THE OVERALL ABUNDANCES OF GLOBULAR CLUSTERS

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1. INTRODUCTION

At a meeting on globular clusters held five years ago, Zinn(1981) made the following comments:

> "In summary, there are clearly large differences in metal line strength between 47 Tuc giants and the giants in the other clusters. These differences suggest that there are substantial differences in metal abundance, which conflicts with the measurements obtained from echelle spectrograms, and there appears to be no simple way of reconciling these results. Until this is done, the metallicity scale for globular clusters hangs in limbo."

Is this still true? Can we understand the reasons why different methods for getting the abundances of globular cluster stars give different results? It now appears that a plausible reason for some of the discrepancy between the high dispersion results and the results given by other methods has been found. I will give this explanation subsequently in the talk. However, prior to this, I will briefly discuss the various methods used to obtain abundances for individual cluster stars and for clusters as a whole. There are a whole variety of methods ranging from observations of individual stars to studies of the geometry of color magnitude diagrams to measurements of the integrated light of the cluster. Zinn and West (1984) have intercompared the results from many of these methods, and their conclusions are very similar to mine.

2. SPECTROSCOPIC OBSERVATIONS OF INDIVIDUAL STARS

2.1 High Dispersion Spectroscopy.

The queen of the methods is clearly that of high dispersion spectroscopy. This is virtually the only method which allows us to find the abundances of individual elements. The first high dispersion

J. E. Grindlay and A. G. Davis Philip (eds.),
The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, 79–92.

analyses of globular cluster stars used photographic spectra obtained with the coude' spectrograph on the 200 inch telescope. Helfer, Wallerstein and Greenstein (1959) found [Fe/H] < -2.0 for M 92 and < -1.3 for M 13. Owing to the faintness of the stars, exposure times of over 12 hours were needed to obtain the spectra. Probably because of this, stars in other globular clusters were analyzed only after about twenty years had passed. Cohen (1978, 1979) found [Fe/H] = -1.6 for M 13, -1.8 for M 3, -2.35 for M 92 and -2.20 for M 15, in essential agreement with the previous results. Her subsequent work for M 67 (Cohen 1980a, 1980b), where she obtained [Fe/H] = -0.3, did not raise any eyebrows, but the result for M 71 was much more surprising and controversial, since she obtained [Fe/H] = -1.3. While many people probably felt that the M 67 result was a bit low, it was not alarmingly so and did give a lot of weight to the M 71 value. Cohen's M 71 result was also in agreement with a study of 47 Tuc, where Pilachowski, Canterna and Wallerstein (1980) found [Fe/H] = -1.2.

The high dispersion work continued with analyses of other globular clusters, including Omega Cen and M 22, and the very extensive paper by Pilachowski, Sneden and Wallerstein (1983) gave results for stars in seven clusters as well as re-analyzing other data. Pilachowski (1984) gives the results of high dispersion analyses for stars in 24 clusters. Stars in additional clusters have been studied by Geisler (1984) but few details of the analysis are given.

2.2 Low Dispersion Spectroscopy

This can be subdivided into two sets of observations, the ΔS measurements and the rest. The ΔS system, invented by Preston and used extensively by Butler and, more recently, by Smith (see Smith 1984a for a review), defines the difference between the spectral types of an RR Lyrae variable, judged from the K line and judged from the hydrogen lines, to be the quantity ΔS. For an individual star, ΔS does depend on pulsation phase and so, for abundance work, observed ΔS values have to be corrected to a constant phase. ΔS ranges from about 14 for metal poor stars to 0 for metal rich ones. The K line is chosen as the metal abundance indicator because there are few other metallic lines easily visible in low dispersion spectra of metal poor RR Lyraes. In practice, a vexing problem is presented by the interstellar K line, whose velocity and strength both affect ΔS.

