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A COMMENT ON THE METAL ABUNDANCE OF THE GLOBULAR CLUSTER M71

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ABSTRACT

Cohen's analysis of echelle spectra of four red giants in the globular cluster M71 gives an iron abundance of [Fe/H] = −1.4. This disagrees strongly with the previously accepted value of [M/H] ≈ −0.3, which was mainly based on photometric data, and raises questions on the interpretation of the photometry. We have investigated the problem de novo by applying synthetic colors to the interpretation of the available photometry and by reexamining the echelle data. An overall metal abundance of [M/H] = −0.9 is suggested. Some suggestions for additional observations which may clarify the situation further are made.

Subject headings: clusters: globular — stars: abundances

I. INTRODUCTION

There has been considerable recent work on the abundances of metal-rich globular clusters such as M71 and 47 Tuc. Dickens, Bell, and Gustafsson (1979) used *uvby* photometry of red horizontal-branch stars to suggest that the abundance of 47 Tuc was [M/H] = −0.8, while Pilachowski, Wallerstein, and Leep (1980) analyzed echelle spectra of two red giants and found [Fe/H] = −1.2. Cohen (1980) obtained echelle spectra of four red giants in M71 and found [Fe/H] = −1.27.

A metal abundance of about one-tenth that of the Sun for 47 Tuc does not appear to disagree with other observational data for the cluster stars, i.e., DDO photometry, *UBV* photometry, and low-dispersion spectra, although the presence of TiO bands in the latter may well argue for a metal abundance of −0.8 rather than −1.2 (Dickens, Bell, and Gustafsson 1979).

The metal abundance of one-twentieth solar for M71 does disagree with the previously accepted value, although this value was based on rather weak evidence. In view of this and the importance of the globular cluster abundance scale to other fields of astronomy, such as the abundance gradient in the galactic halo, the population synthesis of galaxies, and the study of the chemical evolution of the Galaxy, we have compared Cohen's results with results from photometric studies and have made a new estimate of the metal abundance of M71. Our estimate is based in part on the application of synthetic colors and in part on a rediscussion of Cohen's data. The synthetic colors used are the DDO colors of Bell and Gustafsson (1978) and the new colors for the Searle and Zinn (1978, hereafter SZ) system. These latter colors were computed using the same synthetic spectra that were used for the DDO colors.

II. THEORETICAL COLORS FOR THE SEARLE-ZINN SYSTEM

A detailed analysis of our theoretical SZ colors is given elsewhere (Bell and Gustafsson 1982). The following comments are intended to justify our application of these colors to the abundance analysis of M71. We shall show that the colors give plausible results for metal-poor clusters. Unfortunately, no observations of metal-rich stars which could serve as further checks on the theoretical calibration have been published for this system.

The SZ colors are found from flux measurements obtained using the 5 m telescope and the Oke multichannel scanner. The fluxes, in magnitude units, are plotted versus ψ. The ψ scale is chosen to remove the effects of interstellar reddening with $\psi = 1.30\lambda^{-1} - 0.60$ for $\lambda^{-1} \leq 2.29$; and $\psi = 0.75\lambda^{-1} + 0.65$ for $\lambda^{-1} > 2.29$. The slope of the flux-ψ relation for passbands between 5000 Å and 7620 Å defines a quantity Ψ, expressed as the magnitude difference between 5000 Å and 8000 Å. This quantity clearly depends on the stellar temperature. The differences, in the blue and ultraviolet, between the observed fluxes and fluxes predicted by this slope are then found. Integration of these differences over the wavelength interval 3800–4920 Å gives an index, S, describing the line blocking.

We have computed values of S and Ψ from our synthetic spectra. By estimating the variation of $T_{\rm eff}$ and $\log g$ along the giant branches of globular clusters of different metal abundances, it is possible to find the positions of these branches in S-Ψ (or, equivalently, [S, $B - V$]) diagrams. These diagrams cannot be used for the present problem because the lines for [A/H] = −0.5 and −1.0 are almost identical. The location of

