THE ASTROPHYSICAL JOURNAL, 228:423–429, 1979 March 1

TiO BAND STRENGTHS IN METAL-RICH GLOBULAR CLUSTERS. II.

JEREMY MOULD, DEBORAH STUTMAN, AND DOUGLAS MCELROY
Kitt Peak National Observatory,* Tucson, Arizona
Received 1978 August 10; accepted 1978 September 11

ABSTRACT

Band strength spectrophotometry between 7000 Å and 1 μm is presented for the reddest stars in M4, M14, M28, M69, M22, NGC 6304, and NGC 6366. Metallicities are derived for these clusters from the threshold temperature for TiO formation by using a calibration developed in an earlier paper. The results are in quite good agreement with a recent calibration of integrated cluster colors. It is shown that, in combination with other metallicity parameters, TiO band studies can yield both the cluster reddening and metallicity simultaneously.

Subject headings: clusters: globular — stars: abundances — stars: late-type

I. INTRODUCTION

Detailed study of the metal-rich globular clusters in the Galaxy has lagged behind that of the classical metal-poor clusters for a number of reasons. Among these are their location in crowded, photometrically difficult fields, the considerable obscuration, and the need for rather sensitive metallicity criteria to rank the clusters effectively. A proper understanding of the chemical evolution of the galactic halo, however, will require that equal attention be given to the metal-rich component of the abundance distribution. In addition, if the initial burst theory of star formation is a good general approximation for spheroidal systems, study of the metal-rich globular clusters will forge a useful link with elliptical galaxies and assist in understanding them.

With these considerations in mind, we have greatly extended the band strength photometry of globular clusters commenced by Mould and McElroy (1978, hereafter Paper I). The TiO band strength technique is effective against crowding and reddening problems because (*a*) the method necessarily involves the brightest stars in the cluster, and (*b*) the effects of undetected reddening on the $1\mu\Delta_1$ abundance parameter are opposite in sign on all other abundance parameters. Useful metallicity determinations are presented here for NGC 6121, 6304, 6366, 6402, and 6637. Upper limits are obtained for NGC 6626 and 6656.

II. PHOTOMETRY

The results of Paper I suggested that only for clusters with metallicity greater than one-tenth solar does the giant branch become cool enough for M stars to appear at the tip. Accordingly, the small sample of Paper I (NGC 6171, 6712, and 6838) for which positive results were obtained was extended to include all clusters with [M/H] > -1 in the estimation of Kukarkin (1974). Other criteria applied were that the angular diameter listed by Sawyer Hogg (1963) exceed 3'.5 and that the clusters be located north of $-35°$ declination. NGC 6266 was omitted from the resultant list, and NGC 6402 (M14) and NGC 6656 (M22) were added because of suggestions by Hesser, Hartwick, and McClure (1977) and McClure and Norris (1977) that these clusters might share the anomalous properties of ω Cen.

Photometry of the giant-branch tip stars in these clusters was carried out at the KPNO 1.3 m telescope on six nights in 1978 May and June. The instrumentation and the photometric system employed were described in Paper I. The only change made for this season's observations was the incorporation of an extra filter at 8120 Å from the Wing (1971) system. This filter measures the $\Delta v = 2$ band sequence of CN and yields a band strength $D(8120)$, defined similarly to the TiO band strength $D(7120)$. The two other derived quantities are the flux ratio or color $m(7540) - m(10175) \equiv 1\mu\Delta$ and the monochromatic magnitude at 10175 Å, $m(1\mu)$.

Most of the clusters studied have published color-magnitude diagrams, and in general our observing procedure was to start with the reddest stars and work down the giant branch until the measured band strengths (displayed in real time by the Computer Photometer) became insignificant. For two clusters (NGC 6402 and 6626) no identification material was available, and our procedure was simply to measure a sample of the clusters' brightest stars. Figure 1*a* is a finding chart for the stars measured in NGC 6402. A chart subsequently kindly provided by Wehlau (private communication) has permitted identification of some of these stars with those studied by Kogon, Wehlau, and Demers (1974). For NGC 6626 a finding chart is provided in Figure 1*b*.

