palomar 5 as well. [But note the obvious nebulosities with $\text{SB} \simeq 25 \text{ mag}/\square''$ in the adjacent Sky Survey fields centered at $14^{\text{h}}48^{\text{m}}, +0^\circ$ ($b = 50^\circ$), and $15^{\text{h}}36^{\text{m}}, +0^\circ$ ($b = 42^\circ$). These betray dust clouds with absorption contrasts of $\Delta M \simeq 0.3 \text{ mag}$, or $E(B - V) \simeq 0.10 \text{ mag}$, if Eq. (8) of Sandage (1976) applies.] (e) A method based on the consistency of $\delta(U - B)$ and $(B - V)_{0,g}$, discussed in Sec. III, gives $E(B - V) = 0.03 \pm 0.02$.

The last two methods have the highest weight, and we adopt $E(B - V) = 0.03$ for Palomar 5.

The HB occurs at $V = 17.35 \pm 0.05$. With $A_V = 0.09$, and $M_V(\text{RR}) = +0.6$ (assumed), the distance modulus is $(m - M)_0 = 16.66$ or $D = 21.5 \text{ kpc}$. With Galactic coordinates of $l = 1^\circ$, $b = +45^\circ$, the cluster is on the other side of the Galactic nucleus with $X_\odot = 15.2 \text{ kpc}$, $Z_\odot = 15.2 \text{ kpc}$, or X_{GC} (relative to Galactic center) = 5.2 kpc , $Z_{\text{GC}} = 15.2 \text{ kpc}$ (if $R_\odot = 10 \text{ kpc}$). Hence, the cluster is closer to the center in X than the Sun, and is moderately high in the halo.

III. THE METAL ABUNDANCE

The observed color of the subgiant branch at $V = 17.3$ is $(B - V)_g = 0.85 \pm 0.01$, which, with our adopted reddening, becomes $(B - V)_{0,g} = 0.82 \pm 0.03$. Hence, the cluster is not as metal poor as M15 and M92, where $(B - V)_{0,g} \simeq 0.69$, but rather is similar to M3, M5, and M13, where $\langle (B - V)_{0,g} \rangle \simeq 0.81$.

This red value of the subgiant color of Palomar 5 is the same as we obtained from the preliminary CM diagram in 1969, based on the first ten photoelectric stars. But the conclusion of intermediate metal abundance was unbelievable to one of us (AS) because of a conviction (now clearly wrong) that the relation between remoteness from the Galactic center and the metal abundance was unique. The result was discounted by questioning the photoelectric photometry, and hence the $E(B - V)$ and $(B - V)_{0,g}$ values.

But, in the meantime, the intermediate metallicity of Palomar 5 has been proved by two independent studies. Hartwick, who was convinced from the 1969 results that the cluster is not metal poor (based on reasons connected with Fig. 3, discussed later), recently worked with Hesser and McClure (Hesser *et al.* 1977) using the DDO intermediate-band system on individual globular cluster stars. From that study the authors showed that five individual giants in Palomar 5 have an intermediate abundance of $[\text{Fe}/\text{H}] \simeq -1.5$. In addition, Zinn and Searle (1976, private communication), who are mapping

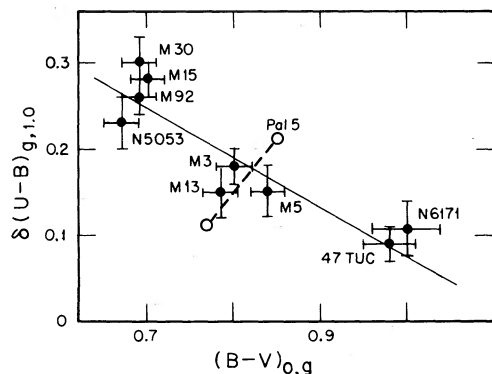


FIG. 3. Correlation of reddening-corrected values of the ultraviolet excess of giant stars at $(B - V)_0 = 1.0$ with the color of the subgiant sequence at the level of the HB for well-observed clusters listed in Table III.

the chemical composition within the halo by determining the metallicities of all Galactic globular clusters using a new photometric system, have also shown that Palomar 5 has about the same composition as M3 and M13. Zinn and Searle's indices are reddening free, hence, unlike our result, their metallicity cannot be uncertain due to poor knowledge of $E(B - V)$.

