

## ABUNDANCES IN GLOBULAR CLUSTER RED GIANTS. V. THE METAL-RICH GLOBULAR CLUSTERS<sup>1</sup>

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### ABSTRACT

Low-dispersion scans of stars in eight metal-rich globular clusters are used to estimate the metallicity scale of the metal rich clusters relative to 47 Tuc. Various arguments are presented which establish  $[\text{Fe}/\text{H}]_{\odot} = -0.6$  to  $-0.8$  dex for 47 Tuc. A new set of high-resolution, high-precision CCD spectra demonstrates that systematic errors have occurred in the placement of the continuum in previously published echelle analyses of metal-rich clusters. Reconciliation of analyses of low-dispersion scans and high-dispersion equivalent widths can be achieved with  $[\text{Fe}/\text{H}]_{\odot} = -0.7 \pm 0.1$  dex for 47 Tuc. This value is in good agreement with Bell and Gustafsson's scale established via photometric indices computed from synthetic spectra and model atmospheres.

The metal-rich globular clusters reach the solar abundance.

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

### I. INTRODUCTION

In a series of papers (Cohen 1978, 1979, 1980, and 1981), I attempted to provide a fundamental calibration of the abundances of the chemical elements in globular clusters using high-dispersion echelle spectra of individual stars. The low metallicity ( $[\text{Fe}/\text{H}]_{\odot} = -1.3$  dex) which I obtained for M71 and which Pilachowski, Canterna, and Wallerstein (1981) derived for 47 Tuc (confirmed by Cottrell and Da Costa 1981) by a similar method disagree strongly with the abundance scale established from low-dispersion spectra by Hesser, Hartwick, and McClure (1977) and by Searle and Zinn (1978). There was also serious disagreement with the abundance scale given by Bell and Gustafsson (1982 and earlier references) via photometric indices computed from synthetic spectra and model atmospheres. Pilachowski, Sneden, and Canterna (1980), Pilachowski, Sneden, and Green (1981), Geisler and Pilachowski (1981), and Gratton (1981) recently derived controversial abundances for NGC 3201, NGC 6171, and NGC 6352 which are in marked disagreement with Zinn's (1980) rankings. Although Hesser, Hartwick, and McClure (1977), Searle and Zinn (1978), Zinn (1980), and Mould, Stutman, and McElroy (1977) observed some of the more metal-rich globulars, all of these studies present ranking schemes. Fundamental calibrations are offered only in the echelle analyses described above, in the  $\Delta S$  method applied to three clusters (Butler 1975; Keith and Butler 1980), and in the theoretical model atmosphere calibration of various photomet-

ric systems given by Bell and Gustafsson (applied to 47 Tuc by Dickens, Bell, and Gustafsson 1979 and to M71 by Bell and Gustafsson 1982). A preliminary calibration of the TiO index used by Mould, Stutman, and McElroy (1977) has been given by Johnson, Mould, and Bernat (1982). (See also Picarillo, Bernat, and Johnson 1981.)

All these efforts suffer more or less severely from possible contamination by field stars, from reddening uncertainties, and from the difficulty of working in crowded fields on relatively faint stars. I therefore present here a new corpus of observations for individual stars in eight metal-rich globular clusters, check membership status insofar as is feasible, and attempt to derive metallicities for these clusters. The abundances derived for 47 Tuc and M71 are considerably higher than those previously published from high-dispersion echelle analyses. Therefore a new set of high-dispersion, high-precision data was acquired to try to produce concordance among the various determinations and to find the source of the discrepancies.

### II. OBSERVATIONS AND MEMBERSHIP

The observations to be discussed in the first part of this paper consist of moderate dispersion, fully sky-subtracted spectral scans made with the intensified reticon detector constructed by S. Shectman mounted at the Cassegrain focus of the 2.5 m DuPont telescope at the Las Campanas Observatory in 1980 May and 1981 May. All of the scans were made with an identical instrumental configuration which gives a 3 pixel resolution of 1.7 Å, and are identical to the "high-dispersion" observations in Cohen (1982, hereafter C82). The wavelength

<sup>1</sup>Based in part on observations made at the Las Campanas Observatory of the Carnegie Institution of Washington.

region 4800–6300 Å was covered. A pair of apertures 2"×2" each with a fixed separation were used. He-Ar comparison scans for wavelength calibration were made at the beginning and end of observations of stars within a particular globular cluster, and at hourly intervals if the time spent within a cluster was longer. The data were processed and analyzed on the PDP 11/34 and the VAX 11/780 computers at Caltech using programs written by K. Horne, S. Mochnacki, and J. Pier.

Globular clusters were chosen for inclusion in the program if, in the ranking by Zinn (1980), they were more metal-rich than M71 and if a color-magnitude diagram existed in the literature. High-scale photographs were taken of those clusters without C–M diagrams to verify that their fields are, in all cases, so crowded that any attempt to obtain a C–M diagram for a sample dominated by members seemed doomed to failure without an effort of heroic proportions. A few clusters of somewhat lower metallicity were added as calibration objects.

Stars were selected that were probable K giant members according to the color-magnitude diagrams. It was clear that field star contamination would be a major problem, and when this project was begun radial velocities for many of the globular clusters to be studied were not known. Radial velocities were determined for each star using a cross-correlation with 47 Tuc or M71 stars as the templates. Template spectra were separated by not more than two nights from those of the program stars and were usually from the same night. No attempt was made to determine  $v_r$  for the stars which turned out to be of late M spectral type.

In Table 1 we list the resulting heliocentric  $v_r$ , assuming that of 47 Tuc is  $-12 \text{ km s}^{-1}$  and that of M71 is  $-25 \text{ km s}^{-1}$ . The dispersion about the mean for the stars found to be members is also listed. These dispersions were normally found by choosing one star within

each cluster as a local template and cross-correlating the others against its scan. The estimated accuracy of our tabulated  $v_r$  is  $\pm 15 \text{ km s}^{-1}$ ; the uncertainties are due to an inadequate appreciation when the observations were planned of the systematic drifts of the reticon system, which problems could have been avoided with more frequent wavelength calibration arc scans and observations of template stars. For each cluster, the reference for the visual photometry diagram is given, as are the identifications of the nonmembers and late M stars found here. For NGC 6553, no clear separation of members versus field stars was possible. For the remaining clusters, it is believed that most of the field stars have been eliminated from our sample. A few additional new globular cluster radial velocities are given in Appendix A.

Since this project was undertaken, an exhaustive literature survey for radial velocities of globular cluster stars by Webbink (1981) has been completed. Most of the program clusters appear, with very low weights, in his tabulation. Preliminary results of an extensive survey by Shawl, Hesser, and Meyer (1981) (henceforth SHM) are also now available. Our radial velocities support those of SHM and indicate that many of the low-weight radial velocities listed by Webbink have substantial errors.

Infrared observations of giants in M4, discussed in Frogel, Persson, and Cohen (1983), indicated some anomalies; identical low-dispersion scans to those of the program clusters were secured for eight members, and the results are described in Appendix B.

### III. ABUNDANCES

#### a) The Derived Abundances Relative to 47 Tucanae

Pseudo-equivalent widths were measured from the scans using the procedure described in detail in C82.