Table 1 presents the results of the photometry described here. The figures in parentheses following the quoted colors and magnitudes are Poisson statistical errors in units of 0.01 mag. Observations whose statistical errors were greater or equal to 10

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

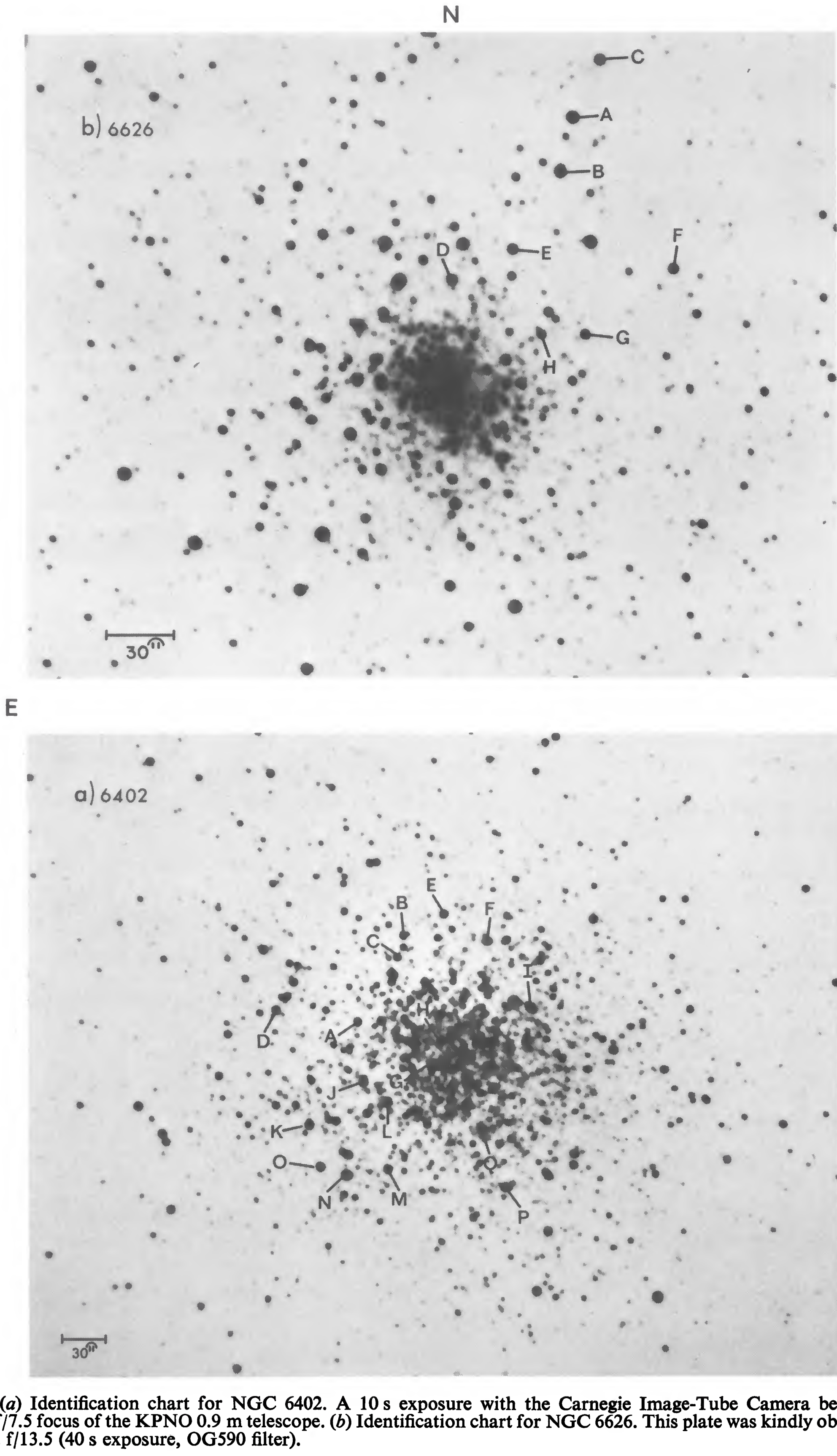

FIG. 1.—(*a*) Identification chart for NGC 6402. A 10 s exposure with the Carnegie Image-Tube Camera behind an OG590 filter at the f/7.5 focus of the KPNO 0.9 m telescope. (*b*) Identification chart for NGC 6626. This plate was kindly obtained by Gisler and Friel at f/13.5 (40 s exposure, OG590 filter).