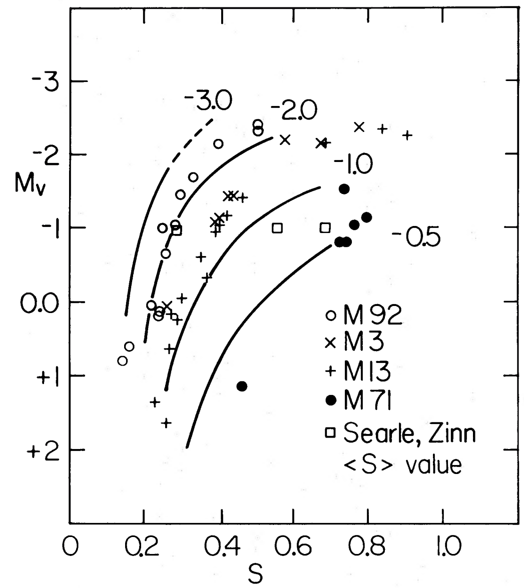

FIG. 1.—M_v is plotted vs. the Searle-Zinn line-blocking index, S, for theoretical cluster giant branches of different abundances. Stars in M92, M3, M13, and M71 are plotted. The star in M71 at $M_v = -1.5$ is star 46. The calibration by Searle-Zinn of their quantity $\langle S \rangle$ for abundances [M/H] = −2.0, −1.0, and −0.5 is also given.

stars in M92, M3, and M13 in the (S, $B - V$)-diagram are as predicted by the theory.

In order to study metal-rich clusters, it is necessary to plot S-M_v diagrams. Such a diagram is given in Figure 1. The ordinates have been deduced in part from stellar evolutionary calculations (Sweigart and Gross 1978) and in part from V magnitudes and distance moduli for stars in M92, NGC 6397, M3, M13, and 47 Tuc. In their calibration, SZ found the value of S at $M_v = -1.0$, denoted as $\langle S \rangle$, for a cluster and correlated this with Butler's (1975) abundances, which are based on ΔS measures of RR Lyrae stars. SZ did not use Butler's result for M71, which must be considered uncertain in any case since the single star observed may not be a member (Cohen 1980). Figure 1 shows that our calibration agrees quite well with SZ for [A/H] = −2.0 and −1.0, but differs for −0.5.

We give the SZ observations of M92, M3, M13, and M71 stars in Figure 1. It is apparent that the fit to the three former clusters is quite good and yields metal abundances of −2.0, −1.4, and −1.2, respectively. These values may be underestimates because of carbon depletion effects, discussed later. The M_v values used are taken from SZ who use the M71 reddening of $E(B-V) = 0.27$ (Burstein and McDonald 1975) and the distance modulus of $V_0 - M_v = 13.07 \pm 0.3$ (Arp and Hartwick 1971). The reddening is uncertain, and a smaller value (e.g., $E[B-V] = 0.21$; Dickens and Rolland 1972) may be preferable. Lower reddening or a smaller distance modulus (e.g., 12.9; Frogel, Persson, and Cohen 1979) would make the stars intrinsically fainter and would increase the abundance found by this method.

Cohen (1980) found a relatively high Ca abundance for M71—a mean value for her four stars is [Ca/H] = −0.64. We have found that S is dependent on the H and K line absorption and thus on the Ca abundance (Bell and Gustafsson 1982). It might therefore be expected that a misleadingly high value of [M/H] would be deduced from the S-M_v diagram. Also, in a general study of synthetic colors (Gustafsson and Bell 1979), we have found that the calculated ultraviolet line blocking for Population I red giants is smaller than the observed. This effect becomes smaller with decreasing metal abundances and is unimportant for extreme Population II giants. To examine these two points, we computed an index, S', which is identical to S except that the wavelength region 3800–4120 Å was not included in the integral defining S'.

Figure 1 shows that the S-M_v diagram for M71 gives [M/H] = −0.6. A similar result is given for the S'-M_v diagram (Fig. 2). The uncertainty of ±0.3 mag in the distance modulus causes an uncertainty of less than ±0.2 in [M/H] for M71. The uncertainty in the theoretical calibration of the S-M_v diagram is probably more important—here we rely partly on the use of clusters of known distance moduli and abundances, and partly on theoretical evolutionary tracks.

III. RESULTS FROM DDO PHOTOMETRY

The theoretical DDO colors of Bell and Gustafsson (1978) and the T_{eff} and log g values for the cluster giant branches give the giant branch lines in the $C(42–45) = C(45–48)$ diagram plotted in Figure 3. We have also plotted a Population I luminosity class III line using the T_{eff} and log g values of Gustafsson and Bell (1979). All colors are computed on the assumption that the abundances of all metals vary in unison. The colors of stars in M92, M3, M13, M71, and Population I standards are also plotted, using the data from Hesser, Hartwick, and McClure (1977), Norris and Zinn (1977), and McClure (1980).