TABLE 1  
RADIAL VELOCITY DATA

CLUSTER (NGC)	C–M REFERENCE	NO. OF MEMBERS	$V_r$ ( $\text{km s}^{-1}$ )	$\sigma$ ( $\text{km s}^{-1}$ )	PUBLISHED $V_r$		LATE M STARS	NONMEMBERS
					Webbink ( $\text{km s}^{-1}$ )	SHM ( $\text{km s}^{-1}$ )		
104 .....	1	15	...	...	–14	–12	...	...
3201 .....	2	9	...	...	+494	...	...	...
5927 .....	3	6	–74	15	–78	–84	none	none
6171 .....	4	7	–25	13	–147	–15	none	none?
6352 .....	5	8	–104	15	...	–121	L36, 113	17, 18
6553 .....	6	5?	–32?	40	–33	–18	II-59, IV-7, V-4	?
6637 .....	7	7	+43	10	+50	+48	I-43, II-37, III-43	I-2, III-26
6838 .....	8	7	...	...	–19	–21	...	none?

REFERENCES.—(1) All photometry is taken from Frogel, Persson, and Cohen 1981. (2) All photometry is taken from Frogel, Da Costa, and Cohen 1981. Radial velocities for most of the stars observed are given there. (3) Menzies 1974. (4) Sandage and Katem 1964. (5) Hartwick and Hesser 1972 except L36 from Lloyd Evans and Menzies 1977. (6) Hartwick 1975. (7) Hartwick and Sandage 1968. (8) All photometry is taken from Frogel, Persson, and Cohen 1979. Radial velocities for four of the stars observed are given in Cohen 1980.

The set of continuum and line bandpasses adopted by the computer to generate  $W_\lambda$  are those of Table 4B of C82. The bandpasses are shifted according to the radial velocity of the cluster. Pseudo-equivalent widths are measured for the Mg triplet near 5175 Å, the Na D doublet, and the 5270 and 5206 Å Fe blends. The sum of  $W_\lambda$  for the last two is denoted as Fe\*. The measured  $W_\lambda$  for the calibration clusters 47 Tuc and NGC 3201 are in Table 2B of C82;  $W_\lambda$  for the program stars are given in Table 2. These values have an uncertainty of  $\pm 1$  Å.

Reddening values for these clusters are highly uncertain. Table 3 summarizes the determinations for the program globular clusters (excluding the three calibrators, 47 Tuc, NGC 3201, and M71) based on integrated light photometry by Zinn (1980) and on studies of field

TABLE 2  
MEASURED  $W_\lambda$

Cluster (NGC)	Star	$(V-K)_0$ (mag)	Mg (Å)	Fe* (Å)	Na (Å)
5927 .....	587	2.70	8.6	6.2	5.6
	563	2.74	6.1	4.9	5.3
	857	2.94	7.5	5.9	7.1
	23	2.97	9.6	4.5	6.6
	157	3.09	8.8	7.8	5.2
	536	3.23	10.2	7.4	5.8
6171 .....	245	3.14	5.5	5.5	2.0
	243	3.17	5.7	5.3	2.4
	LM1	3.25	6.4	4.6	3.2
	F	3.40	6.5	5.6	3.1
	273	3.69	7.8	5.4	2.9
	E	3.76	6.7	4.7	3.9
6352 .....	217	4.08	9.4	6.7	5.4
	40	2.29	4.2	2.6	4.4
	118	2.52	6.5	3.9	4.9
	111	2.68	6.0	4.3	4.5
	142	2.79	6.6	4.0	3.6
	181	2.97	7.0	5.0	6.0
6553 .....	37	3.10	9.1	6.5	6.3
	55	3.55	9.2	6.5	6.4
	187	3.61	10.5	8.0	6.8
	III-15	3.4	7.2	6.1	3.4
	III-3	3.5	10.0	8.3	5.8
	II-44	3.35	10.5	7.2	6.6
6637 .....	II-54	3.39	7.8	5.3	5.0
	II-95	3.69	12.5	8.6	6.9
	I-4	2.42	2.6	2.0	4.0
	P17	2.94	6.9	3.1	3.9
	in III-3	3.12	7.1	4.5	4.8
	II-19	3.42	8.7	5.2	3.5
6838 .....	in I-30	3.58	8.3	5.5	3.7
	in II-14	3.87	9.5	6.3	4.5
	I-40	4.19	8.0	6.5	3.8
	21	2.84	5.2	3.7	2.2
	S	3.12	5.7	4.2	2.9
	A9	3.37	6.8	5.2	3.1
	A4	3.55	7.5	4.7	3.1
	30	3.59	9.5	7.4	3.8
	45	3.60	8.1	7.3	4.0
	46	3.64	8.9	6.8	3.5

TABLE 3  
REDDENING DETERMINATIONS

CLUSTER (NGC)	$E(B-V)$ (mag)		
	Zinn (1980)	Field Stars	Adopted
104 .....	0.06	...	0.04
3201 .....	0.27	...	0.28
5927 .....	0.42	0.43 <sup>a</sup>	0.46
6171 .....	0.38	0.28 <sup>b</sup>	0.38
6352 .....	...	0.23 <sup>c</sup>	0.25
6553 .....	0.78	...	0.79
6637 .....	0.17	...	0.17
6838 .....	0.26	...	0.25

<sup>a</sup>Menzies 1974.

<sup>b</sup>Dickens 1970.

<sup>c</sup>Hesser 1976.

stars adjacent to the clusters. Determinations relying on matching observed C-M diagrams to that of 47 Tuc are not included. The adopted values, generally a mean of those of Harris and Racine (1979) and of Zinn (1980), are given in the last column of Table 3.

Infrared photometry for all these stars is available from Frogel, Persson, and Cohen (1983), and the  $(V-K)_0$  colors listed in Table 2 are taken directly from that source.

The analysis of the  $W_\lambda$  assumes that all lines are on the damping part of the curve of growth and used the scaling factors given in C82. We explicitly assume that over the range in metallicity spanned by the eight globular clusters, the relative abundances of the chemical elements with respect to Fe are fixed, and the clusters have differing values of Fe/H only. Our high-dispersion echelle analyses indicate that this is at least crudely correct. We also ignore the second-order effects of the range in metallicity among the program clusters. Use of model atmospheres of identical  $T_{\text{eff}}$  and surface gravity ( $g$ ) with a factor of 10 difference in metal abundance to analyze a line of a given ion with a fixed  $W_\lambda$  leads to only small changes in the deduced abundance (see Cohen 1978, Table 5 or Cohen 1980, Table 4). The effect of the range in luminosity at a fixed  $T_{\text{eff}}$  as the cluster giant branches shift with metallicity is more serious, but the total range in  $M_{\text{bol}}$  at, for example,  $T_{\text{eff}} = 4200$  K, is less than 1.8 mag, corresponding to a 0.7 dex range in  $\log(g)$ . Given the overall level of uncertainty in our abundances, we do not make any gravity correction. However, based on the two tables in my previous work, the sense of the error made is that the abundances in the high-gravity, high-metallicity clusters may be somewhat underestimated (by up to 0.2 dex) relative to the more metal-poor clusters.

