

ABUNDANCE DETERMINATIONS FOR THREE GALACTIC GLOBULAR CLUSTERS

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ABSTRACT

Abundances, as well as temperatures and membership criteria, are determined from photoelectric photometry on the revised Washington system of 22 stars in the Galactic globular clusters NGC 1261, NGC 6541, and NGC 7099. No evidence is found for a metallicity spread in any of the clusters; however, possible CN-strength variations are detected among the NGC 6541 giants. The derived mean cluster abundances are $[M/H] = -0.92 \pm 0.25$ for NGC 1261, -0.99 ± 0.2 for NGC 6541, and -1.81 ± 0.15 for NGC 7099. The values for NGC 1261 and NGC 7099 are in reasonable agreement with previous estimates, but we find NGC 6541 to be much more metal rich than other studies have indicated.

Key words: abundances—clusters: globular

I. Introduction

Globular clusters are the “Rosetta Stones” of the galactic historian. These relics of the earliest generations of the Galaxy provide important clues to its formation and subsequent dynamical and chemical development. Recent years have seen a resurgence of research on these objects, particularly with regard to their composition. A number of important results have emerged. Among these are: (1) the bimodal nature of the cluster system, with distinct halo and disk components of differing metallicities, kinematics, and spatial distribution (Zinn 1985); (2) the intriguing correlation between the slope of the cluster luminosity function and composition (McClure *et al.* 1986); (3) the important role of O (now known to be generally enhanced in globular clusters—e.g., Pilachowski, Snedden, and Wallerstein 1983; Gratton 1987) in determining cluster ages and, hence, a lower limit to that of the Galaxy (McClure *et al.* 1987); and (4) the resolution of the controversy concerning the appropriate abundance scale for metal-rich globular clusters (e.g., Gratton, Quarta, and Ortolani 1986).

These results emphasize the need for continuing studies to refine our knowledge of globular clusters, especially their abundances. The Washington photometric system has proven to be very useful as a broad-band system that gives accurate abundances for red giants (Canterna 1975; Canterna and Schommer 1978; Geisler 1986*b*) as well as for integrated light (Harris and Canterna 1977). Recent

revisions (Canterna *et al.* 1986; Geisler 1986*a*), based on high-dispersion spectroscopy, have secured the abundance calibrations and demonstrated the extreme metallicity sensitivity of the $(C - M)$ index.

As part of a long-term project to investigate abundances in open and globular clusters, Washington photometry was obtained for NGC 1261, NGC 6541, and NGC 7099. Until recently, little was known about these globular clusters, in particular regarding their abundance. The existing color-magnitude diagrams only reach the horizontal branches in NGC 1261 (Alcaino 1979*a*) and NGC 6541 (Alcaino 1979*b*). NGC 7099 has received much more attention. Main-sequence photometry has been published by Alcaino and Liller (1980), Piotto *et al.* (1987), and especially Bolte (1987), who presents a beautiful CCD color-magnitude diagram to $V \sim 24$. Zinn and West's (1984) compilation of metallicity determinations for globular clusters gives $[Fe/H] = -1.31$, -1.83 , and -2.13 for NGC 1261, NGC 6541, and NGC 7099, respectively. The value for NGC 1261 is based on a variety of techniques, while those for NGC 6541 and NGC 7099 rely heavily (exclusively in the former case) on Zinn's (1980*a*) integrated Q_{39} measurements. Since Q_{39} may be slightly affected by horizontal-branch morphology (Smith 1984), and as these clusters all have extreme horizontal branches ($B/B + R = 0.04$, 0.94 , and 0.95 , respectively—Zinn 1980*b*), further abundance analyses are needed to confirm these values. Indeed, Smith (1984) gives significantly higher abundances for NGC 1261 (-1.08 ± 0.2) and NGC 7099 (-1.96 ± 0.25) from the ΔS method.

In this paper, we first present Washington-system observations of stars in these globular clusters (Section II). In the following section (III) we derive temperatures,

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membership criteria, and abundances for the giants. We then discuss possible abundance variations and mean cluster metallicities and compare our results to previous ones.