Our method, using subgiant colors, can be strengthened by combining $(B - V)_{0,g}$ with the ultraviolet excess for giants, $\delta(U - B)_{g,1.0}$, read at $(B - V)_0 = 1.0$, known to correlate with metal abundance via the blanketing effect. From a literature search we collect in Table III data for those clusters with reliable photometry, reddening, and ultraviolet-excess values at the $\sim \pm 0.02$ -mag level. Also shown in column 6 are the $[\text{Fe}/\text{H}]$ values determined from the DDO indices by Hesser *et al.* (1977) from interpolation between Butler's (1975b) directly calibrated relations that involve Preston's (1959) ΔS index. Butler's values are in column 7. The final column of Table III gives the sources for CM diagrams and the photometry.

The $E(B - V)$ and $\delta(U - B)$ values in Table III are not averages from all available data in the literature, but rather are based on what appear to us at the moment to be the most trustworthy results for given clusters. Hence, the values often differ slightly from those in the valuable summary discussions of cluster reddenings by Racine (1973), Harris and van den Bergh (1974), Burnstein and McDonald (1975), Harris (1976), and others.

Preference has been given here to those methods that use photoelectric photometry of individual blue cluster HB stars or the edge positions of the RR Lyrae gap. Next preference is three-color photoelectric photometry of field dwarfs used in the normal way with the two-color diagram. The weight of the determination has also been considered, as judged from the number of photoelectric stars involved.

Different judgments by others would clearly lead to slightly different results—but as the reddenings in Table III are generally small (or well determined from field subdwarfs as for NGC 6171), and as our values do agree within ≈ 0.03 mag with values listed in the above summary compilations, the general sense of Fig. 3 does not depend on the precision of these judgments at this level of accuracy.

Because both $(B - V)_{0,g}$ and $\delta(U - B)_{g,1.0}$ are separately correlated with $[\text{Fe}/\text{H}]$, they should correlate with each other. The data in Table III are plotted in Fig. 3, where the error bars are estimates of the combination of photometric uncertainties and errors in the reddening. It can be shown that the reddening vector in the diagram is nearly perpendicular to the correlation line, and hence $E(B - V)$ can be found if the U photometry of cluster members is good enough.

Data for Palomar 5, read from Figs. 1 and 2, show that the $(B - V)_{0,g}$ and $\delta(U - B)_{g,1.0}$ values change in such a way as to give $(B - V)_{0,g} = 0.85$, $\delta(U - B)_{g,1.0} = 0.21$ if $E = 0$; 0.82, 0.16 if $E = 0.03$; and 0.77, 0.11 if $E = 0.08$. Two of these pairs are plotted in Fig. 3. Clearly, no value of $E(B - V)$ can put the cluster with the low-metal

TABLE III. Clusters with well-observed ultraviolet excess and subgiant colors.

Name	M	$E(B - V)$ (mag)	$(B - V)_{0,g}$ (mag)	$\delta(U - B)_{g,1.0}$ (mag)	$[\text{Fe}/\text{H}]$ (HHM)	$[\text{Fe}/\text{H}]$ (Butler)	Source
47 Tuc	...	0.04	0.98 ± 0.03	0.09 ± 0.02	-0.4	...	1, 2, 3
NGC 5053	...	0.01	0.67 ± 0.02	0.23 ± 0.03	...	...	4
5272	3	0.00	0.80 ± 0.02	0.18 ± 0.02	-1.5	-1.6	5
5904	5	0.01	0.84 ± 0.02	0.15 ± 0.03	-1.0	-1.0	6
6171	107	0.28	1.00 ± 0.04	0.11 ± 0.03	...	-0.8	7, 8, 12
6205	13	0.03	0.78 ± 0.02	0.15 ± 0.03	-1.6	-1.0	9, 5
6341	92	0.02	0.69 ± 0.02	0.26 ± 0.02	-2.2	-2.2	10, 5
7078	15	0.12	0.69 ± 0.02	0.28 ± 0.02	-1.9	-2.0	5
7099	30	0.03	0.69 ± 0.02	0.30 ± 0.03	...	-2.0	11, 13
Pal 5	...	0.03	0.82 ± 0.02	0.16 ± 0.04	-1.5	...	Here

Sources for $E(B - V)$ and the CM diagrams:

- (1) Hartwick and Hesser (1974).
- (2) Cannon (1974).
- (3) Lee (1977).
- (4) Sandage, Katem, and Johnson (1977).
- (5) Sandage (1970).
- (6) Arp (1962).