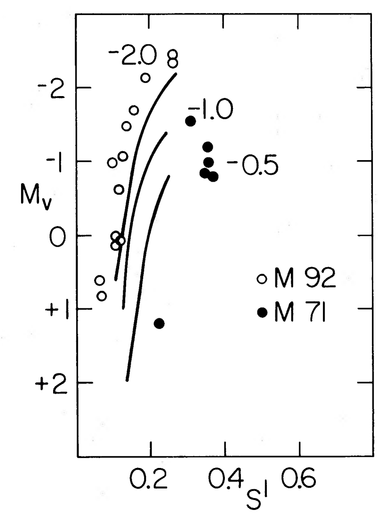

FIG. 2.—As Fig. 1, except the line-blocking index, S', is computed over the wavelength interval 4120–4920 Å. The systematic displacement of the M92 stars is probably due to their carbon deficiency.

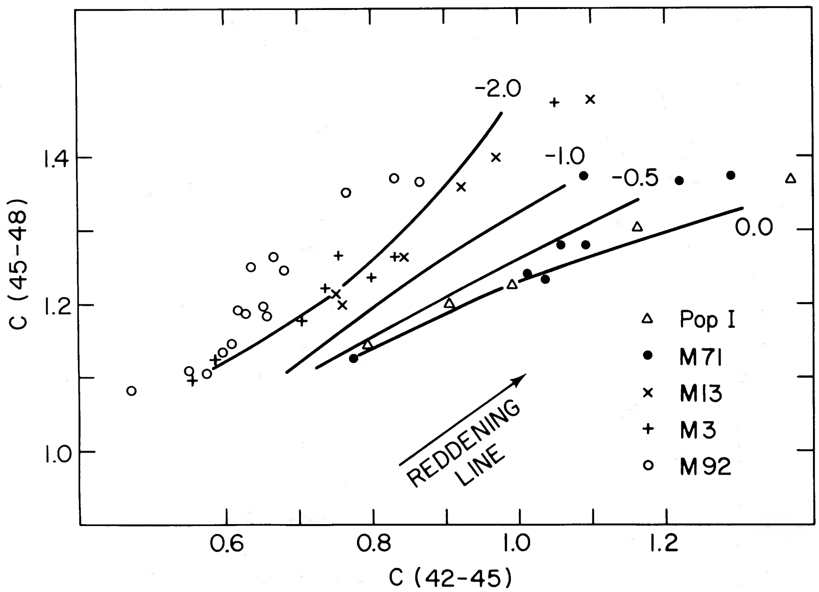

FIG. 3.—The DDO color $C(45\text{–}48)$ is plotted vs. $C(42\text{–}45)$ for theoretical cluster giant branches of different abundances. A Population I luminosity class III line is also given. The colors of stars in M92, M3, M13, and M71 and of some Population I class III standards are plotted.

The colors of the M92, M3, and M13 stars have been discussed elsewhere (Bell, Dickens, and Gustafsson 1979; Bell and Dickens 1980). The great departure of the more luminous M92 stars, for example, from the [A/H] = −2.0 line is believed to be due to their low carbon abundance, with the consequent weakening of the CH lines in the 42 bandpass. The Population I class III line in Figure 3 gives a good fit to the standard stars, at least for those bluer than $C(42\text{–}45) = 1.0$. Note that the dereddened colors of the M71 stars are close to those of the standards, κ Oph (K2 III), 39 Cyg (K3 III), and α Tau (K5 III), and clearly do not lie near the [A/H] = −1.3 line.

Figure 3, in fact, suggests that the abundance of the M71 stars is about [M/H] = −0.5. This result does not depend on the value used for the reddening ($E[B-V] = 0.21$ was used), since the reddening line is almost parallel to the cluster lines. Any reduction in the carbon abundance in the M71 stars analogous to that found in other clusters will only cause us to underestimate the overall abundance, although the effect would probably be smaller than in more metal-poor clusters, such as M92, owing to saturation effects on CH lines. The effect of carbon abundance increases is discussed in § V.