II. Observations

Observations were obtained of 22 suspected giants in the globular clusters NGC 1261, NGC 6541, and NGC 7099 (M 30). Data were taken over a total of 14 photometric, mostly-dark nights between November 1984 and September 1987 using the CTIO 1.5-, 1.0-, 0.9-, and 0.6-m telescopes. All observations employed a single-channel photometer and a dry-ice-cooled RCA 31034 or Hamamatsu R943-02 GaAs pulse-counting photomultiplier. One of the standard filter sets of the revised Washington system (Canterna 1976; Geisler 1984) was used for all observations. The observational procedure and photometric reductions followed the general precepts outlined in Geisler (1986*b*). Diaphragm diameters for the program stars ranged from 11"–16", depending on crowding and seeing, which was usually between 1".5 and 2". The mean nightly rms error of the transformation to the standard system was 11, 9, 10, 17, and 13 mmag (0.001 mag) in $(C-M)$, $(M-T_1)$, (T_1-T_2) , $(M-51)$, and T_1 , respectively.

Table I presents the photometry for the globular-cluster stars. The star designations are from the sources given in the table. For each color or magnitude, we list the mean observed value, the standard deviation of one observation (σ), and the number of observations (N = the number of different nights observed). A few deviant ob-

servations of the faint NGC 1261 stars, obtained during bright moon, were discarded.

The photometric errors of the cluster observations depend on apparent magnitude and telescope aperture. The mean cluster errors have been assessed and are presented in Table II. Included are the mean error of one observation ($\langle\sigma\rangle$) and the mean standard error of the mean ($\langle\sigma\rangle/\langle N\rangle^{1/2}$). The table indicates that the photometry is rather poor for the much fainter stars in NGC 1261, but it is quite precise for the NGC 6541 and NGC 7099 stars (with the exception of the $(C-M)$ error for NGC 6541).

III. Results

The observed colors were dereddened using the reddening given by Zinn (1985) and the reddening ratios of Harris and Cantenna (1979). The reddenings for NGC 1261 and NGC 7099 are very low ($E(B-V) = 0.00$ and 0.04, respectively), while that for NGC 6541 is somewhat larger (0.18). The temperature, two independent abundance indices, and a membership criterion (if $(M-51)$ photometry was available) were then determined for each star, using the calibrations discussed in Geisler (1984, 1987). All stars with $(M-51)$ photometry were found to be giants from the strength of the Mg features near 5200 Å and thus are very likely cluster members. Thus, we have considered all stars as cluster members in determining the mean abundances.

The derived temperatures and abundance indices are given in Table III. The expected temperature errors are $\lesssim 100$ K. A colon in front of an abundance index indicates

TABLE I
Observed Colors and Magnitudes

Star	C-M	σ	N	M-T ₁	σ	N	T ₁ -T ₂	σ	N	M-51	σ	N	T ₁	σ	N
NGC 1261 ¹															
21	1.398	18	3	0.952	22	3	0.634	14	4	0.015	19	3	13.903	57	4
53	1.357	54	4	0.889	14	4	0.623	14	4	0.027	32	3	14.178	33	4
76	1.256	6	2	0.867	46	2	0.561	14	2	-0.012	...	1	14.367	49	2
96	1.543	25	3	0.995	28	3	0.699	14	3	0.017	17	3	13.565	23	3
122	1.349	98	4	0.891	13	5	0.640	33	5	0.045	25	4	13.629	102	5
I	1.237	42	4	0.861	21	5	0.573	36	5	0.030	34	4	14.137	42	5
J	0.909	49	2	0.757	9	2	0.523	19	2	-0.005	40	2	14.463	13	2
NGC 6541 ²															
I- 19	1.301	56	2	0.950	13	2	0.685	10	2	0.067	10	2	12.548	33	2
I- 21	1.568	22	4	1.080	11	4	0.755	9	4	0.065	12	2	11.807	23	4
I- 66	1.410	92	2	0.963	10	2	0.674	6	2	0.060	13	2	12.444	14	2
II- 73	1.844	5	2	1.226	7	2	0.831	0	2	...	...	...	11.445	2	2
II- 76	1.581	17	4	1.093	18	4	0.747	9	4	0.075	9	2	12.037	11	4
II- 89	1.398	13	2	0.996	1	2	0.710	7	2	0.074	8	2	12.328	23	2
II-113	1.584	26	4	1.063	2	4	0.733	8	4	0.073	21	2	11.900	7	4
II-128	1.919	33	2	1.228	6	2	0.812	5	2	...	...	...	11.422	4	2
NGC 7099 ³															
155	1.637	20	5	1.132	15	5	0.752	17	5	...	...	...	11.413	22	5
156	1.123	6	3	0.879	10	3	0.613	9	3	0.068	7	3	12.461	3	3
157	1.112	18	7	0.886	11	7	0.632	12	7	0.050	40	3	12.418	26	7
158	1.237	14	7	0.944	12	7	0.656	8	7	0.073	30	3	11.924	27	7
D	1.190	16	7	0.914	15	7	0.641	13	7	0.074	7	3	12.224	33	7
F	1.083	16	3	0.858	8	3	0.609	10	3	0.065	12	3	12.516	10	3
H	0.993	16	3	0.782	18	3	0.584	7	3	0.044	19	3	13.044	17	3