In most applications, the ΔS measurements have been calibrated in terms of [Fe/H] from studies of field RR Lyraes (Butler 1975), although Manduca (1981) has published a spectrum synthesis calibration. The two calibrations are in reasonable agreement except at the metal-rich end, where Manduca finds that a given value of ΔS corresponds to a lower metal abundance.

The ΔS method has been applied to numerous clusters, Smith (1984b) giving a list of abundances. The most metal rich clusters in the list are NGC 6712 and NGC 6723, at [Fe/H] = -0.57 and -0.68, respectively. Unfortunately the method cannot be used for M 71, which does not contain RR Lyraes, and the results for 47 Tuc are uncertain. While there are three RR Lyraes near 47 Tuc, the question of membership is uncertain for at least two of them and the abundance is not settled for the third star, V9 (Smith 1984b). Smith finds that V9 has an abundance of [Fe/H] = -0.8 ±0.2 but Keith and Butler (1980) found it to have -1.1 ±0.14.

The current tendency with low dispersion digital spectra is to compute spectral indices (e.g. Suntzeff 1980, Canterna, Harris and Ferrall 1982, Burstein, Faber and Gonzalez 1986) although graphical comparisons of observation and calculations are also made. The indices are plotted versus a reddening corrected color. These index, color diagrams are then used in either of two ways. In the first way, the calibration is provided by other observations e.g. high dispersion spectroscopy or ΔS. In this method, the low dispersion data are essentially being used to interpolate between the standard clusters. Alternatively, the low dispersion spectra provide a "ranking" of the cluster abundances. The second means of calibration is again a spectrum synthesis one. The synthetic spectra of various models are analyzed in the same way that the observations are and the resulting indices and colors of the models are directly compared with the observations. This calibration method has advantages and disadvantages. It is clearly a very flexible method, since the synthetic spectra can be computed for any desired abundance, temperature and gravity. It can also utilize the results of stellar interior calculations. On the other hand, without carrying out detailed checks of the synthetic spectra, the accuracy of the results is not known. This is particularly true for the analysis of observations in the ultra-violet of metal-rich stars.

Some of these data illustrate the abundance differences found using high and low dispersion methods. Bell (1984) gives synthetic spectra for the wavelength interval 3600-4600 Å, intended to represent the spectra of stars on the giant branches of clusters with metal abundances [A/H] = -0.5, -1.0, -2.0 and -3.0. These spectra have been used to compute indices which can be compared with the observations of Canterna, Harris and Ferrall. It is quite clear from plots of M(V) versus indices such as mHK, mCa, mG and mCN (which are measures of the strength of H and K, Ca I 4226, the G band and the 3883 Å CN) that the 47 Tuc stars always have stronger spectral features than do NGC 288 stars. The calibration, made on the basis of synthetic spectra, suggests that 47 Tuc has a metal abundance of [M/H] = -0.8 while NGC 288 has an abundance of perhaps -1.1 and M 15 has [M/H] = -2.0. The results from high dispersion work quoted by Pilachowski (1984) for 47 Tuc are -1.09 ±0.2, -1.0 ±0.2 and -0.95 ±0.25 and, for NGC 288 and M 15, the results quoted are -0.95 ±0.15 and -1.76 ±0.25, respectively. If anything, this suggests that 47 Tuc is more metal poor than NGC 288, contrary to the low dispersion spectroscopic result.

Synthetic spectra, as shown by Bell (1984), were the main reason why it was very hard for me to accept a very low abundance for 47 Tuc. When we (Dickens, Bell and Gustafsson 1979) were studying 47 Tuc we compared our synthetic spectra with our low dispersion observations. It was apparent that the Ca I 4226 line in the cooler stellar spectra was always too weak in the spectra computed with [A/H] - 0.5 and always too strong when compared with spectra computed for [A/H] = -1.0.

3. PHOTOMETRIC OBSRVATIONS OF INDIVIDUAL STARS

3.1 The UBV system.

It is certainly possible to obtain some idea of the metal abundances of a star from its ultra-violet excess and this result has been employed for clusters (Sandage 1970, Carney 1979). However, I think that this approach is probably now more useful in exploratory work on field stars than it is for cluster stars.