The difference between our result and that of Hesser, Hartwick, and McClure (1977) arises from the failure of the empirical method for calibrating DDO photometry for globular clusters (Osborn 1973). Metal-rich clusters are outside the range of the calibration, so Hesser, Hartwick, and McClure (1977) simply adopted [Fe/H] = 0.0 for M71, basing this adoption on the similarity of DDO photometry for M71 and NGC 6352, and on the value of [Fe/H] implied by $\delta(U-B)$ for the latter cluster (Hartwick and Hesser 1972). Because of its low galactic latitude, their reddening of NGC 6352 was uncertain, and the abundance calibration based on its ultraviolet excess must also be uncertain.

IV. THE SPECTROSCOPIC DATA

From the photometric data, we have found a value for the metal abundance [M/H] of M71 of about −0.6. It is important to investigate the reason for the great difference between that value and that of Cohen's (1980) spectroscopic determination of −1.27. Cohen uses a model with [A/H] = −0.5 to derive the iron abundance of −1.27. A change to an [A/H] = −1.0 model would lead to a decrease in [Fe/H] by 0.11, as Cohen mentions. Consequently, Cohen's abundance for M71 is approximately [Fe/H] = −1.4.

We have calculated equivalent widths for iron lines in model atmospheres with parameters close to those of Cohen's four stars. We assume a solar logarithmic iron abundance of 7.5 on a scale with hydrogen equal to 12. The results have been summarized in Figure 4, where theoretical curves of growth for two different models have been plotted. We also considered the effects of continuum scattering but found them to be of small importance for the equivalent widths. In Figure 5 a comparison is made with the observed equivalent widths. The four stars have very similar parameters, according to Cohen, so the mean value of W_λ has been plotted for every line to reduce the scatter. In plotting the abscissae, we have adopted *gf* values from a recent compilation of corrected oscillator strengths by Petford and Blackwell (1980).

The iron abundance derived from Figure 5 seems to depend on which part of the curve of growth is used. Using the linear part (neglecting the scatter) gives a value of [Fe/H] ≈ −0.9. If, in turn, the flat part is used, either a lower abundance results or the microturbulence parameter is found to be considerably lower than 2 km s^{-1}. These results are independent of the damping treatment. It is clearly more difficult to analyze echelle spectra than conventional grating spectra, since the properties of an

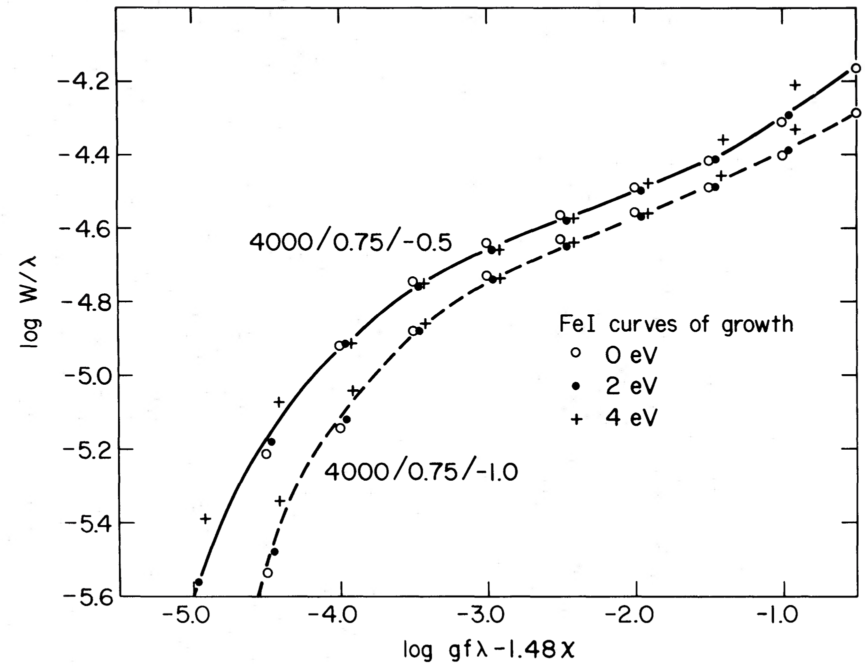

FIG. 4.—Curves of growth are plotted for Fe I lines of 0, 2, and 4 eV excitation potential for the model atmospheres 4000/0.75/ −1.0 and 4000/0.75/ −0.5 (T_{eff}/log g/[A/H]). A Doppler broadening velocity of 2 km s^{-1} and an excitation temperature of θ_{exc} = 1.48 are used.