TABLE 1

OBSERVATIONS

Cluster NGC	Star	1μΔ	D(8120)	D(7120)	m(1μ)	#	Ref.
6121	219	.85 (1)		.06 (2)	8.79 (1)	2	1
(M4)	243	.75 (1)		.03 (2)	9.66 (1)	1	1
	398	.76 (1)		-.01 (2)	9.75 (1)	1	1
	515	.97 (1)	.05 (1)	.12 (1)	8.26 (1)	2	1
	516	.94 (1)	.04 (1)	.14 (1)	8.48 (1)	2	1
	529	.77 (1)		.03 (2)	9.73 (1)	1	1
	571	.83 (1)	.04 (1)	.04 (2)	8.70 (0)	2	1
	522	.91 (1)	.02 (1)	.08 (1)	8.24 (0)	2	2
6304	1208	.86 (5)	.03 (5)	.11 (5)	12.36 (2)	2	3
	1232	1.14 (3)	.03 (3)	.31 (4)	11.68 (1)	1	3
	2236	.89 (3)	.07 (4)	.32 (4)	12.09 (2)	1	3
	3238	.97 (3)	-.02 (4)	.31 (5)	12.45 (2)	1	3
	4203	1.07 (3)	.08 (5)	1.13 (8)	11.57 (2)	1	3
	4223	.99 (2)	.00 (3)	.42 (4)	11.01 (1)	1	3
	4238	.92 (3)	.09 (4)	.14 (4)	12.18 (2)	1	3
	9054	1.06 (2)	.02 (3)	.48 (4)	11.10 (1)	1	3
6366	I-68	1.09 (2)	.06 (3)	.05 (3)	11.47 (1)	1	4
	I-73	1.10 (2)	.08 (3)	.14 (3)	10.91 (1)	1	4
	II-70	1.10 (2)	.08 (3)	.26 (3)	10.39 (1)	1	4
	III-50	1.23 (2)	.04 (3)	.60 (3)	10.03 (1)	2	4
	III-55	1.18 (2)	.04 (3)	.23 (3)		1	4
	IV-50	1.14 (2)	.03 (3)	.32 (3)	10.42 (1)	1	4
	IV-70	1.08 (3)	.02 (3)	.04 (3)	11.44 (1)	2	4
6402	A	.93 (3)		.00 (4)	11.47 (2)	1	
(M14)	B	.80 (3)		.05 (4)	12.05 (2)	1	
	C	.95 (3)		-.02 (4)	11.63 (2)	1	
	D	1.05 (3)	.07 (3)	.11 (5)	11.30 (2)	3	
	E	.98 (4)		.20 (5)	11.31 (2)	1	
	F	1.03 (2)		.29 (3)	11.21 (1)	1	5
	G	.92 (2)		.18 (3)	10.50 (1)	1	
	H	.83 (2)		.10 (3)	10.81 (1)	1	
	I	1.00 (4)		.17 (6)	11.07 (2)	1	5
	J	.91 (3)		.09 (4)	11.19 (2)	1	
	K	1.02 (3)		.17 (4)	11.33 (1)	1	5
	L	.94 (2)		.02 (3)	11.06 (1)	1	
	M	1.01 (2)	.03 (3)	.47 (4)	11.30 (1)	1	
	N	.98 (3)	.06 (4)	.05 (4)	10.70 (2)	1	5
	O	1.06 (6)	.07 (8)	.11 (9)	11.63 (3)	1	
	P	.43 (6)	.11 (8)	-.01 (7)	11.96 (4)	1	5
	Q	.79 (4)	.04 (5)	.02 (5)	11.14 (2)	1	5
6626	A	.94 (2)	.04 (3)	.01 (3)	10.32 (3)	1	
(M28)	B	.75 (2)	.00 (3)	.02 (3)	10.79 (3)	1	
	C	.77 (2)	.08 (3)	.12 (3)	10.92 (3)	1	
	D	.71 (3)	-.02 (5)	-.01 (5)	11.21 (5)	1	
	E	.73 (3)	-.01 (3)	.03 (3)	11.22 (3)	1	
	F	.80 (3)	.02 (4)	-.07 (4)	11.25 (4)	1	
	G	.65 (4)	.03 (5)	-.01 (5)	11.58 (5)	1	
	H	.60 (3)	-.01 (4)	.03 (4)	11.56 (4)	1	