Sources for the star designations are:

¹ Alcaïno (1979a).

² Alcaïno (1979b).

³ Alcaïno and Liller (1980).

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TABLE II
Mean Cluster Photometric Errors

Cluster	Error of One Observation (mmag)					Standard Error of the Mean (mmag)				
	C-M	M-T ₁	T ₁ -T ₂	M-51	T ₁	C-M	M-T ₁	T ₁ -T ₂	M-51	T ₁
NGC 1261	42	22	21	28	46	24	12	11	16	24
NGC 6541	33	9	7	12	15	20	5	4	9	9
NGC 7099	15	13	11	19	20	7	6	5	11	9

TABLE III
Temperatures and Abundance Indices
for Cluster Giants

Star	T _{eff} (K)	$\Delta(M-T_1)$	$\Delta(C-M)$
NGC 1261			
21	4240	0.069	0.179
53	4280	0.119	:0.196
76	4500	:0.046	0.130
96	4020	...	...
122	4220	:0.137	:0.240
I	4460	:0.073	:0.185
J	4640	0.090	:0.358
NGC 6541			
I- 19	4500	0.123	:0.272
I- 21	4260	0.098	0.192
I- 66	4540	0.091	:0.130
II- 73	4000	...	...
II- 76	4300	0.076	0.162
II- 89	4420	0.120	0.254
II-113	4340	0.089	0.131
II-128	4080	...	...
NGC 7099			
155	4140	...	...
156	4520	0.112	0.380
157	4460	0.135	0.448
158	4380	0.105	0.369
D	4440	0.118	0.385
F	4540	0.126	0.407
H	4640	0.158	0.420

relatively high uncertainty, due to the large photometric errors for that star. For the coolest giants (those with $(T_1 - T_2)_0 > 0.67$), abundance indices have not been determined, since they lie outside the calibration.

Since CN-strength variations occur in many globular clusters (Hesser, Hartwick, and McClure 1976), and as the $\Delta(C-M)$ index does retain some CN sensitivity (Canterna *et al.* 1986; Geisler 1986*a, b*), it is necessary to first investigate the possibility of CN variations before determining mean cluster metallicities from these data. By comparing the expected errors in the abundance indices, based on the photometric errors, with their observed range, we can estimate the likelihood of real abundance variations. Table IV presents this comparison,

TABLE IV
Expected and Observed Errors in the
Abundance Indices

Cluster	Expected Error		Observed Error	
	$\Delta(M-T_1)$	$\Delta(C-M)$	$\Delta(M-T_1)$	$\Delta(C-M)$
NGC 1261	0.028	0.051	0.034	0.079
NGC 6541	0.013	0.028	0.018	0.061
NGC 7099	0.016	0.022	0.019	0.029

where the expected errors are derived from the standard error of the mean values in Table II and the observed errors are the standard deviation of the indices in Table III, giving equal weight to all stars. In each case, the observed range in the $\Delta(M-T_1)$ indices within a cluster is consistent with that expected from photometric errors alone, supporting the anticipated intracluster metallicity uniformity (since $\Delta(M-T_1)$ is only sensitive to Fe-peak abundance—Canterna 1976). The same is true for the $\Delta(C-M)$ indices, with the exception of NGC 6541, where the observed error is more than twice that expected. It is suspicious that the two extreme $\Delta(C-M)$ values for this cluster come from the two giants with by far the largest photometric errors in $(C-M)$; however, there are two other giants with good photometry that have very comparable $\Delta(C-M)$ indices. If we eliminate the two giants with very uncertain indices, the observed range in $\Delta(C-M)$ is still almost a factor of two more than expected. We conclude that stars I-66 and II-113 are likely CN-strong candidates and will eliminate them from the determination of the mean $\Delta(C-M)$ index.