3.2 The Washington system.

This system uses four filters, C, M, T_1 and T_2. The filters are centered at approximately 4000, 5000, 6000 and 8000 Å and have FWHM of 1000 Å. This width makes the system a potentially attractive one for observing faint stars. The index (T_1 - T_2), corrected for reddening, is used to deduce temperatures while the index (M-T_1) is intended to serve as an abundance indicator. It has been stated that (C-M) is an indicator of molecular band strength as well as a general abundance indicator. I do not believe that the last conclusion is supported by any calculations and more recent observational work (Geisler 1986a) seems inconclusive on this point.

A plot of (M-T_1) versus (T_1 - T_2), derived from synthetic spectrum calculations, using the photoelectric sensitivity functions of Geisler and Kapranidis (1983), shows that the abundance sensitivity is relatively weak, particularly for metal poor stars ([M/H] <-1.0). Much greater abundance sensitivity is seen in the (C-M), (T_1 - T_2) diagram.

3.3 The DDO system.

Hesser, Hartwick and McClure (1977) found cluster abundances from the positions of stars in C(38-42), C(45-48) and C(42-45), C(45-48) diagrams, using a calibration based upon M 92, M 13 and M 71 as standard clusters. Janes(1979) provided a calibration based upon the difference in C(45-48) between a cluster star and a Population I star of the same C(42-45).

Many of the DDO system filters were chosen to measure the strengths of molecular bands e.g. the 3883 and the 4215 CN bands (the C38 and C41 filters) and the G band (the C42 filter). This is a photometric system which, like high dispersion spectroscopy, can be used to find the abundances of particular species such as CH and CN.

In particular, any use of the C(42-45), C(45-48) diagram which is based upon an empirical calibration does assume that the depletion of carbon is the same in all clusters of that overall metal abundances. Bell, Dickens and Gustafsson (1979) used this diagram to assess the carbon abundances of stars in NGC 6397 and M 92.

3.4 The Searle and Zinn (1978) observations.

This method uses spectral scans of stars in 18 pass bands. After correction for reddening, a least squares fit is made to the fluxes between 5000 and 7620 Å. This fit is used to define a fiducial continuum and the magnitude differences between this continuum and the observed magnitude are summed over the interval between 3800 and 4840 Å, to yield the quantity S. The mean value of S at M(V) = -1.0 is <S> and abundances are found from [Fe/H] = 3.73 <S> - 3.05.

This system has been analyzed by Bell and Gustafsson (1983) using synthetic spectra. Their results agree with those of Searle and Zinn to within +0.35 in [M/H] for all clusters in the sample. The Bell and Gustafsson result for M71 is [M/H] = -0.5.

This system is a very interesting one, giving at least the possibility of searching for anomalies in the abundances of different elements. It is unfortunate that one or two galactic clusters were not observed in order to tie down the metal-rich end.

3.5 TiO Observations.

TiO bands are seen in Population I stars with T_{eff} < 4000 K. The strengths of the TiO lines, do, of course, depend strongly on the temperature as well as the abundances of the star. A model with (T_{eff}/log g/[A/H]) 3800/0.5/-0.5 is found to have a stronger TiO line spectrum than 4000/0. 75/0.0 has (the models referred to are either those published by Bell et al. 1976 or have been computed using the programs of Gustafsson et al. 1975). The TiO lines in the spectrum of the model 4250/1.5/0.0 are over ten times weaker than those of 4000/0.75/0.0.