units were rejected from Table 1. Blanks in column (4) indicate that the CN filter was skipped for this star.

III. METALLICITY RANKING

The basis of the metallicity ranking proposed in Paper I is the threshold color for TiO band detection $1\mu\Delta_1$. It is important that this parameter be properly corrected for reddening, as uncertainties of ± 0.05 in $E(B - V)$ translate to errors of ± 0.18 in [M/H]. A compilation of reddening determinations for the program clusters is given in Table 2. With consideration for the reliability of the different methods used, we have adopted some value together with what seems a realistic uncertainty. We shall return to this matter of the reddening in the following section.

The run of TiO band strength (which is reddening-free) with de-reddened $1\mu\Delta$ is shown for separate pairs of clusters in Figure 2. The linear rise of band strength with color above a threshold value is best

TABLE 1—*Continued*

Cluster NGC	Star	1μΔ	D(8120)	D(7120)	m(1μ)	#	Ref.
6637	I-12	.63 (2)		.36 (2)	10.32 (1)	1	6
(M69)	I-30	.53 (3)		.06 (4)	11.39 (2)	1	6
	I-42	.57 (3)		.04 (4)	11.94 (2)	1	6
	I-40*	.68 (2)		.60 (3)	10.75 (1)	1	6
	I-43*	.81 (1)		.69 (2)	10.11 (1)	1	6
	II-14	.61 (3)		.22 (4)	11.42 (2)	2	6
	II-19*	.52 (3)		.17 (4)	12.13 (2)	1	6
	II-35	.22 (3)		-.07 (4)	12.04 (2)	1	6
	II-37*	.91 (2)		1.06 (5)	10.68 (1)	1	6
	II-53	.34 (3)		-.04 (4)	11.60 (2)	2	6
	III-3	.48 (3)		.01 (4)	11.21 (2)	2	6
	III-26*	.56 (4)		.12 (5)	12.44 (5)	2	6
	III-41, 42*	.59 (2)		.40 (3)	11.01 (1)	1	6
	III-43	.76 (2)		.50 (3)	10.90 (1)	1	6
	IV-11	.72 (2)		.72 (4)	10.58 (1)	1	6
	IV-20	.52 (2)		.07 (3)	11.45 (1)	1	6
	IV-27,28	.69 (2)		.46 (3)	11.06 (1)	1	6
6656	II-26	.69 (1)		.03 (2)	9.28 (1)	1	7
(M22)	II-67	.75 (1)	.06 (1)	.04 (2)	9.17 (1)	2	7
	II-80	.74 (1)		.02 (2)	9.45 (1)	1	7
	III-3	.72 (1)	.01 (1)	.01 (1)	8.86 (1)	2	7
	III-12	.68 (1)	.01 (2)	.02 (2)	9.57 (1)	1	7
	II-14	.75 (1)	-.01 (1)	.00 (1)	8.97 (1)	1	7
	II-15	.74 (1)	-.01 (2)	-.02 (2)	9.28 (1)	1	7
	III-26	.71 (1)	-.02 (1)	.02 (1)	9.03 (1)	2	7
	IV-17	.76 (2)	.00 (2)	.05 (2)	9.25 (1)	1	7
	IV-97	.72 (1)	-.04 (2)	-.02 (2)	8.88 (1)	1	7
	IV-102	.74 (1)	-.03 (2)	.01 (2)	8.96 (1)	1	7
	V-9	.71 (1)		.01 (1)	8.98 (1)	1	7

References:
1 Alcaino 1975
2 Greenstein 1939
3 Hesser & Hartwick 1976
4 Pike 1976
5 Wehlau (priv. comm.)
6 Hartwick & Sandage 1968
7 Arp & Melbourne 1959

Alternative identifications in reference 5: F = C II-12a, I = B II-47,48, K = D IV-104, N = D IV-61, P = C III-105, 6, Q = B II-55.