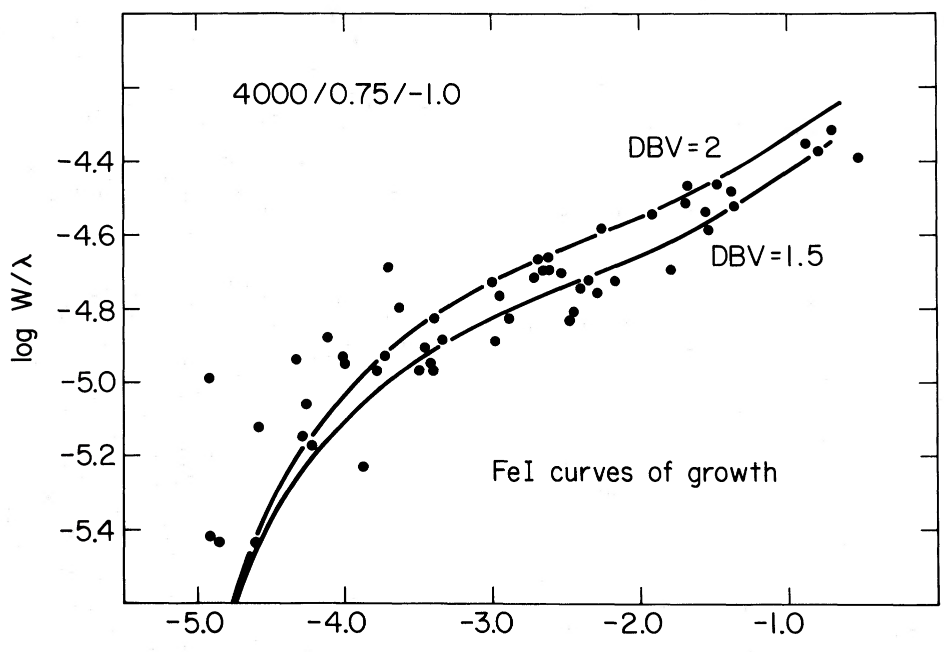

FIG. 5.—The curve of growth for the model atmosphere 4000/0.75/ −1.0 is plotted for Doppler broadening velocities of 2.0 and 1.5 km s^{-1}. The mean value of the equivalent width of each line for the four M71 giants is also shown. The gf values are from Petford and Blackwell (1980), and the excitation temperature of θ_{exc} = 1.48 is used.

echelle require that a curved "continuum" level be drawn for each order, and, furthermore, each order must be reduced separately.

Cohen is able to fit the observed curve of growth with a calculated curve, characterized by a microturbulence parameter as high as 2 km s^{-1}. We have also found this to be possible, if we accept a significantly lower metal abundance than [Fe/H] = -1.0. However, with our choice of *gf* values, this would not fit the lines on the shoulder of the curve of growth.

The Petford and Blackwell *gf* values are systematically 0.08 dex lower than those of Cohen. For the lines on the shoulder of the curve of growth, the difference is even greater, and, moreover, the weak lines used by Cohen (but not included in the list of Petford and Blackwell) all happen to fall below the mean curve of growth. Therefore, if we had used Cohen's *gf* values, we would have derived an abundance of [Fe/H] = -1.2. However, considering the uncertainties in the *gf* values and the uncertainty in using the saturated lines on the shoulder and the flat part of the curve of growth for determining abundances, we suggest that a value of [Fe/H] close to -1.0 is quite consistent with Cohen's equivalent widths.

V. DISCUSSION AND CONCLUSIONS

We have found that the photometric observations of red giants in M71 by the SZ and the DDO systems seem to suggest an overall metal abundance [M/H] of about -0.6, while the spectroscopic data of Cohen (1980) suggests an iron abundance of -0.9 or even less. In view of the great importance of knowing the metal abundance of the most metal-rich globular clusters, the reason for this discrepancy between the results of different methods deserves some discussion.

Several different explanations for the discrepancy may be considered:

1. The cluster may not be chemically homogeneous in iron-peak elements, as seems to be the case for ω Cen (Mallia and Pagel 1981). The sample of stars from DDO observations does not include any of Cohen's stars, and the sample of SZ only includes one of them (No. 46). This star is also separated from the others in the S-M_v diagram (cf. Fig. 1), suggesting that it has a metal abundance around -1.0. However, a situation where all four spectroscopically observed stars have a low iron abundance while nearly all photometrically observed stars have a higher metal abundance is not very probable.