Mould and his collaborators (see Mould and Bessell 1982) have used TiO line strengths to obtain cluster abundances. They use two filters, at 7120 Å and 7540 Å, to measure TiO band strength and another filter at 10175 Å, which is used with the 7540 filter to give a continuum gradient. The observations of 47 Tuc give [M/H] = -0.5 ± 0.1 whereas measurements of M 71 give [M/H] = -0.3 ±0.2, using the calibration of Johnson, Mould and Bernat (1982) in both cases. The important feature of this work is that it gives an abundance ranking for the most metal rich clusters. The derivation of abundances does depend upon the assumption that [Ti/H] = [O/H] = [A/H], unless the abundances of the individual elements are known from other work. In such cases a correction to the uniform depletion abundances can be found provided the depletion of oxygen by CO and SiO formation can be allowed for. The calibration by Johnson, Mould and Bernat uses gravities which are about 1.0 dex higher than those appropriate for Population I giants and globular cluster giants. In view of this and the dependence of TiO band strength on surface gravity at a given T_{eff} and abundance, and the great sensitivity of TiO band strength to details of the models, it is possible that the calibration of the models could be slightly improved.

3.6 The Strömgren system.

It may appear strange to discuss a system which has been used only sparingly in globular cluster research apart from work on blue horizontal-branch stars (see Philip 1987). The observations of Gustafsson and Ardeberg (1981) were used to find an abundance for 47 Tuc while the photometry of turn off region stars in NGC 6397 by Ardeberg, Lindgren and Nissen (1983) does confirm the very low abundances of this cluster. If more precise photometry of cluster stars in the turn off region can be obtained on the Strömgren system (and the Thuan-Gunn system), it would be very valuable in studies of the ages of the clusters and in studies of the properties of very metal-poor faint field stars.

4. THE PERIODS OF RR LYRAE STARS

Sandage (1982) has extended earlier work by Arp (1955) to show that the mean periods of the RR Lyrae variables in a cluster are strongly correlated with the cluster abundance. In addition to providing another ranking parameter, this result also forms a challenge to those calculating stellar interior models.

5. COLOR MAGNITUDE DIAGRAMS

A number of properties of a cluster color-magnitude (CM) diagram can be used as abundance indicators. These are: S, the slope of the line from the horizontal-branch - subgiant branch intersection to a point 2.5 mag. in V up the giant branch; $(B-V)_{o,g}$, the intrinsic color of the subgiant branch at the level of the horizontal branch; ΔV, the V magnitude difference between the HB and the GB measured at $(B-V)_o$ = 1.4.

In practice, the calibration of these quantities is carried out using clusters of "known" abundance although it could be done using a combination of stellar evolution and stellar interior techniques (some authors have compared their calibration with the stellar evolution results).

There are some difficulties associated with the use of these indicators. Any observed color, such as $(B-V)_g$, must be corrected for reddening before use in this way. This requires knowledge of both

E(B-V) and the color excess ratios for other colors e.g. E(J-K)/E(B-V) for (J-K) and so on. (Alternatively, if one is confident enough of the cluster abundance, $(B-V)_{o,g}$ could be used to obtain the reddening.) A scarcity of stars on the GB may affect the determination of ΔV.

Rather than give a resume of current results for these indices, I simply refer to Bell and Gustafsson (1983) which gives plots of the abundance indicators versus abundances obtained from an analysis of Searle and Zinn's (1978) photometry, and go on to discuss a variant of this approach.

Frogel, Cohen and Persson (1983 and references cited therein, hereafter FCP) and their collaborators have published JHK and CO and H_2O measurements for giant stars in about 60 clusters. The CO measurements are a rich source of astrophysical data. The JHK colors have been used to determine two quantities: $(J-K)_o$ is the color of a cluster GB read at $M(K_o) = -5.5$; log T_{eff}(GB) is obtained at M(Bol) = -3.0. The color $(J-K)_o$ is thus analogous to $(B-V)_{o,g}$ except that cluster distances must be available. It refers to more luminous stars. FCP have calibrated their work using [Fe/H] values of Cohen (1983) and the integrated light measurements of Zinn (1980).