For each star,  $W_\lambda$  for Fe\* and for Mg are analyzed differentially with respect to the mean relationship between  $W_\lambda$  and  $(V-K)_0$  color established by the exten-

TABLE 4  
ABUNDANCES RELATIVE TO 47 TUCANAE<sup>a</sup>

Cluster (NGC)	Mg	$\sigma$	Fe*	$\sigma$	[M/H] <sub>47 Tuc</sub>
6553 (five stars) ...	+0.17	0.3	+0.24	0.2	+0.20
6553 (two stars) ...	+0.43	...	+0.37	...	+0.40
5927 .....	+0.61	0.2	+0.57	0.3	+0.59
6352 .....	+0.44	0.3	+0.33	0.2	+0.38
6637 .....	-0.03	0.2	-0.24	0.2	-0.13
6838 .....	-0.09	0.2	-0.03	0.2	-0.06
6171 .....	-0.28	0.1	-0.16	0.3	-0.22
3201 .....	-0.85	0.2	-0.51	0.2	-0.68

<sup>a</sup>[M/H]<sub>47 Tuc</sub> (dex).

sive 47 Tuc measurements. The Na D lines are not used as substantial interstellar absorption is undoubtedly present. For each of the two absorption features utilized, the derived abundances for all the stars in a given cluster are averaged, and the deduced abundances are given in Table 4. The dispersion of the individual values about the cluster mean is also listed, and is in most cases consistent with a 1 Å uncertainty in the pseudo-equivalent widths. For NGC 6553, where the membership status of any star is still questionable, we list the mean using all the observed stars and that of the two highest metallicity stars only.

Reddening uncertainties are serious. For a 0.05 mag underestimate in  $E(B-V)$ , an underestimate of up to 0.2 dex in [M/H] results, depending somewhat on the  $(V-K)_0$  colors of the stars involved. Overestimates of  $E(B-V)$  seem rather unlikely.

#### b) Comparison with Previous Results

Since no previous abundance determination procedure (see references in § I) treats more than two of the five program globulars, a detailed comparison with our results is not feasible. Lloyd Evans and Menzies (1977) have derived the near infrared color-magnitude diagrams of metal-rich clusters, and suggest a range in metal content of a factor of 3 to 10 among the globular clusters of integrated spectral type G1–G5. Their ranking of the four clusters in common is similar to ours. In general terms, we differ significantly from the echelle analyses, summarized by Pilachowski, Sneden, and Green (1981) which find M71, 47 Tuc, NGC 3201, NGC 6171, and NGC 6352 to have the same abundance,  $-1.1 \pm 0.2$  dex, whereas we find these clusters to span a range of over 1 dex. It is not possible to attribute this difference to variations only in the light elements controlling the electron pressure (hence affecting the position of the giant branch in C–M diagrams), as was suggested by Pilachowski, Sneden, and Green (1981).

Table 4 shows that the strong Fe lines follow the same trends as the Mg triplet, both qualitatively and even quantitatively, to within the uncertainties of the analysis.

We now demonstrate to any skeptical reader that the weak as well as the damped absorption lines are in fact stronger in those clusters with higher metal abundances according to Table 4. (Recall that Peterson 1981 showed that the high dispersion spectra of M5 and M71 stars of similar  $T_{\text{eff}}$  are not in fact identical and are best represented by synthetic spectra with abundances of  $-1.5$  and  $-1.0$  dex, respectively.) In Figure 1 we display enlargements of our reticon spectra from 6050 to 6150 Å for three stars in NGC 6352 and three in 47 Tuc, two clusters which Geisler and Pilachowski (1981) found to have identical abundances. These spectra were all taken on the same night. The vertical axis gives the actual accumulated counts per pixel, while the vertical scale of each panel has been adjusted so that lines of equal equivalent width will appear equally deep in all the panels of Figure 1. The  $(V-K)_0$  values for each star are indicated. It is clear that most of the features in this spectral region are stronger in the NGC 6352 stars than in the 47 Tuc stars, although, admittedly, none of them are on the linear part of the curve of growth.

There are two minor discrepancies in that Hesser, Hartwick, and McClure (1977) ranked M71 as more metal rich than 47 Tuc, although here (and in Frogel, Persson, and Cohen 1981) the two are indistinguishable. Also Mould, Stutman, and McElroy (1979) have a reversed ranking of M69 with respect to M71 than that found here (and in Frogel, Cohen, and Persson 1983). These disagreements are relatively small and may be caused by the inclusion of some variables or nonmembers among the photometric sample, by the effects of the bimodal CN distributions now known to exist in many globular clusters (see Norris and Freeman 1979 and Smith and Norris 1982), by reddening uncertainties or spatial variations across the field of a cluster, or by the errors in both analyses.



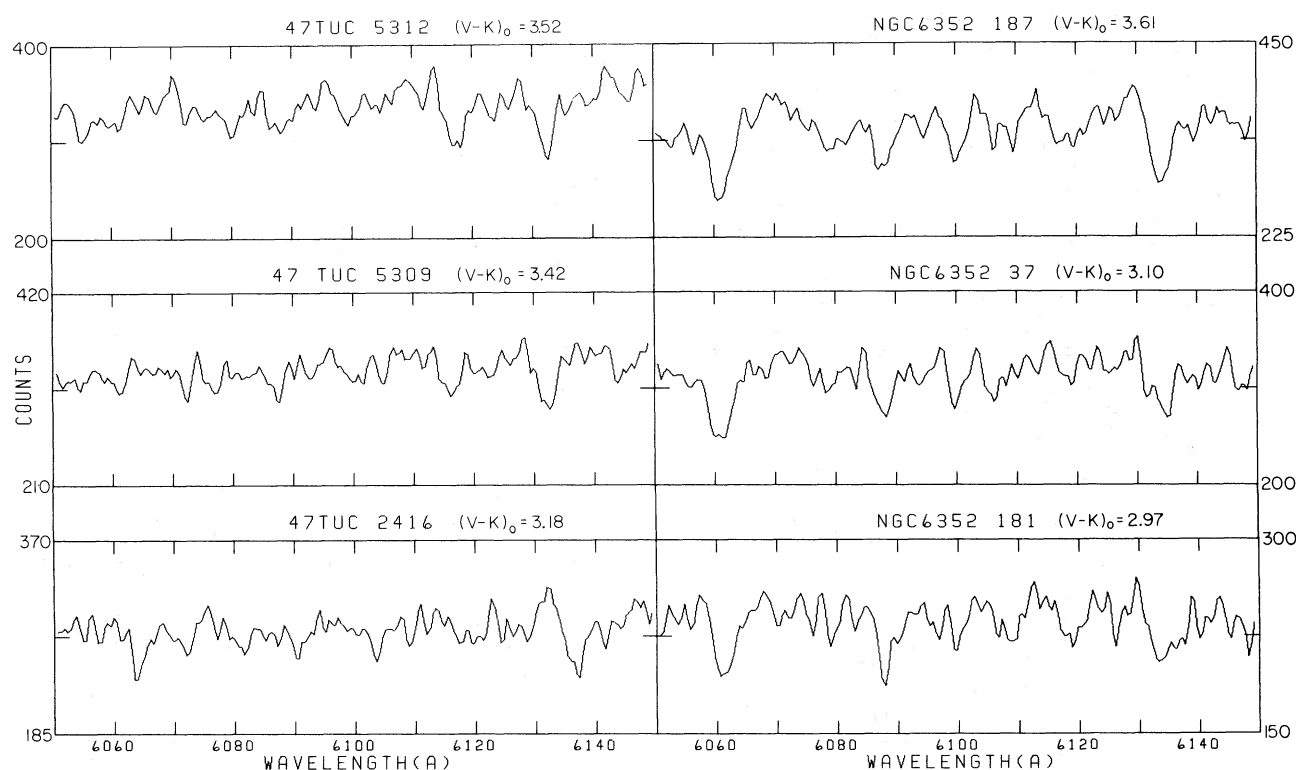


FIG. 1.—A comparison of reticon spectra from 6050 to 6150 Å of three stars in 47 Tuc with three stars in NGC 6352 is shown. The  $(V-K)_0$  color for each star is indicated. The vertical axis is counts per pixel, and the vertical scale is adjusted so that lines of equal  $W_\lambda$  appear equally strong in each of the panels.