*Outer annulus

TABLE 2

REDDENING

Cluster NGC	Other Results				$E(B-V)$ Ref.[1]	Adopted $E(B-V)$
	$E(B-V)$	Ref.	$E(B-V)$	Ref.		
6121...........	0.36	2	0.45	4	0.49	0.42 ± 0.05
	0.55	3	...		...	...
6304...........	0.58	9	0.56	5	0.58	0.58 ± 0.05
6366...........	0.72	8	...		...	0.72
6402...........	0.35	6	...		0.60	0.47 ± 0.1
6626...........	...		...		0.45	0.45
6637...........	0.28	7	...		0.16	0.20* ± 0.04
6656...........	0.25	2	0.25	10	0.43	0.32 ± 0.07
	0.32	5	...		...	...

* Revised in § IV; see text.

REFERENCES.—[1] Kron and Guetter 1976; [2] Eggen 1972; [3] Alcaino 1975; [4] Newell 1970; [5] Hesser 1976; [6] Kogon *et al.* 1974; [7] Hartwick and Sandage 1968; [8] Pike 1976; [9] Hesser and Hartwick 1976; [10] Arp and Melbourne 1959.

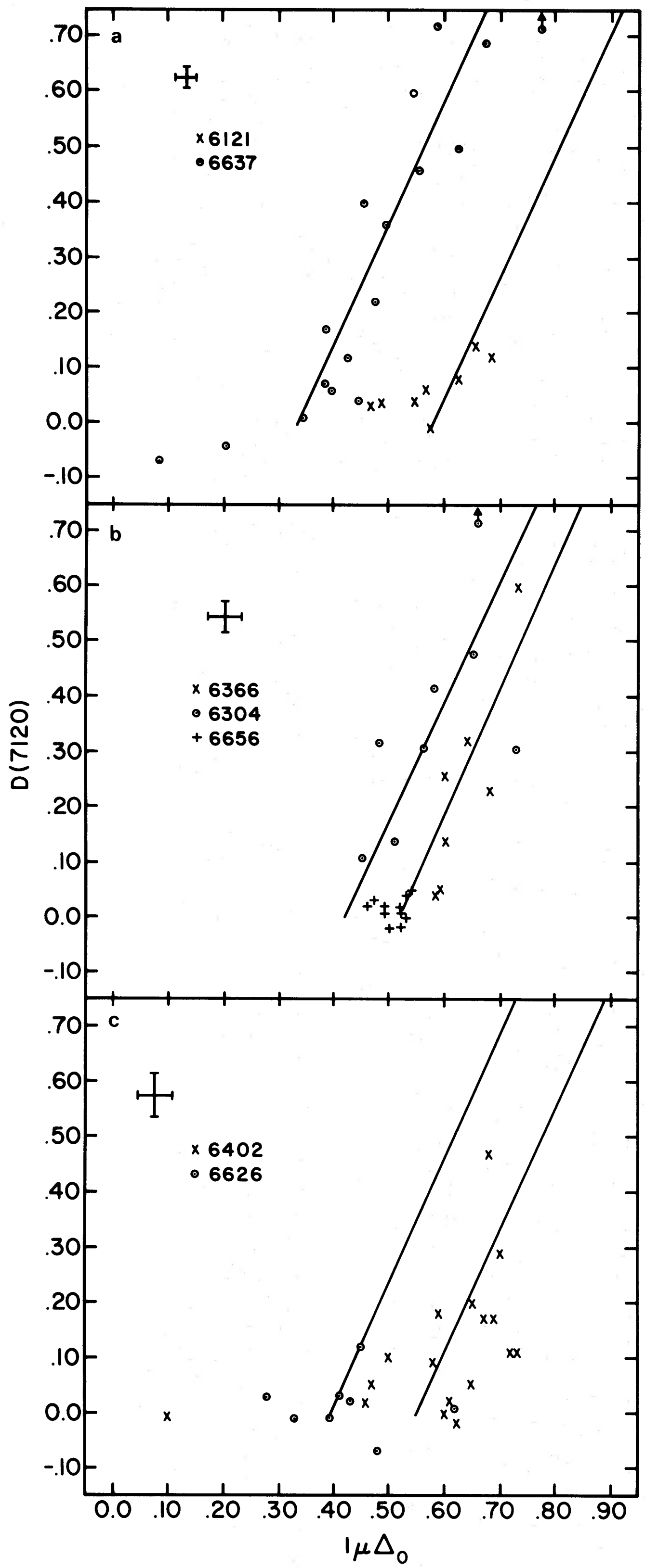

FIG. 2.—TiO band strength is plotted against $1\mu\Delta$ color for all the stars in Table 1. The error bars represent the mean photometric errors. Determination of the threshold color $1\mu\Delta_1$ is discussed in the text.

TABLE 3

METALLICITY RESULTS

Cluster NGC	$1\mu\Delta_1$	[M/H] This Paper	$(B-V)_{0,g}$	$(V-K)_0$[a]	[M/H] from $V-K$	[M/H] Kukarkin
6121......	0.575 ± 0.07	−1.06 ± 0.35	0.83	2.53	−0.8	−1.11
6304......	0.42 ± 0.04	−0.28 ± 0.17	0.98	3.01	−0.1	+0.08
6366......	0.49 ± 0.04	−0.66 ± 0.17	0.95	...	...	±0.1:
6402......	0.55 ± 0.07	−0.95 ± 0.36	0.77	2.53	−0.8	−1.14
6626......	>0.62 ± 0.05	< −1.28 ± 0.22	...	2.17	−1.65	−0.90
6637......	0.33 ± 0.03	+0.14[b] ± 0.14	1.00	2.60	−0.70	−0.18
6656......	>0.49 ± 0.06	< −0.66 ± 0.28	0.70	2.27	−1.3	−1.68
6171[c].....	0.54 ± 0.06	−0.9 ± 0.3	0.91	2.36	−1.1	−0.80
6838[c].....	0.45 ± 0.04	−0.4 ± 0.2	0.96	2.71	−0.5	−0.36

NOTES.—[a] $V-K$ from Aaronson *et al.* 1978, de-reddened as in Table 2. [b] Revised to −0.2 for $E(B-V) = 0.1$ (see text). [c] Results from Paper I.