- (7) Sandage and Katem (1964).
- (8) Dickens and Rolland (1972).
- (9) Arp and Johnson (1955).
- (10) Sandage and Walker (1966).
- (11) Dickens (1972).
- (12) Dickens (1970).
- (13) Reinterpretation of original data.

TABLE IV. Luminosity function for Palomar 5.

V	Giants + subgiants	HB + RR Lyrae	Total
15.60–15.79	1		1
15.80–15.99	2		2
16.00–16.19	1		1
16.20–16.39	1		1
16.40–16.59	3		3
16.60–16.79	3		3
16.80–16.99	0		0
17.00–17.19	0		0
17.20–17.39	3	6 + 5	14
17.40–17.59	1	8	9
17.60–17.79	3	3	6
17.80–17.99	3		3
18.00–18.19	3		3
18.20–18.39	2		2
18.40–18.59	2		2
18.60–18.79	3		3

objects of M15, M30, M92, and NGC 5053. The indicated reddening is $E(B - V) \simeq 0.03$, resulting in $(B - V)_{0,g} = 0.82 \pm 0.02$, and $\delta(U - B) = 0.16 \pm 0.04$, which places Palomar 5 in the M3, M5, M15 metallicity grouping, in agreement with Hesser *et al.* (1977), and with Zinn and Searle.

IV. LUMINOSITY FUNCTION, MASS, AND TIDAL RADIUS

The cluster is among the faintest known. There is no unresolved, continuous central surface brightness distribution as with more luminous globular clusters, and it is difficult to find Palomar 5 on the Sky Survey prints.

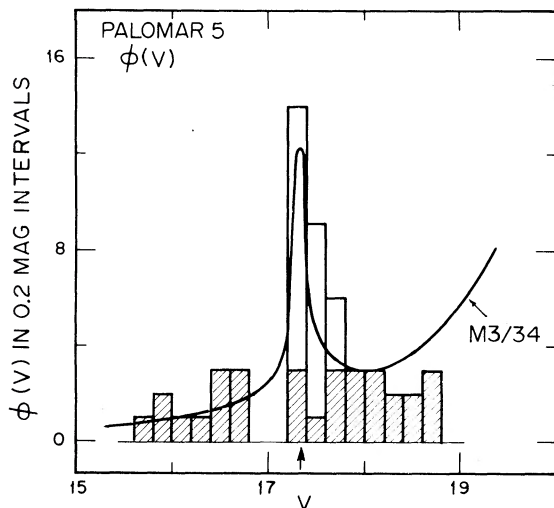


FIG. 4. Luminosity function for Palomar 5 (histogram), compared with that for M3 (continuous curve) reduced by the normalization factor of 34. The HB is shown by open bars. The RR Lyrae stars for both clusters (five for Palomar 5, 200 for M3) are included.

An estimate of its richness can be made by considering the ratio of the luminosity functions of the cluster to M3. Counts in Tables I and II give the luminosity function listed in Table IV and plotted in Fig. 4. The open bars represent the HB, including the five known RR Lyraes. The M3 luminosity function (Sandage 1954), including its variables, is shown as a continuous line, reduced by a factor of 34, and shifted in V until the horizontal branches coincide at $V = 15.73$ for M3 and $V = 17.35$ for Palomar 5.

The fit of the M3 luminosity function, so normalized, is good, showing that the giant-poor character of Palomar 5 is due only to the sparseness of the cluster as a whole. The HB of Palomar 5 is abnormally heavily populated. There are 21 HB stars (including the five variables). Applying the overall normalization of 34 would give 714 HB stars in M3, if the giant-to-HB ratio were similar for the two aggregates. The true number in M3 is only ~ 400 (including the ~ 200 RR Lyraes), showing that Palomar 5 has an abnormally strong HB. It is also "variable rich" with five RR Lyraes which would normalize to 170 in M3. Although this is smaller than the 207 actually known in M3, it is nevertheless much larger than for most clusters normalized to the same absolute luminosity (e.g., Hogg 1973).