#### IV. THE ABSOLUTE ABUNDANCE OF THE METAL-RICH GLOBULAR CLUSTERS

##### a) A New Calibration of the Zinn Scale

One of our goals is to provide a calibration of the Zinn (1980) ranking system, as he has observed the vast majority of the galactic globular clusters. In Figure 2 we show his reddening-free abundance ranking parameter  $Q_{39}$  versus our derived abundances for the eight globular clusters studied here. Although Zinn did not observe NGC 6352, he tabulates a metallicity (deduced from the DDO ranking of Hesser, Hartwick, and McClure 1977), and we invert Zinn's  $[\text{Fe}/\text{H}]-Q_{39}$  relationship to derive a  $Q_{39}$  index. The two values of metallicity for NGC 6553 (all five program stars being members versus only the two strongest lined stars belonging to the cluster) are connected by a solid vertical line. Open circles mark the positions of the clusters with  $E(B-V) > 0.4$  mag assuming a 10% underestimate of the reddening has occurred. The error bar at the lower right is typical of all the points except NGC 6553, whose  $Q_{39}$  has a  $\pm 0.05$  mag uncertainty (as indicated in Fig. 2) due to the extremely dense stellar background and locally variable reddening.

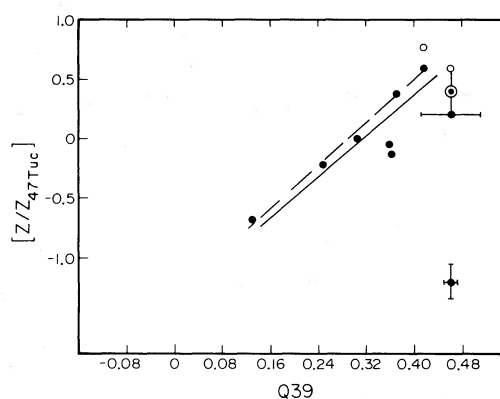


FIG. 2.—The deduced abundances of the metal-rich globular clusters relative to 47 Tuc are shown as a function of Zinn's (1980) ranking parameter  $Q_{39}$ . For clusters with  $E(B-V) > 0.40$  mag, the open circles indicate the effect of a 10% underestimate of the reddening. The two possible abundances for NGC 6553 (all stars or only the two strongest lined stars are members) are connected by a solid vertical line. The error bars of all the points are as indicated at the lower right, except for NGC 6553, which has a larger uncertainty in  $Q_{39}$ , as indicated. The solid line is the least squares fit to the data excluding NGC 6553. The dashed line is a least squares fit which includes also M71 and M69.

Two points lie systematically low in Figure 2, M71 and M69. It seems likely that the extreme sparseness of M71, superposed on a relatively rich stellar background, could lead to systematic errors in Zinn's integrated light photometry both through centering problems and through background correction errors. M69 is a less extreme example of a faint cluster in a rich field. Even within an annulus from radius  $0.5-1'$ , two of the six brightest stars in  $V$ , which will dominate the integrated light at ultraviolet wavelengths as compared to the giants, are not members. It is interesting to note that in an identical plot to Figure 2 using  $Q(ugr)$  or  $Q(ugr) + Q(vgr)$  as the horizontal axis, both M71 and M69 are much closer to the mean line. These two reddening-free parameters have observational errors which are typically half those of the narrower bandpasses used to define  $Q(39uw)$  and  $Q(39vg)$ , which in turn determine  $Q39$ .

Even with these two somewhat problematical cases, a clear trend exists of increasing metallicity as  $Q39$  increases. Ignoring NGC 6553, the cluster with the most uncertain membership, reddening, and hence metallicity, a least squares fit to the data for the remaining seven clusters yield

$$[Z/Z_{47\text{ Tuc}}] = 4.33 Q39 - 1.37. \quad (1)$$

This is the solid line shown in Figure 2.

If one is prepared to accept the suggestion made above that the measured  $Q39$  values for M71 and M69 have larger errors than those assigned by Zinn, and omits these two clusters, the least squares fit to the remaining five clusters is

$$[Z/Z_{47\text{ Tuc}}] = 4.54 Q39 - 1.32. \quad (2)$$

This is the dashed line drawn in Figure 2. (The slope of Zinn's original calibration is 4.40.)

The metal-poor clusters have sufficiently weak lines that line crowding problems and consequently continuum location uncertainties are minimal. We therefore accept as correct the previously published echelle abundance analyses. The metallicity of 47 Tuc can now be determined by using the abundances for the metal-poor calibrating clusters (M92, M15, M3, M13, and M22) given in my previous papers, combined with their  $Q39$  indices measured by Zinn. This relationship is plotted in Figure 3. A least squares fit to this data yields

$$[\text{Fe}/\text{H}] = 6.22 Q39 - 2.03. \quad (3)$$

This is the solid line drawn in Figure 3. Zinn's original fit is shown as the dashed line in Figure 3.

The range of  $Q39$  for these five metal-poor calibrating clusters is only 0.11 mag, so we try adding the  $\Delta S$  results. Butler (1975), Smith and Butler (1978), and Smith (1981) analyzed RR Lyrae variables in five globular clusters with  $Q39 > 0.08$  mag. (The results of Keith

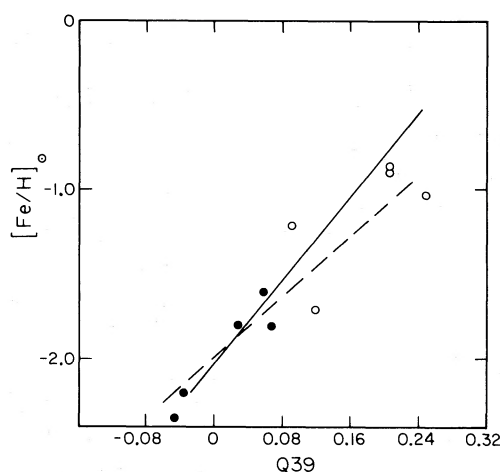


FIG. 3.— $[\text{Fe}/\text{H}]_{\odot}$  is shown as a function of Zinn's (1980) ranking parameter  $Q39$  for the calibrating metal-poor globular clusters. The open circles represent abundances derived via  $\Delta S$  measurements by Butler (1975), Smith and Butler (1978), and Smith (1981). The solid line is a least squares fit to the abundances derived from my echelle data. The dashed line is Zinn's (1980) original metallicity calibration for  $Q39$ .

and Butler 1980 for 47 Tuc are excluded due to severe membership uncertainties.) These, with a  $-0.2$  dex shift to make their abundance scale agree with the echelle analysis of the metal-poor calibrating clusters, are shown as open circles in Figure 3 and weakly support a calibration intermediate between the least squares fit to the echelle analyses and that originally used by Zinn.