delineated in the case of NGC 6637 (Fig. 2*a*). A regression line fitted to points in the interval $0.05 < D(7120) < 0.75$ has slope 2.21 and standard error $(s_{y/x})$ 0.03. The scatter is thus comparable with observational errors, consistent with a giant branch homogeneous in abundance. Lines of the same slope were then fitted to the stars in the remaining clusters within the same band strength interval. The observations were weighted inversely as the statistical errors. The intercept at zero band strength is defined as $1\mu\Delta_1$ and is recorded in Table 3. In NGC 6304 star 1232 lay more than 4 σ from the remaining stars and was rejected from the fit. Considerable scatter is present in the results for NGC 6402. This should probably be ascribed to somewhat larger photometric errors for this cluster. Without identification material our approach to the cluster was less systematic, resulting in too short integrations on a number of stars. Further study of NGC 6402 is required to assess the reality of the scatter. An indication of the metal-poor limit of the present system is provided by three remaining clusters. No stars with $D(7120) > 0.05$ were found in NGC 6656, and only one star met this criterion in NGC 6626. For these clusters the values of $1\mu\Delta_1$ in Table 3 (taken from the reddest band-free star observed) should be regarded as upper limits. Finally, in NGC 6121 there are only four stars with $D(7120) > 0.05$. We consider this just sufficient to define the onset of TiO absorption in the cluster and derive a value $1\mu\Delta_1 = 0.575$. However, if a more severe cutoff were chosen [$D(7120) = 0.1$], this value would increase by 0.035 mag. We adopt this as the uncertainty in the present determination, and consider NGC 6121 to define the limit of applicability of the TiO band strength method.