6. INTEGRATED LIGHT MEASUREMENTS

Zinn (1980) has made integrated light observations of 79 clusters, using filters very similar to those of the uvgr system (Thuan and Gunn 1976) and two filters which measure the absorption in the region of the H and K lines. These filters are centered at 3910 and 3955 Å, respectively and have FWHM of 180 and 90 Å. A measurement of the H and K lines is needed to study clusters which may be more metal deficient than M 92. The data are used to construct an index, Q39, which is reddening free and a measure of metal line strength. The Q39 indices for M 92 and 47 Tuc are -0.047 and 0.304, respectively. In a later paper, Zinn and West (1984) have measured other spectral features in integrated light and have correlated these features with Q39. Zinn and West also give a convenient table of abundances found by various means and discuss the anomalous abundances which some clusters have when measured in some systems.

The calibration of this quantity is again done using a set of calibrating clusters and there will again be the problem with interstellar H and K lines. Any measurement of the integrated light from a globular cluster is obviously affected by the relative numbers of stars in the different regions of the HR diagram. If we make measurements in the IR, for example, the giant stars will supply the most light, whereas UV measurements are affected by the hotter HB stars. Unusually large or small numbers of these stars will affect the measurements of clusters in our galaxy and will give results which are discordant with those given by other methods. Smith (1984b) has derived a correction to Q39 abundances based upon the relative numbers of blue and red horizontal-branch stars. While such a correction does improve the fit between Q39 and ΔS abundances, it is not clear if such a correction is valid for clusters of all abundances. Manduca (1983) has studied this problem using synthetic spectra. While the effect of the HB is undeniably a disadvantage, this does give us an idea of the problems likely to be encountered in analyzing observations of extragalactic globular clusters.

7. WHY WERE DIFFERENT RESULTS OBTAINED FOR METAL RICH CLUSTERS?

During the period 1980-1985, there were some criticisms of the high dispersion results (c.f. the discussion of several papers at IAU Colloquium 68 in addition to the comments by Zinn quoted above) but the only papers by high dispersion spectroscopists which, to my knowledge, criticized other high dispersion results were those of Cohen (1983) and Bessell (1983). Cohen's criticism was not based on high dispersion spectroscopic data but used some moderate dispersion spectral scans. She found that her clusters, which included M 71, 47 Tuc, NGC 3201, NGC 6171 and NGC 6352, had abundances which differed by 1 dex while Pilachowski, Sneden and Green (1981) found all these clusters to have an abundance of -1.1 ± 0.2 dex. Cohen also argued that the abundance of 47 Tuc was -0.6 ±0.1, although this result was again not based on high dispersion spectroscopy.

Why are the high dispersion results different from those given by other methods? At least part of the answer appears to be given in a recent paper by Geisler (1986b), who has obtained new spectra of four of the six stars observed by Pilachowski, Canterna and Wallerstein (1980) (hereafter PCW) and Cottrell and Da Costa (1981). While the data were obtained with an echelle spectrograph, Geisler has combined the data from a number of different orders to obtain a single spectrum covering 1200 Å. The presence of TiO bands in the spectrum of both the PCW stars is quite evident. While PCW noted the presence of TiO bands at wavelengths longer than the limit of their tracings, they did not recognize it as an absorber in the wavelength region which they analyzed. Spectrum synthesis calculations reveal that TiO lines are present over the wavelength interval 5000-7000 Å that is used for much of the high dispersion spectroscopy.

While a curve of growth analysis of a star is a fairly direct process to undertake, its use of the equivalent widths of weak lines does place very heavy demands upon the quality of the observational data. The dispersion employed must be high enough that the instrumental profile does not significantly add to the broadening of the spectral lines and, in addition, the signal/noise must be high enough that the continuum is well defined. In a situation where TiO lines are present in the spectra but are not allowed for in the measurements, it is in general likely that the continuum will be wrongly drawn and that the equivalent widths measured for the lines being analyzed will be too small. This is not true in all cases. If an iron line coincides with one of the stronger TiO lines, such as a Q branch line of $Ti^{48}O$, then the blending will cause the measured equivalent width to be too large. The possibility of this occurring for the [OI] lines at 6300 and 6363 Å must be examined. The effect of this blending will, of course, depend upon the Ti and O abundances of the star and will also depend strongly upon its temperature. In fact, the bluest (B-V) color at which TiO bands are seen in the spectra of globular cluster stars has been used as an abundance indicator.