Superposing Figures 2 and 3 defines  $[\text{Fe}/\text{H}]_{\odot}$  for 47 Tuc as  $-0.6 \pm 0.1$  dex.

Thus the suggested calibration for the Zinn  $Q39$  index is that given by equation (2) for  $Q39 > 0.12$  mag, and

$$[\text{Fe}/\text{H}]_{\odot} = 5.3 Q39 - 2.0 \quad (4)$$

for  $Q39 < 0.12$  mag. When using Zinn's  $Q39$  values, one should recall the possibility for sparse clusters of random errors due to background corrections larger than the photometric errors quoted by Zinn, as well as the possible effects of variation of the horizontal branch discussed by Manduca (1982).

A second estimate of the absolute abundance of 47 Tuc can be obtained by assuming that the abundance determined from 3 RR Lyrae variables in NGC 6171 by Butler (1975) is, with the  $-0.2$  dex scale correction, identical to that we obtain for NGC 6171 from the low-dispersion scans as given in Table 4.  $[\text{Fe}/\text{H}]_{\odot}$  is thus determined to be  $-0.80$  dex for 47 Tuc.

#### b) Comparison with Previous Analyses

In the calibration presented above, M71 has an abundance of  $-0.65$  dex with respect to the Sun, and 47 Tuc

is at  $-0.6$  dex. Thus there is serious disagreement with the absolute scale of the abundances deduced by Cohen (1980) for M71 and by Pilachowski, Canterna, and Wallerstein (1981) for 47 Tuc. However, good agreement is obtained with the abundances established from synthesizing narrow-band spectral indices by Bell and Gustaffson (1982) and Dickens, Bell, and Gustaffson (1979) and from the latest stellar evolution codes as applied to globular cluster giant branch locations in the H-R diagram (Demarque, King, and Diaz 1982) as well as with the  $\Delta S$  results summarized by Smith and Perkins (1982).

One cannot try to explain part of this discrepancy by changing the overall absolute scale. Even though my scale appears to be lower than that of Pilachowski by 0.2 dex for the metal-poor clusters, the abundances established here for the metal-rich clusters are on my scale. Any adjustment in the metal-poor cluster scale simply propagates to all the globular clusters.

The most likely source of this discrepancy is errors in continuum placement. Even working with high-dispersion spectra longward of  $5000 \text{ \AA}$ , it is hard to define the continuum for cool stars in such metal-rich clusters and still harder to find lines on the linear part of the curve of growth (see also Bell 1981). It seems probable that the fault lies with the echelle analyses, rather than the moderate dispersion scan analysis presented here. Because the present analysis deals with very strong features, a 10% underestimate in the continuum level changes  $W_\lambda$  by about 25%, which corresponds to an underestimate of 0.3 dex in abundance. Furthermore, since everything here is done differentially with respect to 47 Tuc, only the differential error in continuum location due to differential blanketing from changing metallicity is relevant. For the weaker lines used in the echelle analysis, a similar underestimate in the continuum level corresponds to more than a 50% change in  $W_\lambda$ . For lines not on the linear part of the curve of growth, the underestimate in abundance is very large (see also Deming 1980).

#### V. NEW OBSERVATIONS TO RESOLVE THE DISCREPANCIES

We are faced with a discrepancy of 0.4–0.6 dex between the echelle abundance of 47 Tuc (Pilachowski, Canterna, and Wallerstein 1981) and that deduced in § IVa, as well as a discrepancy of similar magnitude for M71 from the echelle analysis of Cohen (1980). We have suggested in § IVb that systematic errors in continuum placement give rise to this distressing dissonance.

A new set of observations was obtained in an attempt to resolve this enigma. One star in M13, one in M4, two in M5, and four in M71 were observed with the red camera of the Double Spectrograph (see Oke and Gunn 1982) on the Palomar 5 m telescope in 1982 June and July. A  $1200 \text{ g mm}^{-1}$  grating was used in second order

so that  $0.35 \text{ \AA}$  per pixel was obtained. With a  $1''$  entrance slit the FWHM of the comparison lines was less than 2 pixels. In spite of severe vignetting due to the extreme grating tilt, in 1 hour exposures for each star more than 15,000 electrons per 15 microns (the width of 1 pixel) were accumulated (in the continuum) spread out over a vertical height of less than 7 pixels. Given the low readout noise of the Texas Instruments CCD chip, this guarantees an accuracy of at least 2% for each pixel over the  $270 \text{ \AA}$  interval ( $6130\text{--}6400 \text{ \AA}$ ) observed. Cross-correlations show that Lee 3303 is not a member of M4 and that star 78 is possibly not a member of M71; these stars are not included in the subsequent discussion.

A comparison of one of the original echelle spectra used in Cohen (1980) with a CCD spectrum of the same star, M71 A4, is shown for a  $40 \text{ \AA}$  bandpass in Figure 4. The original continuum used to measure equivalent widths from the tracing of the echellogram is indicated by a thin line. It should be noted that the raw CCD counts, divided by the flat field, and summed over a 7 pixel height, are displayed. The photon noise level on the CCD spectrum, with a total of about 34,000 counts per pixel width (equivalent to 51,000 detected photons per pixel) in the continuum is less than half of a small division on the vertical scale of the figure. Furthermore, the resolution of the CCD spectrum is only slightly degraded from that of the echellogram. Note that the wavelength region displayed in Figure 4 includes the center of the echelle order at about  $6212 \text{ \AA}$ ; the region with  $\lambda < 6180 \text{ \AA}$  in that same order is much noisier than the segment displayed due to vignetting in the camera and to the dropping echelle blaze function. The region displayed is also one of the two most line-free regions in the bandpass covered by the CCD spectrum. The ease of determining the continuum in the CCD spectrum as compared to the echelle spectrum should be obvious to the reader.

The CCD frames were divided by a flat field to remove the pixel-to-pixel variation, then summed over a 5–7 pixel height corresponding to the  $2''\text{--}3''$  seeing. The resulting one-dimensional spectra were divided by that of a standard blue star to remove the slight curvature of the grating blaze. The continua were defined by plotting the entire  $270 \text{ \AA}$  spectral range compressed onto a television monitor and picking out with a cursor the highest points every  $20\text{--}40 \text{ \AA}$ . The spectra were then flattened to a constant continuum level, and equivalent widths were measured using the cursor to trace the line profile and consulting the Arcturus atlas (Griffin 1968) for blends. I am indebted to A. Saha for the use of this software. The measured  $W_\lambda$  for lines included in the echelle analyses of M13 or M71 plus one added weak line of Fe I are listed in Table 5. Colons denote uncertain values; double colons are even more blended lines. It was a very sobering experience to look at these high-resolution and high-precision spectra.