Figures 1 and 2 show the reddening-corrected two-color diagrams for the globular-cluster giants, from which the two abundance indices, $\Delta(C-M)$ and $\Delta(M-T_1)$, are derived. All giants within the temperature calibration are plotted. Also included are the observations of 47 Tucanae and M 4 giants taken from Pilachowski, Canterna, and Wallerstein (1980) and Geisler (1986*a, b*). The relations for the indicated abundances are from Geisler (1986*a*). It is seen that the NGC 1261 and NGC 6541 giants lie near the $[M/H] = -1$ relation in both diagrams, while the NGC 7099 giants are close to the $[M/H] = -2$ relation.

The mean cluster abundances and their associated errors are presented in Table V. The second column gives the mean $\Delta(M-T_1)$ index, followed by its standard error of the mean, the number of giants, the derived abundance, and its uncertainty. The corresponding values for $\Delta(C-M)$ are found in the seventh through eleventh columns. The last two columns give the final cluster abundance and its estimated uncertainty. These values were derived by weighting the two separate abundance

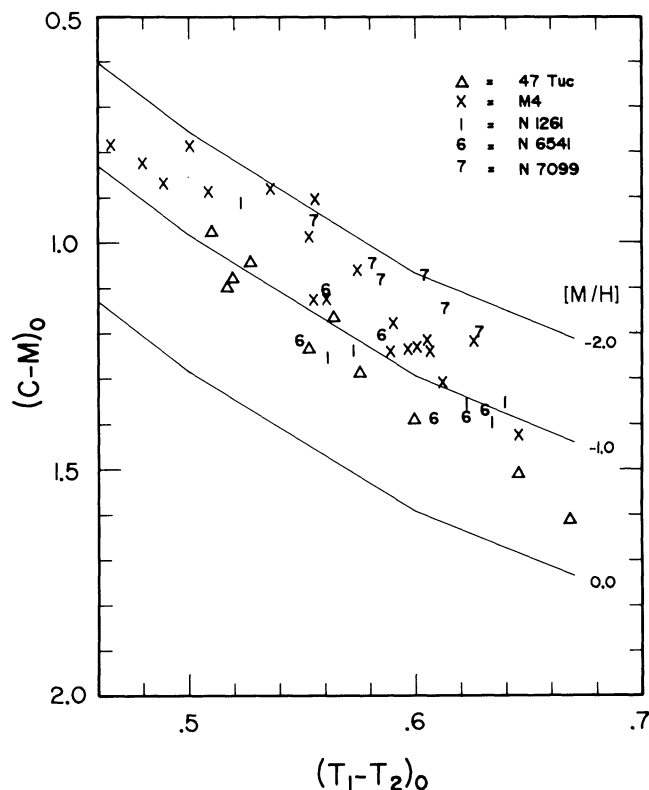


FIG. 1—Intrinsic $(C-M)$ vs. (T_1-T_2) diagram for the globular-cluster giants. Included are the observations for the NGC 1261, NGC 6541, and NGC 7099 stars as well as previously-published observations of giants in 47 Tuc and M 4. The lines show the relations for the indicated abundances.

determinations inversely by their uncertainties, and by attempting to allow for the difference between the two abundance estimates, their individual formal mean errors, and possible external errors in assessing the total uncertainty. Note that the $\Delta(M-T_1)$ index is very insensitive to metallicity for $[\text{Fe}/\text{H}] < -1$ (Geisler 1986a), as shown by Figure 2, so that the derived value for NGC 7099 (shown in parentheses in Table V) is very uncertain.