It also appears to be quite possible that the unsuspected presence of TiO bands has affected Cohen's original observations of the M 71 stars, since the objects which she observed all have $T_{eff} < 4100$ K and the wavelength interval covered (5200-6800 Å) contains numerous TiO bands. The M 67 stars which Cohen observed have T_{eff} greater than 4300 K and model calculations show that TiO lines would not be expected in their spectra. The models do, however, show a delicate balance between abundance and temperature. The TiO lines in the spectrum of 3800/0.5/-1.0 are quite weak and would be unlikely to affect equivalent width measurements of iron and other metal lines. It remains to be seen if models can predict the correct strength of TiO lines in Population I giants and confirm that TiO is present in sufficient strength in the spectra of 47 Tuc giants with an abundance of [Ti/H] = [O/H] = -0.8. Most of the critics of the high dispersion work did focus their criticism on the possibility of errors in continuum location, noting that the use of echelle spectrographs did make this problem a much more difficult one than it was with conventional spectra. Bell and Gustafsson (1982) remarked that there were systematic differences in equivalent width in lines in different echelle orders, in terms of how well they fitted the model atmosphere curve of growth. This problem may still be plaguing the analyses of the more metal rich stars.

8. ABUNDANCES - A RECOMMENDATION

At this point it seems appropriate to tabulate the abundances of individual clusters. In order to do this, the following sets of results are intercompared: the high dispersion results, taken from Pilachowski (1984); the ΔS results, from Smith (1984b); the infra-red CM diagrams results; the Q39 results from Zinn (1980); results from $(J-K)_0$, calibrated using the results of Bell and Gustafsson (1983). Some results from the TiO work of Mould are also quoted. The reddening (from Zinn 1980) is given, since the abundances which are derived from colors are reddening dependent, while both Q39 and ΔS must be affected by interstellar lines. The results are given in Table I. Clusters where only Q39 abundances are available are not tabulated. Comments on some individual clusters follow, when the results from the different methods are sufficiently different.

NGC 288: the low abundance from Q39 is probably caused by the very large number of blue horizontal branch stars;

NGC 362: the high dispersion abundance is slightly high;

NGC 4833: the high dispersion abundance is somewhat high;

NGC 5272 (M 3): the result from $(J-K)_0$ is slightly high;