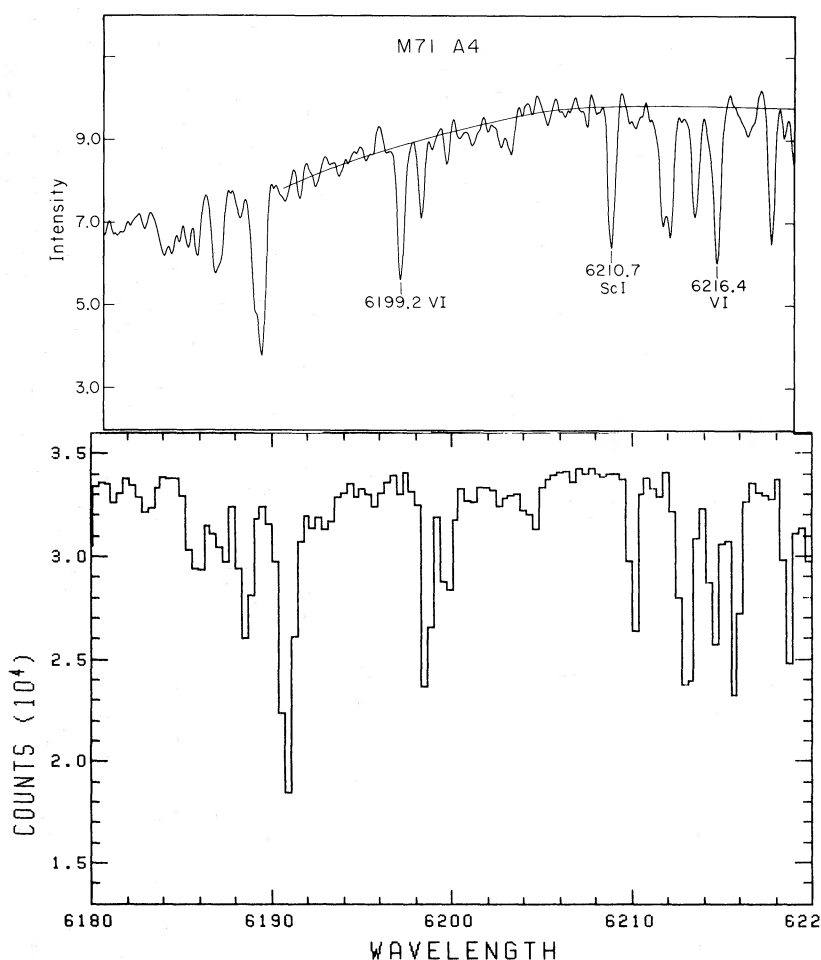


FIG. 4.—The spectrum of M71 A4 over a 40 Å bandpass (6180–6220 Å). The upper panel is the original tracing of an echellogram taken on the KPNO 4 m telescope through an image intensifier lens coupled to a IIIa-J photographic plate. The vertical intensity scale can be multiplied by an arbitrary constant for this panel. The thin line is the original choice of continuum. The lower panel is a CCD spectrum observed using the red camera of the Double Spectrograph on the 5 m telescope.

Figure 5 shows independent measurements of  $W_\lambda$  from two spectra taken consecutively of M13 III-56. The open circles are the blended lines, and a 45° line is drawn. Even at this resolution and signal-to-noise ratio, one of the sets of measurements has a systematically lower choice of the continuum than the other, but the general agreement and small scatter are very encouraging.

Figure 6 (*left*) displays the comparison of the echelle equivalent widths from Pilachowski, Wallerstein, and Leep (1980) with our new CCD  $W_\lambda$  for M13 III-56, while Figure 6 (*center*) shows the same for M5 I-68, and Figure 6 (*right*) shows echelle  $W_\lambda$  from Cohen (1980) for M71 A4 versus those listed in Table 5. The open circles in Figures 6 (*left*) and 6 (*center*) denote blended lines as judged from the CCD spectra; the filled circles indicate lines whose  $W_\lambda$  should be reliable. As might be

expected, for the lower metallicity clusters the continuum placement in the echelle spectra can be either overestimated or underestimated. Most of the scatter is probably due to the much lower precision of the image tube echelle spectra. In Figure 6 (*left*), the data scatter distressingly broadly about the 45° line, but there is no obvious mean departure from equality for lines with  $W_\lambda$  less than 120 mÅ. The equivalent widths for the stronger lines appear to be too large in the echelle measurements, but such lines are not used in most abundance analyses in any case. Figure 6 (*center*), on the other hand, shows that the  $W_\lambda$  given by Pilachowski, Wallerstein, and Leep (1980) for M5 I-68 are systematically too large independent of  $W_\lambda$ . In Figure 6 (*right*), asterisks denote lines blueward of 6240 Å, while open circles denote lines redward of that wavelength. The equivalent widths of lines in the bluer echelle order in M71 A4 are systemati-



TABLE 5  
 $W_{\lambda}$  FROM CCD SPECTRA

CLUSTER STAR ( $V-K$ ) <sub>0</sub>	M13 III-56 3.31	M5		M71		
		I-20 3.04	I-68 3.24	S 3.12	A9 3.37	A4 3.55
6150.2 V I ...	86	64	120	126	160	242
6151.6 Fe I ...	95	96	95	124	123	116
6154.2 Na I ...	27:	21	20	52	45	55
6157.7 Fe I ...	68	75	75	86	101	92
6160.7 Na I ...	...	...	...	...	89:	...
6161.3 Ca I ...	...	...	...	...	133:	...
6162.2 Ca I ...	224:	235:	248:	252:	254	326
6165.3 Fe I ...	27	37:	28:	47	60	56
6166.4 Ca I ...	78	89	101	113	126	135
6199.2 V I ...	99	85:	115:	157::	163:	157:
6200.3 Fe I ...	111	128	119	128::	130	95:
6210.7 Sc I ...	41	33	67	78	113	144
6216.4 V I ...	113	95:	139:	135:	172	188
6219.3 Fe I ...	149	...	150	160::	156	160
6224.5 V I ...	64	37	114	122	138	194
6226.5 Fe I ...	17	30	41	61	59	81
6229.2 Fe I ...	64	59	...	71:	87	...
6232.7 Fe I ...	...	...	...	...	123::	...
6233.2 V I ...	...	...	...	...	100::	...
6237.3 Si I ...	20	29	20	45:	38:	...
6238.4 Fe II ...	33:	34	22	41:	40:	...
6245.6 Sc II ...	76::	47::	75::	70::	100:	65:
6246.3 Fe I ...	125::	117::	141::	105::	113:	117:
6247.5 Fe II ...	29	26	29	29	39:	19
6251.8 V I ...	97::	50::	131::	118::	154:	162:
6252.7 Fe I ...	154::	169::	213::	125::	135:	164:
6254.3 Fe I ...	143	178	152	158:	169	163
6261.1 Ti I ...	127	122	165	160	176	240
6265.1 Fe I ...	141	157	166	163:	157	149
6266.3 V I ...	44	25:	83	79	111	131
6270.2 Fe I ...	68	95	87	89:	102	105
6274.7 V I ...	65	...	147	89	113	148
6300.3 O I ...	...	41::	...	...	...	...
6301.5 Fe I ...	88::	103::	106:	...	...	91::
6302.5 Fe I ...	94::	71::	74::	105::	104::	110::
6309.9 Sc II ...	34:	21:	32	61:	58:	56:
6314.7 Ni I ...	125:	125:	101:	126:	141::	143:
6318.0 Fe I ...	156	171	181	176:	195::	200:
6322.7 Fe I ...	125	97	111	120	132:	143
6327.6 Ni I ...	81	91	93	102:	102:	94:
6330.1 Cr I ...	68	58	95	86:	97:	117
6335.4 Fe I ...	166	163	206	196::	195:	178:
6336.1 Ti I ...	...	...	...	79::	91::	99::
6336.8 Fe I ...	93::	...	...	100::	113::	95::
6353.8 Fe I ...	14	17	30	43:	49	72:
6355.0 Fe I ...	101	118	106	128	115	132
6357.3 V I ...	...	...	11	...	10	37
6362.9 Cr I ...	61	46:	69	120:	91::	158:
6363.8 O I ...	19::	12::	28:	33::	72::	66:
6390.5 La II ...	34	...	...	29	...	50
6392.5 Fe I ...	39::	...	...	83::	...	75:
6393.6 Fe I ...	151	...	...	170::	...	202:

cally too small, while those in the redder order (except for two lines near the edge of the order) scatter closely about the  $45^\circ$  line.

If we assume that the bluer orders in the M71 stars have systematically underestimated continua and hence equivalent widths, this effect should be visible in the

echelle analyses by splitting the set of lines at some wavelength and comparing the mean abundances for each group. If we perform this test for Fe I such that there are equal numbers of lines in each group, the split occurs at 6000 Å, and the longer wavelength group gives abundances systematically higher by 0.07 dex for four

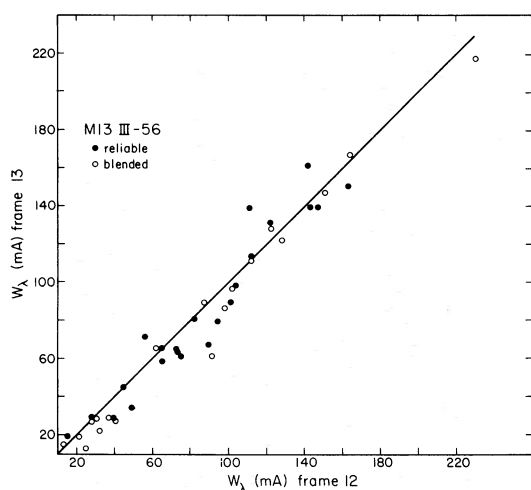


FIG. 5.—Equivalent widths measured from two successive CCD frames of M13 III-56 are compared. The solid line corresponds to equal  $W_\lambda$  in each spectrum. The filled circles denote unblended lines, while the open circles are blended absorption lines at this spectral resolution.

stars. For a split made at  $6240 \text{ \AA}$ , as suggested by the CCD data, the longer wavelength group (with one-third of the total Fe I lines) gives abundances higher by 0.17 dex.

These spectra clearly demonstrate that systematic continuum placement errors have occurred in the previous echelle analyses. This is not surprising, given that the continuum must be determined over several points within each echelle order. Each order is reasonably exposed only over a segment  $50 \text{ \AA}$  wide, and even within that small range large variations in the echelle reflectivity occur.

We now determine the abundance of M71 relative to the metal-poor clusters, where as discussed in § IVa we have confidence in the echelle procedure. Figure 7 (*left*) shows Fe I lines (*filled circles*) and V I lines (*open circles*) from Table 5 for M5 I-68 and M13 III-56. These two stars have  $(V-K)_0$  of 3.31 and 3.24 and  $M_{\text{bol}}$  of  $-2.96$  and  $-3.07$ , respectively. M5 I-68 appears to have slightly stronger Fe I lines and considerably stronger V I lines. As the Fe I lines vary only slightly with temperature while the V I lines become much stronger as  $T_{\text{eff}}$  declines, we find that M5 has  $[\text{Fe}/\text{H}] = 0.2 \pm 0.1$  dex with respect to M13, and M5 I-68 is in fact about 50 K cooler than the M13 giant. Figure 7 (*right*) shows a comparison of M71 A9 [with  $(V-K)_0 = 3.37$  and  $M_{\text{bol}} = -1.38$ ] with M13 III-56. Based on the V I lines, the M71 star is cooler by about 100 K. Looking only at the weakest neutral iron lines, the difference in observed line strengths only implies M71 has  $[\text{Fe}/\text{H}] = +0.7 \pm 0.1$  dex relative to M13. We can ignore any difference in microturbulent velocity and use the mean of the corrections for differing surface gravity and metallicity from Table 5 of Cohen (1978) and from Table 4 of Cohen (1980) to find  $\Delta[\text{Fe}/\text{H}] = 0.85$  dex for M71 with respect to M13, or  $[\text{Fe}/\text{H}]_\odot = -0.8$  dex for M71.

Frogel, Persson, and Cohen (1979) give effective temperatures and surface gravities for the three M71 stars with CCD spectra, which we adopt. If we follow exactly the procedure of my earlier echelle abundance analysis (Cohen 1980), then from the 11 Fe I lines with CCD  $W_\lambda$  which are included in Cohen (1980) (two of which must be excluded as  $W_\lambda > 170 \text{ m\AA}$ ), we obtain  $[\text{Fe}/\text{H}]_\odot = -0.8$  for M71 S,  $-0.9$  for M71 A9, and  $-1.0$  dex for M71 A4. Also excluding the extremely blended Fe I line at  $6336.8 \text{ \AA}$ , which leads to a systematically lower abundance than the other iron lines, yield  $[\text{Fe}/\text{H}]_\odot = -0.75$ ,

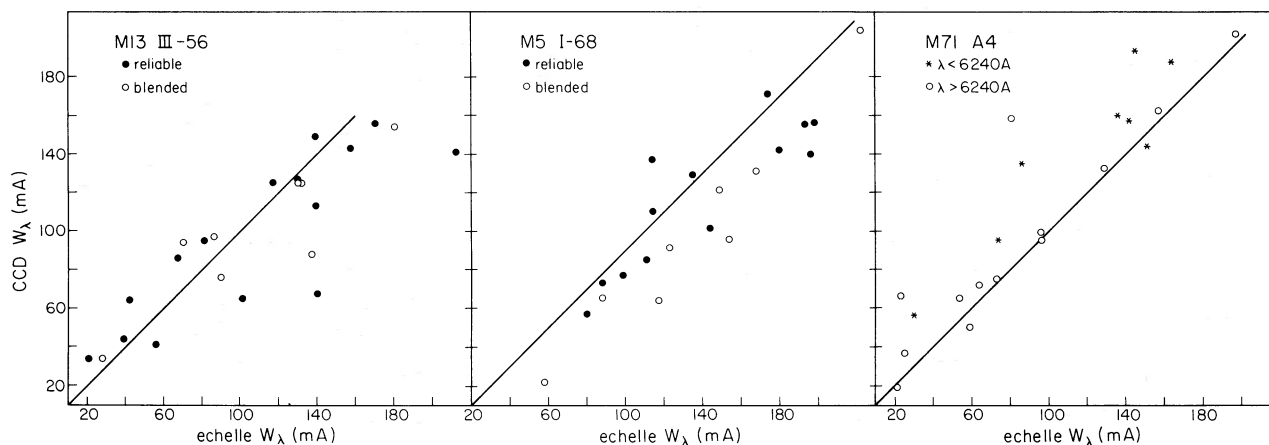


FIG. 6.—Equivalent widths measured from high-precision CCD spectra are compared with those measured from echelle spectra for M13 III-56, M5 I-68, and M71 A4. The solid line is the relationship for equal  $W_\lambda$ . In the first two panels, the filled circles are unblended lines, while the open circles denote blended features. In the last panel, the asterisks are lines blueward of  $6240 \text{ \AA}$ , while the open circles are redward of the wavelength.

