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# THE METALLICITY OF M4: ACCURATE SPECTROSCOPIC FUNDAMENTAL PARAMETERS FOR FOUR GIANTS

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## ABSTRACT

High-quality spectra, covering the wavelength range 5480–7080 Å, have been obtained for four giant stars in the intermediate-metallicity CN-bimodal globular cluster M4 (NGC 6121). We have employed a model atmosphere analysis that is entirely independent from cluster parameters, such as distance, age, and reddening, in order to derive accurate values for the stellar parameters effective temperature, surface gravity, and microturbulence, and for the abundance of iron relative to the Sun, [Fe/H], and of calcium, Ca/H, for each of the four stars. Detailed radiative transfer and statistical equilibrium calculations carried out for iron and calcium suggest that departures from local thermodynamic equilibrium are not significant for the purposes of our analysis. The spectroscopically derived effective temperatures for our program stars are hotter by about 200 K than existing photometric calibrations suggest. We conclude that this is due partly to the uncertain reddening of M4 and to the existing photometric temperature calibration for red giants being too cool by about 100 K. Comparison of our spectroscopic and existing photometric temperatures supports the prognosis of a significant east-west gradient in the reddening across M4. Our derived iron abundances are slightly higher than previous high-resolution studies suggested; the differences are most probably due to the different temperature scale and choice of microturbulent velocities adopted by earlier workers. The resulting value for the metallicity of M4 is $[Fe/H]_{M4} = -1.05 \pm 0.15$. Based on this result, we suggest that metallicities derived in previous high-dispersion globular cluster abundance analyses could be too low by 0.2–0.3 dex. Our calcium abundances suggest an enhancement of calcium, an $\alpha$ element, over iron, relative to the Sun, in M4 of [Ca/H] = 0.23.

*Subject headings:* globular clusters: individual (M4) — stars: abundances — stars: atmospheres — stars: giants

## 1. INTRODUCTION

Determining the metal content of the Galactic globular clusters using photometric and both low- and high-dispersion spectroscopic techniques has been a popular astronomical endeavor over the last two decades. The intermediate-metallicity cluster M4 (NGC 6121), at a distance of ~2.0 kpc and generally favored as being the closest of globular clusters to the Sun (e.g., Greenstein 1939; Alcaino 1975; Cudworth & Rees 1990), has not been ignored by this industry. The situation has been summarized recently by Liu & Janes (1990) who, in their Table 8, provide a useful synopsis of some metallicity determinations for M4 from the literature. In Table 1 we combine with their list some further values culled from the literature. Potentially, the most accurate of the various methods applied to the problem is high-dispersion CCD spectroscopy, as demonstrated in the case of M4 by Gratton, Quarta, & Ortolani (1986), Brown, Wallerstein, & Oke (1990), and at slightly lower resolution by Wallerstein, Leep, & Oke (1987). It is therefore encouraging that these three recent studies, all based, on model atmosphere analyses, are in good agreement among the somewhat desultory array of values listed in Table 1.

A prerequisite for determining accurate abundances from stellar spectra is a knowledge of the fundamental stellar parameters effective temperature ($T_{eff}$), surface gravity (log $g$), and microturbulence ($\xi$). In abundance analyses of stars in globular clusters, effective temperatures have traditionally been chosen on the basis of photometric colors. Surface gravities are then usually derived from estimates of absolute luminosity and by appealing to canonical stellar evolution theory for an estimate of stellar mass. Since accurate relative photometry is routinely achieved for stars in globular clusters and since our canonical stellar evolution theory at present appears to be reasonably robust, the conversion of raw stellar spectra to accurate element abundances might at first sight appear trivial.