From the normalizing factor of 34 relative to M3, the absolute magnitude of Palomar 5 can be calculated to be $M_V(\text{Pal } 5) = -5.0$ [based on $M_V(\text{M3}) = -8.8$ from Kron and Mayall (1960), as modified by Peterson and King (1974), using $(m - M)_0 = 15.13$ for M3]. This is one of the faintest values known. Other faint clusters are NGC 5053 with $M_V = -6.2$ (Sandage, Katem, and Johnson 1977), and Palomar 3 and Palomar 4 with $M_V = -5.3$ and -5.7 , respectively (Burbidge and Sandage 1958). One can appreciate the point by attempting to locate Palomar 5 from only a casual inspection of the Palomar Sky Survey prints.

The mass, assuming a mass-to-light ratio of $M/L = 1.7$ from Illingworth (1973), is $M(\text{Pal } 5) = 1.3 \times 10^4 M_\odot$, which clearly is very small.

We have estimated the tidal radius of Palomar 5 by fitting a King (1966) profile to the counts by King *et al.* (1968). The value, although uncertain because the counts do not extend far beyond the central flat core, give $r_t \simeq 18$ arcmin to within a factor-of-2 uncertainty. With $(m - M)_0 = 16.66$, or $D = 21.5$ kpc, this corresponds to a tidally limited diameter of 225 pc, which of course is very large.

Applying the idea of von Hoerner (1957) and using the modified equation of Burbidge and Sandage (1957) with $M_G = 10^{11} M_\odot$, $M(\text{Pal } 5) = 10^4 M_\odot$, and $R_t = 100$ pc, gives $R_p = 26$ kpc. Although this is larger than the present distance of $R_{GC} = 16.1$ kpc, it is within the multiple uncertainties of the tidal approximations used, and the result should be understood as the qualitative statement that Palomar 5 must have been formed in the halo at distances more remote than ~ 15 kpc.

V. DISCUSSION AND SUMMARY

The cluster is on the other side of the Galactic center from the Sun, at a distance $X = 5.2$ kpc (if $R_{\odot} = 10$ kpc to the center), and is 15 kpc above the plane. Only about 20 other clusters are known to be this remote from the plane, hence its intermediate metal abundance is an important fact in understanding the halo metallicity. Significant in this regard is the very distant cluster NGC 7006 ($l = 64^{\circ}$, $b = -19^{\circ}$; $D = 40$ kpc, $Z = -13$ kpc), which is presently *far* from the Galactic center ($R_{GC} = 42$ kpc) and has a perigalactium distance of $R_g \sim 14$ kpc (Peterson 1974), but which also has an intermediate metal abundance $[Fe/H] = -1.6$, according to Hesser *et al.* (1977). Clusters of very low metal abundance such as M15, M30, and M92 are not now so remote in the halo, and in fact have very small perigalactium distances according to Peterson.

The conclusion is, then, that the enrichment history of the halo has not been smooth. Rather, stars formed at any given halo position can be possessed of a variety of metal abundances, governed by a distribution function that apparently does progressively change toward lower metallicities in the more remote halo regions, but nevertheless is broad enough that clusters formed at say ~ 15 kpc from the center can have $[Fe/H]$ values between -1.0 and -2.0 .

Of course, it need not be surprising that the chemical history has been spotty, with spatial inhomogeneities that depend on random enrichment events with stirring on time scales that are greater than the free-fall collapse time of $\sim 10^9$ yr. What mixing was present was insufficient to achieve spatial uniformity of the enrichment products during the Galactic collapse. Indeed, the relatively high metallicity of Palomar 5 and NGC 7006 seem to require such a spotty picture.