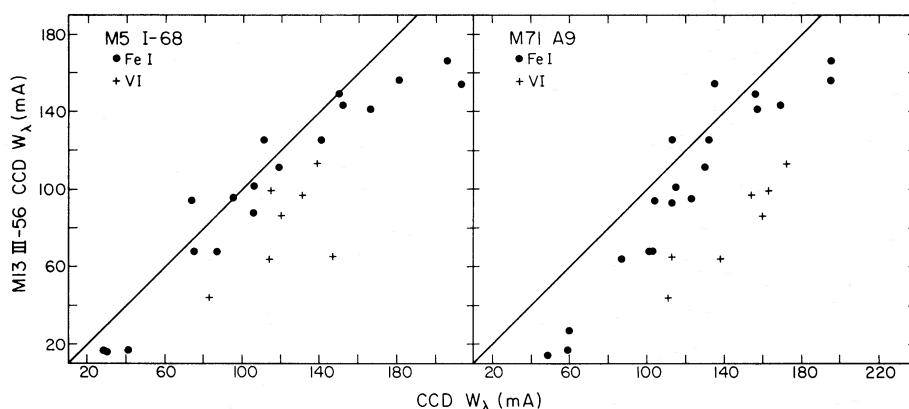


FIG. 7.—The  $W_\lambda$  measured for lines in M13 III-56 are compared with  $W_\lambda$  for the same features in M5 I-68 (*left*) and in M71 A9 (*right*). The solid line is that for equal  $W_\lambda$ . Filled circles denote Fe I lines, while crosses symbolize V I lines.

−0.8, and −0.85 dex for the 3 M71 stars with high precision CCD spectra.

Thus, the high-dispersion weak line analysis of our new CCD data gives results in concordance with the low-dispersion scans presented earlier in this paper. The abundance with respect to the Sun of M71 lies between −0.85 and −0.65 dex. We adopt −0.75 dex, with 47 Tuc at −0.7 dex.

#### VI. SUMMARY

Spectral scans of a sample of probable members of five metal-rich globular clusters (NGC 5927, 6171, 6352, 6553, and 6637) and three calibrating clusters (NGC 104, 3201, and 6838) have been obtained with a digital linear array detector. New radial velocities for the program globular clusters were determined. The spectral scans have been analyzed, with the aid of published optical and infrared photometry, to yield metal abundances relative to 47 Tuc. These are used to calibrate the  $Q39$  ranking by Zinn (1980) defined from his integrated light photometry of approximately 80 globular clusters.

The combination of the present crude analyses and

my previously published model atmosphere analyses for metal-poor clusters is used with Zinn's photometric ranking parameters to determine the metallicity of 47 Tuc. A high abundance is obtained ( $[Fe/H]$  between −0.6 and −0.8 dex with respect to the Sun). A new set of high-resolution, high-precision CCD spectra are described which give abundances consistent with the lower dispersion scans. Equivalent widths measured from these CCD spectra demonstrate that systematic errors were made in the placement of the continuum in previously published echelle analyses of giants in metal-rich globular clusters (Cohen 1980 included). A calibration of the Zinn  $Q39$  index over the entire metallicity range spanned by globular clusters is offered. This calibration indicates a metallicity scale for the galactic globular clusters which is much closer to that in general use several years ago, before the echelle analyses were published. However, the new calibration given here rests on a sound foundation over the entire metallicity range.

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#### APPENDIX A

Radial velocities were measured from spectra of the integrated light of five globular clusters and from a sample of six randomly chosen bright red stars near the center of NGC 6569. The intensified reticon scans used were of relatively high dispersion and had twice the resolution of the spectra in the main body of the present paper. They cover the wavelength region 3500–4200 Å. Only one of these clusters is listed in Webbink's (1981) compilation, and the agreement is poor. Five of the clusters are included in the SHM study, but in three of these cases the agreement is poor also. The errors listed in Table 6 reflect the differences between measurements from the scans of individual strong features versus cross

TABLE 6  
NEW RADIAL VELOCITIES

Cluster (NGC)	$V_r$ (km s <sup>−1</sup> )	Cluster (NGC)	$V_r$ (km s <sup>−1</sup> )
5694 .....	−117 ± 10	6342 ...	+113 ± 30
5897 .....	+140 ± 40	6558 ...	−174 ± 60
5946 .....	+170 ± 10	6569 ...	−15 ± 20

correlation of the entire scans (omitting the region 3955–3985 Å) without ideal templates.

## APPENDIX B

## M4

Low-dispersion scans identical to those discussed in §§ II and III of this paper were obtained for eight members of M4 in 1982 September. The measured pseudoequivalent widths are listed in Table 7. Using the reddening adopted in Frogel, Persson, and Cohen (1983) of  $E(B - V) = 0.36$  mag, the deduced abundance is half that of 47 Tuc. However, the above authors advocate increasing the reddening of M4 somewhat above this value, and with  $E(V - K)$  0.30 mag larger, the deduced abundance is equal to 47 Tuc. Notice that increasing  $E(B - V)$  increases the abundance derived via the strength of absorption features but decreases the abundance desired from infrared photometry. Thus  $[M/H]$  of M4 must be  $-0.9 \pm 0.2$  dex. This is equal to that obtained from TiO photometry [with an adopted  $E(B - V)$  of 0.42 mag] by Mould, Stutman, and McElroy (1979). The RR Lyrae stars give, via  $\Delta S$ , an abundance of  $-1.4$  (Smith and Butler 1978), but Smith (1983) states that the correction for the interstellar Ca II absorption used by Smith and Butler is probably too large.

TABLE 7  
MEASURED  $W_\lambda$  FOR M4

Star	$(V - K)_0$ (mag)	Mg (Å)	Fe* (Å)	Na (Å)
2626 ...	2.87	4.7	3.0	2.4
2608 ...	2.89	4.7	3.5	2.2
1605 ...	2.92	4.3	3.2	2.3
1403 ...	3.02	4.4	3.4	2.8
3612 ...	3.14	4.6	4.1	3.2
3624 ...	3.20	5.9	3.9	1.8
2617 ...	3.33	5.5	4.4	2.1
3209 ...	3.41	6.9	5.1	2.9

Perhaps the unusually blue horizontal branch, given the metallicity suggested here, directly caused Zinn (1980) to underestimate the metallicity of M4; he deduced an abundance of  $-1.46$  dex. These arguments are discussed in detail in Frogel, Persson, and Cohen (1983) and Frogel, Cohen, and Persson (1983).

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