IV. CALIBRATION AND DISCUSSION

As a metallicity calibration of the $1\mu\Delta_1$ parameter we have adopted the calibration given in Paper I,

$$[\mathrm{M/H}] = -5(1\mu\Delta_1 - 0.36)\,,$$

where M/H refers to all the elements heavier than helium and their abundance ratios are assumed to be solar. The validity of this assumption was discussed in Paper I, and it was pointed out that the presumed causes of CN and CH band anomalies in globular cluster giants would probably not affect TiO band strengths. The abundance ratios assumption remains questionable, however, and can best be tested by high-dispersion abundance analyses of some of our program stars.

The derived metallicities are given in Table 3. The quoted errors take account of the goodness of fit, but are dominated by reddening uncertainties. Also shown are metallicities obtained from the de-reddened integrated $V-K$ colors discussed by Aaronson *et al.* (1978). The agreement is quite good (generally within 0.2 dex in [M/H]) except for NGC 6637.

Figure 3 shows that the probable cause of this discrepancy is overcorrection for reddening. Reddening has opposite effects on the $1\mu\Delta_1$ and the $V-K$ (and most other) abundance parameters. Reduction of the adopted reddening from $E(B-V) = 0.2$ to 0.1 will return NGC 6637 closer to the regression lines populated by the other clusters (including two from Paper I) in the $[1\mu\Delta_1, (B-V)_{0,g}]$ and $[1\mu\Delta_1, (V-K)_0]$ planes. The $(B-V)_{0,g}$ values for the clusters were taken mostly from Philip, Cullen, and White (1976), but those for NGC 6304 from Hesser and Hartwick (1976) and for NGC 6366 from Pike (1976). The revised [M/H] for NGC 6637 corresponding to the reduced reddening is −0.2 in good agreement with a revised value from $V-K$ of −0.3.

We turn briefly to the CN band strength measurements [$D(8120)$] recorded in Table 1. No significant detections were made of this band much above 1 σ, indicating the absence of carbon stars among the reddest stars in NGC 6304, 6366, 6626, and 6656. More limited results are available for NGC 6121 and 6402, but again no carbon stars were seen. By contrast, from a similar sample in ω Cen, Wing and Stock (1973) found two carbon stars with $D(8120) \approx 0.5$ and a number of other CN strong stars [$D(8120) > 0.2$] (Wing, private communication). The analogy discussed by McClure and Norris (1977) among NGC 6402, 6656, and ω Cen does not therefore appear to extend either to the presence of cool carbon stars or to the presence of a metal-rich component (see Paper I for a discussion of ω Cen). This is consistent with the

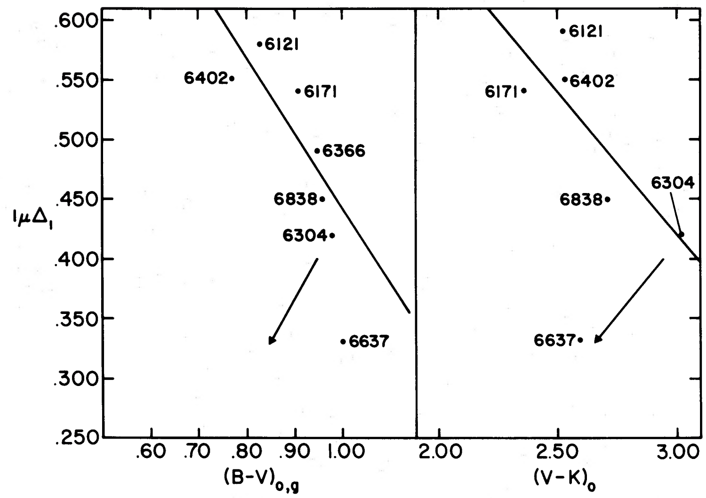

FIG. 3.—The correlation between $1\mu\Delta_1$ and two other metallicity parameters. The arrow indicates a reddening correction of 0.1 mag in $E(B - V)$. Note the discrepant position of NGC 6637.

findings of Lloyd Evans (1978) with regard to the width of the giant branch of NGC 6656. We note from the previous section, however, that the large scatter seen for NGC 6402 in Figure 2*c* remains to be explained, and that an underlying spread in abundance cannot yet be ruled out for this cluster.