TABLE I

Metal Abundances for Globular Clusters

Cluster	HD	ΔS	IR	Q39	(J-K)	E(B-V)
104(47 Tuc)	-1.09 -1.0 -0.95		-0.59	-0.64	-0.60	0.06
0288	-0.95		-1.13	-1.60	-0.90	0.
0362	-0.87	-1.15	-1.39	-1.18	-1.20	0.04
1261		-1.03	-1.24	-1.30	-1.00	0.
1851		-1.07	-1.26	-1.34	-1.00	0.06
1904 (M 79)		-1.43	-1.65	-1.73	-1.60	0.
2298		-1.50	-1.76	-1.84	-1.40	0.15
2808	-1.06		-1.48	-1.25	-0.90	0.22
3201	-1.00 -1.19	-1.33	-1.67	-1.41	-1.30	0.27
4590 (M 68)		-1.94	-1.96	-2.10	-2.00	0.02
4833	-1.37	-1.62	-1.94	-1.86	-1.80	0.34
5024 (M 53)	-1.90	-1.85	-1.98	-1.94	-2.20	0.02
5272 (M 3)	-1.57	-1.57	-1.47	-1.67	-1.20	0.02
5286			-1.85	-1.71	-1.60	0.24
5466	-1.60					
5634		-1.61		-1.87		0.04
IC4499		-1.33				
5897		-1.49	-1.74			
5904 (M 5)	-1.13 -1.2	-1.08	-1.49	-1.59	-1.30	0.03
5927			-0.18	-0.23	-0.50	0.42
6121 (M 4)		-1.24	-0.72	-1.40	-0.60	0.37
6171 (M 107)	-1.05	-0.83	-0.92	-0.97	-0.70	0.38
6205 (M 13)	-1.44	-1.03	-1.47	-1.70	-1.20	0.01
6218 (M 12)				-1.55		0.16
6229	-1.30			-1.48		0.01
6254 (M 10)	-1.32		-1.54	-1.68	-1.10	0.26
6266 (M 62)		-1.16		-1.26		0.48
6284		-0.91		-1.40		0.29
6304				-0.40	-0.10	0.49
6341 (M 92)	-2.06	-2.18	-2.01	-2.12	-2.00	0.03
6342				-0.47		0.46
6352	-0.80		-0.38	-0.66		
6362	-1.00	-0.95	-1.05	-1.06	-0.70	0.10
6397	-2.21		-1.84	-2.17	-1.90	0.16
6402 (M 14)		-1.11		-1.49		0.59
6637 (M 69)			-1.20	-0.49	-0.70	0.10
6656 (M 22)	-1.78 -1.94 -1.67	-1.70	-1.81	-1.72	-1.50	0.37
6681 (M 70)		-1.23		-1.62		0.08
6712		-0.57		-1.14	-0.70	0.39
6715 (M 54)		-1.27		-1.41		0.15
6723	-1.10	-0.68		-1.26		0.05
6752	-1.32		-1.35	-1.55	-1.20	0.00
6838 (M 71)	-1.30 -0.81 -1.07 -0.7 -0.57		-0.60	-0.40	-0.40	0.26
6981 (M 72)		-1.27		-1.56		0.07
7006			-1.55	-1.53	-1.30	0.05
7078 (M 15)	-1.76	-2.04	-2.21	-2.07	-2.40	0.08
7089 (M 2)		-1.43		-1.75		0.03
7099 (M 30)		-1.96		-2.15		0.01

The second, third, fourth, fifth and sixth columns of the table are metal abundances ([Fe/H] or [M/H]) deduced from high dispersion spectroscopy (Pilachowski 1984), ΔS work (Smith 1984b), IR color magnitude diagrams (Frogel, Cohen and Persson 1983), Zinn and West's (1984) or Zinn's (1980) values from Q39 and the present results, found from $(J-K)_0$ using the Bell and Gustafsson (1983) calibration.

NGC 5904 (M 5): the Q39 value is low and the $(J-K)_0$ value is high;

NGC 5927: the $(J-K)_0$ abundance is quite high but hinges upon the adopted value of the reddening;

NGC 6121 (M 4): the higher reddening of 0.47, which is implied by the RR Lyrae period shift versus (J-K) diagram, gives an [M/H] from (J-K) of - 0.9;

NGC 6205 (M 13): Q39 gives a low abundance;

NGC 6362: the RR Lyrae period shift versus abundance relation suggests a higher reddening which yields [M/H] = -1.0 from (J-K);

NGC 6553: the high reddening casts doubt on the $(J-K)_0$ value. TiO data would be of interest;

NGC 6637 (M 69): The adopted reddening is from Mould, Stutman and McElroy (1979). The TiO lines are as strong as in Pop I giants of the same (7540 - 10175) color so the abundance must be high. Geisler's

(1984) result of [Fe/H] = -1.42 seems astonishingly low;

NGC 6712: Frogel (1985) emphasizes the fact that the CO bands are as strong as in field giants and stronger than in 47 Tuc stars. This could be explained by a high C12/C13 ratio in the 6712 stars;

NGC 6838 (M 71): the Q39 and (J-K) values are in good agreement with the TiO result. The high dispersion results range from -1.35 (Pilachowski et al. 1983) to -0.57 (Bessell 1983);

NGC 7078 (M 15): the relatively low abundance from (J-K) supports an increase in the reddening to E(B-V) = 0.12;

ACKNOWLEDGMENTS

This work has been supported by the National Science Foundation under Grant AST85-13872. Some of the calculations were carried out using the SDSC Cray, under NSF Grant AST85-09915, while others were made using a Ridge 32C computer, also purchased with NSF funds. I am grateful for this support.