2. The overall metal abundance determined from the photometry of SZ (using S or S' as blocking measures) and from DDO photometry depends not only on the abundance of iron but also on calcium (the S index) and carbon abundances (S and S' indices and C[42–45]). Using the models 4000/0.75/ -1.0 and 4500/1.5/ -1.0, we have found that an increase of 0.5 in [Ca/H] increases S by 0.05 and 0.06, respectively, while an increase of 0.2 in [C/H] increases S by 0.05 and 0.03, increases S' by 0.02 in both cases, and reddens C(42–45) by 0.09 and 0.06. These changes are not sufficiently great for our [A/H] = -1.0 models to fit the M71 observations. Could the M71 stars be carbon rich? Frogel, Persson, and Cohen (1979) determined a metal abundance for M71 giants of -0.4 dex from CO indices. Even if the high O/Fe ratio of Cohen (1980) is adopted, the observations of Frogel *et al.* may suggest a high carbon abundance. However, this would be inconsistent with the SZ observations for the 4360 Å band, which suggest rather weak G bands for the M71 stars.

3. M71 is located in a rich field of the Milky Way. The star background of the central regions of the Galaxy is so dense that the risk of field star contamination in studies of M71 stars is obvious. Cohen (1980) also suggests contamination with field stars as one of the major reasons for the discrepancy between her metal abundance determination and the previous ones. A study of Plate 2 of Arp and Hartwick (1971) suggests that, statistically, at the most every other star of those studied photometrically in the DDO or SZ systems could be a field star. The proper motion study of Sanders (1971) suggests that two of the stars observed on the DDO system and one of the SZ stars have a low probability of cluster membership, but the data only allow a maximum probability of 0.69 for any star. Since the stars observed photometrically define rather narrow sequences in the S-M_v and C(42–45)-C(45–48) diagrams, we conclude that an important systematic error in our estimated photometric [M/H] value from field star contamination is not probable. The point is that only the assumption that almost all the photometrically observed stars were field stars would change the sequences significantly. The effects on the measured colors from stars other than program stars in the diaphragm of the photometers could possibly be a more severe problem than field star contamination.

The observed colors could be affected by differential reddening. This is unlikely to cause serious problems in the C(42–45)-C(45–48) diagram because the reddening line has a very similar slope to the cluster lines. The observed S values are dereddened, assuming the Whitford reddening law. The M_v values would be affected, but A_v for almost all the stars observed by SZ would have to be too small by ~ 0.8 mag for the S-M_v diagram to give [M/H] ≈ -1.0.

4. The stars analyzed spectroscopically are all located high on the giant branch. They have low gravities and low atmospheric pressures. Their atmospheres may be extended and inhomogeneous and thus may depart considerably from the plane-parallel model atmospheres. Departures from LTE may also significantly diminish the equivalent widths. These problems may be equally important for the calculated colors; however, for the photometrically observed stars further down on the giant branch, the plane-parallel LTE models ought to be more valid.

Further observations seem necessary to disclose the true explanation(s) for the discrepant results of the spectroscopic and photometric methods. The stars observed by Cohen should be studied in the DDO and SZ systems. Field giants of Population I and intermediate Population II should be measured in the SZ system to provide a check on the theoretical calibration for the metal-rich globular clusters. The metal abundance of the horizontal-branch stars in M71 could be estimated using *uvby* photometry (cf. Gustafsson and Bell 1979; Gustafsson and Ardeberg 1978; Dickens, Bell, and Gustafsson 1979). However, this method requires a determination of the reddening of the cluster with an error smaller than 0.04 mag in $E(B-V)$. Accurate *UBV* photometry would be valuable for studying the width of the giant branch. Further high-dispersion spectroscopic observations should be made for the fainter cluster stars, if possible, as well as the brighter ones. Finally, high-precision laboratory measurements of the *gf* values of the weaker lines used by Cohen would be invaluable.

Prior to these new studies, it seems reasonable to adopt a preliminary value of [M/H] between -0.6 and -1.3 for the cluster. We would suggest a value of -0.9 to be a reasonable preliminary choice.

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