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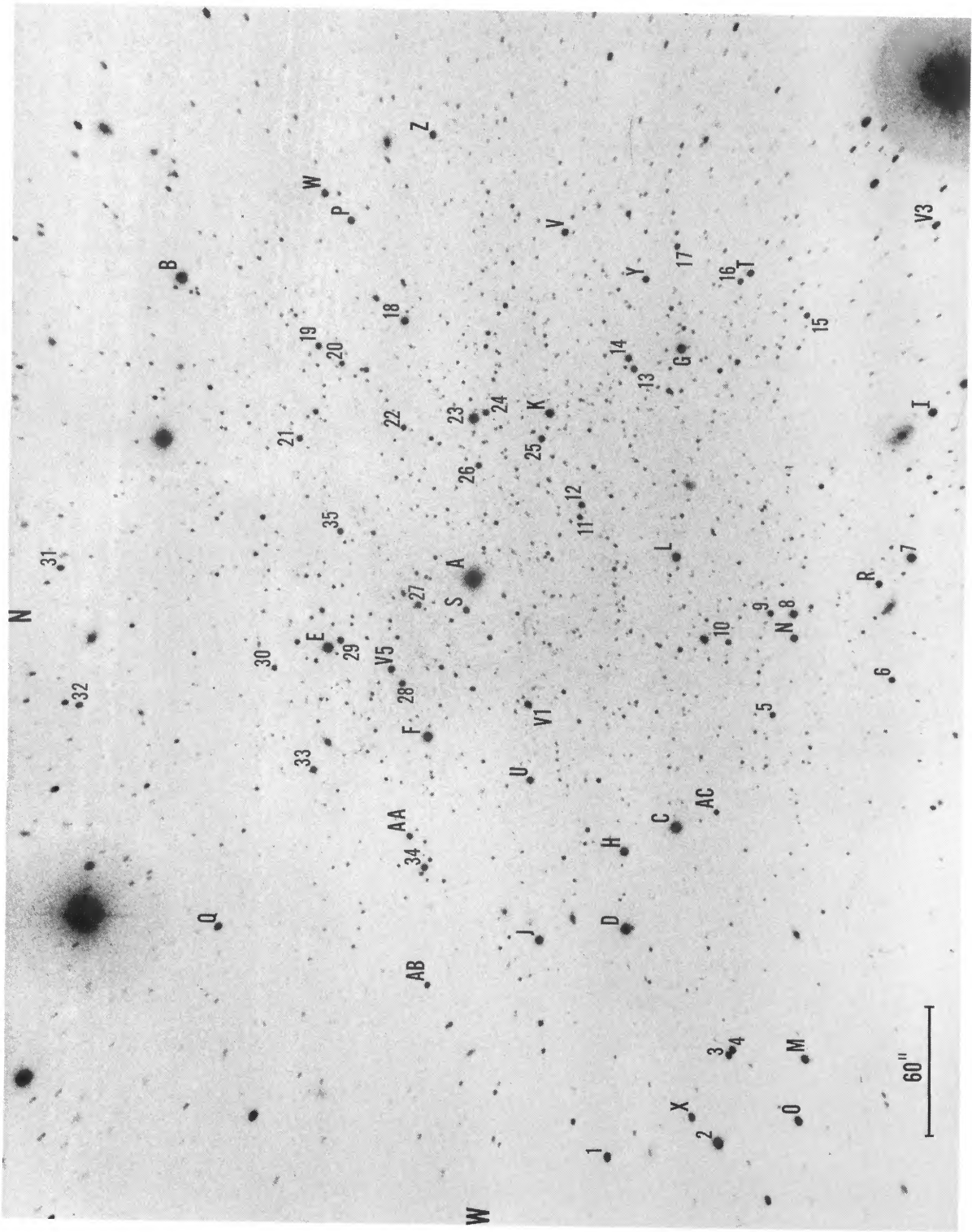


PLATE I (Sandage and Hartwick, p. 459). Identification chart for the photoelectric sequence (letters) of Table I, and the additional program stars (numbers) of Table II. Three of the five known variables are identified by their *V* numbers due to Rosino (1951). Reproduction is from a 25-min exposure on 103a-D + GG11 emulsion plus Schott filter with the Hale 5-m reflector. The abnormally small coma-free field is due to an incorrect positioning of the Ross coma-correcting prime-focus lens on this particular night.