The $(M-T_1)$ abundances for NGC 1261 and NGC 6541 are somewhat higher than the corresponding $(C-M)$ values. However, we do not consider the differences significant. The errors for the faint NGC 1261 giants are large, and the difference would only be 0.06 dex for NGC 6541 if we had included the suspected CN-strong giants.

Previous abundance determinations exist for these clusters with which our values can be compared. Zinn's (1985) compilation is certainly the most comprehensive and uniform available for Galactic globular clusters. He gives $[\text{Fe}/\text{H}] = -1.29, -1.83,$ and -2.13 for NGC 1261, NGC 6541, and NGC 7099, respectively. These values are all significantly lower than ours, especially in the case of NGC 6541. Zinn's abundances for NGC 6541 and

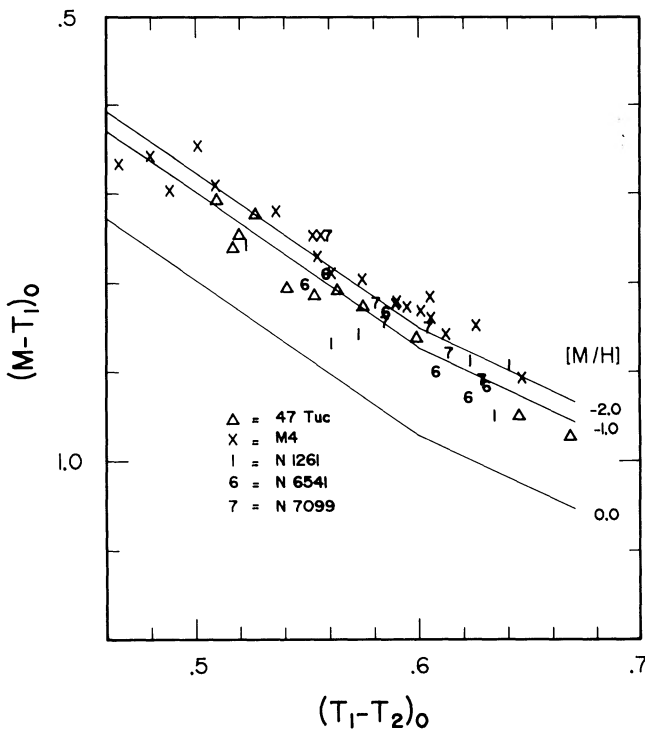


FIG. 2—Intrinsic $(M-T_1)$ vs. (T_1-T_2) diagram for the globular-cluster giants. Symbols are as defined in Figure 1.

NGC 7099 are based almost exclusively on his Q_{39} observations (Zinn 1980a). Smith (1984), among others, has suggested that Q_{39} is slightly sensitive to horizontal-branch type. He has quantified this effect, based on the ΔS abundance scale. His relation predicts that Q_{39} will underestimate the metallicities of NGC 6541 and NGC 7099 by ~ 0.15 dex, as they both have very blue horizontal branches. This effect could account for a large part of the difference between our value and Zinn's in the case of NGC 7099, but not NGC 6541 (nor NGC 1261, where Smith would predict that Q_{39} overestimates metallicity, due to the very red horizontal branch).

Other abundance determinations for NGC 1261 and NGC 7099 are in better agreement with our value. Smith (1984) and Butler (1975) derive $[\text{Fe}/\text{H}] = -1.08 \pm 0.2$ and -1.96 ± 0.25 from ΔS measurements of RR Lyraes in these respective clusters. These values agree with ours to within the errors. We note that our abundance for NGC 1261 would drop to -1.03 if we disregarded star 76, whose abundance in both Washington indices is substantially higher than the cluster mean and which has by far the largest $(M-T_1)$ error of the sample. Abundances determined from the recent deep color-magnitude diagrams of NGC 7099 also tend to confirm our higher abundance. Bolte (1987) finds an excellent fit to his data by scaled-solar Vandenberg and Bell (1985) isochrones with $[\text{Fe}/\text{H}] = -1.8$, or by oxygen-enhanced isochrones with $[\text{Fe}/\text{H}] = -2.0$. Piotto *et al.* (1987) come to identical conclusions. However, the difficulty noted by Heasley and Christian