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DISCUSSION

NEMEC: The observed main sequences of many globular clusters, derived using well calibrated CCD photometry, are often redder by as much as 0.10 mag than the main sequences calculated using theoretical interior plus atmosphere models. Do you see a resolution to this problem?

BELL: There are some comments on this problem in a paper on the Thuan Gunn system by VandenBerg and myself. There does appear to be a very good agreement between observed and predicted colors and temperatures for field F dwarfs so I would not expect a problem in transforming T_{eff} to color for the metal-poor cluster stars. There are possible stellar evolution reasons for color shifts as a function of a high abundance of oxygen. It is not clear that the color transformations used to convert CCD (B-V) values to (B-V) values on the Johnson system are valid for metal-poor stars. We also have to be more fussy about reddening than we have been in the past.

CHRISTIAN: There is one field in which a (B-V) shift is not reconciled with the models. This is the M 92 field that has been calibrated with sequences observed photoelectrically. These sequences have been observed with a number of CCD's with the same filter set, so they have been calibrated "properly". The cluster also has low reddening and obviously low metallicity. So although calibration of CCD photometry can be a problem I do not think it can explain away the effect in this case.

BELL: There is always the question of the oxygen abundance which will affect the tracks. I look forward to seeing the paper giving the M 92 results.

SCHOMMER: Two responses to your comments on the Washington System. I agree that $M-T_1$ has relatively low sensitivity to [Fe/H], and requires very precise photometry. In a recent Astron. J. article by Canterna, et al., a new calibration of the system is presented, and the CM diagram is proposed as a very sensitive abundance indicator, especially useful between $0 < [A/H] < -1$. Secondly, in defense of the carbon sensitivity, I merely mention that the first CH star in a dwarf galaxy was found by this system, and subsequently C stars were found in all dwarf sphereoidals.

BELL: The CM diagram is clearly a better abundance indicator than $M-T_1$, but I am skeptical about the supposed sensitivity to CH and CN. I look forward to seeing the new work.

ZINN: If the period shifts of Sandage are plotted against Q_{39}, a very tight relationship is obtained. Both of these quantities are reddening independent, and their good agreement suggests that they are measures of the same thing, which appears to be metallicity. The poorer agreement between Q_{39} and $(J-K)_0$ which is evident in your diagram may not be, therefore, a consequence of the sensitivity of Q_{39} to variations in horizontal-branch morphology, but a consequence of the sensitivity of $(J-K)_0$ to errors in the reddenings of the clusters.

BELL: I think you misunderstood my remark. I quite agree that the period shift gives a very tight correlation with abundance. The point of showing the period shift, (J-K) diagram is to argue that it would be used as a determination of cluster reddening, by arguing that there should be a tight correction between period shift and (J-K). The same is true for $(B-V)_g$ versus abundance.

WALLERSTEIN: There is a difference between Fe/H and the total metal abundance. In particular Ti and O repeatedly appear to be less deficient than iron. Hence TiO yields small deficiencies of Ti and O, in agreement with high dispersion spectroscopy.

BELL: I think one must be particularly cautious about the overabundances of individual elements. The strengths of H and K and Ca I 4226 low dispersion spectra of in NGC 362 and 47 Tuc stars contradict the high dispersion results. The [O I] lines at 6300 and 6363 may be blended with TiO lines and the equivalent widths may be measured as being too strong. Calculations of CO band strengths do not support large overabundances of oxygen. The similarity of the TiO band strengths at a given color in stars in some clusters and Pop I stars supports Zinn's (1980) abundance scale and the one proposed in this talk.