V. CONCLUSIONS

Metallicities have been derived from TiO band strengths for the majority of northern metal-rich globular clusters accessible to single-channel photometry. The results agree quite well with those of Aaronson *et al.* (1978), which strengthens the credibility of these two independent theoretical calibrations.

Errors in the TiO band strength method are dominated by uncertainties in the reddening. The fact that the reddening and metallicity vectors run parallel for most abundance parameters, but are antiparallel for the $1\mu\Delta_1$ abundance parameter, gives the present method special importance. In principle, by combining TiO band strength measurements with other reliable abundance parameters [such as $(B - V)_{0,g}$ or $(V - K)_0$] it is possible to completely determine both the reddening and metallicity. In practice, we have been able to recognize a discrepancy in the adopted reddening of NGC 6637 (M69). The revised values of [M/H] $= -0.2$, $E(B - V) = 0.1$, make this cluster the most metal-rich we have studied to date. In addition, with this revision the good correlation between the different abundance parameters (Fig. 3) suggests that the metallicities and reddenings of the present sample are self-consistent to better than 0.2 dex and 0.05 in $E(B - V)$.

Further progress with this technique in the northern hemisphere will require two-dimensional photometric methods, as the remaining clusters, some of them of considerable intrinsic interest, are excessively crowded.

We are grateful to M. Aaronson, A. Wehlau, and R. Wing for communication of unpublished results. D. S. and D. M. acknowledge KPNO Summer Research Assistantships.

REFERENCES

Aaronson, M., Cohen, J. G., Mould, J. R., and Malkan, M. 1978, *Ap. J.*, **223**, 824.
Alcaino, G. 1975, *Astr. Ap. Suppl.*, **21**, 5.
Arp, H. C., and Melbourne, W. C. 1959, *A.J.*, **64**, 28.
Eggen, O. J. 1972, *Ap. J.*, **172**, 639.
Greenstein, J. L. 1939, *Ap. J.*, **90**, 387.
Hartwick, F. D. A., and Sandage, A. 1968, *Ap. J.*, **153**, 715.
Hesser, J. E. 1976, *Pub. A.S.P.*, **88**, 849.
Hesser, J. E., and Hartwick, F. D. A. 1976, *Ap. J.*, **203**, 113.
Hesser, J. E., Hartwick, F. D. A., and McClure, R. D. 1977, *Ap. J. Suppl.*, **33**, 471.
Kogon, C. S., Wehlau, A., and Demers, S. 1974, *A.J.*, **79**, 387.
Kron, G. E., and Guetter, H. H. 1976, *A.J.*, **81**, 817.
Kukarkin, B. V. 1974, *The Globular Star Clusters* (Moscow: Nauka).
Lloyd Evans, T. 1978, *M.N.R.A.S.*, **182**, 293.
McClure, R. D., and Norris, J. E. 1977, *Ap. J.* (*Letters*), **217**, L101.
Mould, J. R., and McElroy, D. B. 1978, *Ap. J.*, **221**, 580, (Paper I).
Newell, E. B. 1970, *Ap. J.*, **161**, 789.
Philip, A. G. D., Cullen, M. F., and White, R. E. 1976, *UBV Color Magnitude Diagrams of Galactic Globular Clusters*, Dudley Obs. Repts., No. 11.
Pike, C. D. 1976, *M.N.R.A.S.*, **177**, 257.
Sawyer Hogg, H. B. 1963, *A Bibliography of Individual Globular Clusters* (Toronto: University of Toronto Press).
Wing, R. F. 1971, *Proc. Conf. Late-Type Stars*, ed. G. W. Lockwood and H. M. Dyck (Tucson: Kitt Peak Obs. Contrib. No. 554), p. 145.
Wing, R. F., and Stock, J. 1973, *Ap. J.*, **186**, 979.

D. B. McElroy: Physics Department, Arizona State University, Tempe, AZ 85281

J. R. Mould: Hale Observatories, 813 Santa Barbara St., Pasadena, CA 91106

D. Stutman: Astronomy Department, Pennsylvania State University, State College, PA 16802