TABLE V
Cluster Abundances

Cluster	$\Delta(M-T_1)$	ME	N	$[M/H]_{M-T_1}$	$\pm$	$\Delta(C-M)$	ME	N	$[M/H]_{C-M}$	$\pm$	$[M/H]$	$\pm$
NGC 1261	0.089	0.014	6	-0.68	0.25	0.215	0.032	6	-1.03	0.12	-0.92	0.25
NGC 6541	0.100	0.008	6	-0.87	0.19	0.220	0.026	4	-1.05	0.10	-0.99	0.20
NGC 7099	0.126	0.008	6	(-1.88)	0.45	0.402	0.012	6	-1.80	0.07	-1.81	0.15

(1986) in fitting such isochrones to very metal-poor clusters should be noted. Rose, Stetson, and Tripicco (1987) suggest a value as high as $[Fe/H] \sim -1.5 \pm 0.3$ from integrated spectra of NGC 7099. However, DDO photometry of giants by Clariá, Minniti, and Gómez (1988) suggests a very low abundance— $[Fe/H] \leq -2.4$. The true metal abundance of NGC 7099 is of some interest, as it is usually regarded as one of the most metal-poor globular clusters in the Galaxy. It appears likely from this study that its metallicity lies above -2 .

We are left with the puzzling disagreement between our abundance for NGC 6541 and other values. Indeed, all previous indications point to this cluster as having an intermediate-to-low metallicity. It is the case that other estimates tend to give somewhat higher values than Zinn's -1.83 . Smith (1984) finds -1.54 from his recalibration of Q_{39} . Bica and Pastoriza (1983) derive -1.51 from integrated DDO photometry, Brodie and Hanes' (1986) integrated spectra yield -1.71 , and even integrated Washington photometry (Harris and Canterna 1977) implies $[Fe/H] \sim -1.57$. In addition, the integrated spectral type is F6 (Hesser and Shawl 1985) and the horizontal branch contains almost exclusively blue stars. All of these factors indicate a metal abundance closer to that derived by Zinn than by us (although intermediate).

It is difficult to account for the difference by invoking errors in our analysis, e.g., in the reddening, abundance calibration, or field-star or unresolved background contamination. Even if the reddening were as small as $E(B-V) = 0.1$ (instead of the adopted 0.18), which appears highly unlikely based on the numerous consistent reddening estimates, our value would still be -1.2 . The giants were specifically chosen to be close enough to the cluster center to maximize their membership likelihood but far enough away so that they were isolated and relatively free from the unresolved cluster background. Ring 3 stars were avoided, as Alcaino's (1979b) analysis indicated a probability of membership of only $\sim 40\%$, and only a few accessible giant candidates were present. The ($M-51$) observations virtually ensure that the stars are giants. The possibility that they are field stars can also be assessed by using the galaxy model predictions of Ratnatunga and Bahcall (1985). From their data, we conclude that ≤ 1 of our sample of eight stars could be a field star.

As for contamination from background unresolved cluster light, star I-21, which is the closest to the center, has abundance indices essentially the same as the mean. A comparison of the mean abundances for the three stars in the inner ring vs. the three in the outer ring shows that the inner means are slightly (not significantly) higher (i.e., more metal-poor) than the outer means. This argues against the possibility of background contamination leading to an erroneously high metal abundance. Finally, note that the NGC 6541 stars in Figures 1 and 2 are bracketed by the 47 Tuc and M 4 observations. Their abundance must then lie between that of these two well-studied clusters, irrespective of the Washington abundance calibration. The recent high-dispersion CCD abundance analyses of warm giants in these clusters reveal that $[Fe/H]_{47\text{ Tuc}} = -0.82 \pm 0.15$ and $[Fe/H]_{M4} = -1.25 \pm 0.2$ (Gratton *et al.* 1986; Wallerstein, Leep, and Oke 1987).

In conclusion, we are unable to propose satisfactory explanations for the disagreement between our abundance for NGC 6541 and previous determinations. If indeed the Fe abundance is near -1 , this cluster would be an extreme example of the second-parameter phenomenon. We strongly encourage further metallicity determinations for this cluster. Recent high-dispersion echelle CCD observations of these giants should help to resolve this dilemma.

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