In the case of M4, there are further complications. Accurate absolute photometry appears to be stymied by the dark nebulosity in Sco-Oph, which is interposed in the cluster's line of sight. As a result, authors have disagreed on the cluster reddening, and as pointed out by Cacciari (1979) and Liu & Janes (1990), adopted values of $E(B-V)$ have varied between 0.27 and 0.55. This range of values translates to a large range in stellar effective temperature: e.g., on the $(V-K)$ scale of Bell & Gustafsson (1989) at a mean temperature of 4250 K, it corresponds to the temperature range 4000–4550 K. Furthermore, several workers have presented strong evidence for a differential reddening across the cluster (Newell 1970; Sturch 1977; Frogel, Persson, & Cohen 1983; Kadla, Gerashchenko, & Firmaniuk 1988). Cudworth & Rees (1990) were able to quantify this coarsely in terms of an east-west gradient of $0.083 \pm 0.01$ mag per kiloarcsec and suggested a possible attendant patchiness in the reddening. This gradient corresponds to $\Delta E(B-V) = 0.045$ across the 9′ span of the cluster's central three regions as designated by Lee (1977). On the $(V-K)$ temperature scale this translates to ~90 K at a mean temperature of 4250 K.

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TABLE 1

IRON ABUNDANCES FOR M4 FOUND IN THE LITERATURE

| Source | [Fe/H] | Method[a] |
|---|---|---|
| Eggen 1972 | −0.6 | Multicolor photometry CMD |
| Butler 1975 | −1.24 | $\Delta S$ for four RR Lyraes |
| Sturch 1977 | −0.8 | $\delta(U-B)$ for 15 RR Lyraes |
| Lee 1977 | −0.5 | *UBV* photometry CMD |
| Smith & Butler 1978 | −1.4 ± 0.2 | $\Delta S$ for 21 RR Lyraes |
| Mould, Stutman, & McElroy 1979 | −1.06 ± 0.35 | TiO band strength |
| Cacciari 1979 | −1.0 ± 0.4 | *UBV* photometry CMD |
| Harris & Canterna 1979 | −1.67 | Based on literature data |
| Searle & Zinn 1978 | −1.7 | Spectrophotometry of red giants |
| Harris & Racine 1979 | −1.30 | Based on literature data |
| Zinn 1980b | −1.46 ± 0.09 | $Q_{39}$ spectrophotometric index |
| Zinn 1980a | −1.53 ± 0.1 | Recalibration of Zinn 1980b |
| Smith & Perkins 1982 | −1.4 ± 0.2 | $\Delta S$ for RR Lyraes |
| Caputo, Castellani, & Di Gregorio 1983 | −1.3 ± 0.15 | Based on literature data |
| Cohen 1983 | −0.9 ± 0.2 | Intermediate resolution spectroscopy |
| Frogel et al. 1983 | −1.1 | Infrared photometry |
| Pilachowski 1984 | −1.23 | Based on literature data |
| Richer & Fahlman 1984 | −0.93 ± 0.31 | CCD photometry CMD |
| Zinn & West 1984 | −1.33 ± 0.1 | Based on literature data |
| Geisler 1984 | −0.95 | HR spectroscopy |
| Kodaira & Philip 1984 | −0.4 | HR spectroscopy of blue HB stars |
| Smith 1984 | −1.2 ± 0.2 | $\Delta S$ for RR Lyraes |
| Zinn 1985 | −1.28 | Based on literature data |
| Geisler 1986 | −1.45 ± 0.1 | Washington photometry |
| Gratton et al. 1986 | −1.32 ± 0.15 | HR CCD spectroscopy |
| Wallerstein et al 1987 | −1.2 ± 0.1 | HR CCD spectroscopy |
| Alcaino, Liller, & Alvarado 1988 | −1.27 | *BVRI* CCD photometry |
| Beers et al. 1990 | −1.31 | Ca II K index |
| Liu & Janes 1990 | −0.90 | $\delta(U-B)$ for four RR Lyraes |
| Brown et al. 1990 | −1.3 | HR CCD spectroscopy |
| Lambert et al. 1992 | −1.1 | HR CCD spectroscopy of blue HB stars |
| Mean ± $\sigma_{n-1}$ | −1.17 ± 0.31 | |
| This work | −1.05 ± 0.15 | |

[a] HR = high resolution; CMD = color-magnitude diagram; HB = horizontal-branch.

An additional impediment is the currently rather uncertain photometric temperature scale for metal-poor giants (see Bell & Gustafsson 1989 for a recent discussion). The most frequently used temperature scale at present for globular cluster members is that of Frogel et al. (1983, and references therein), who present infrared photometry, bolometric luminosities, and effective temperatures for giants in 26 globular clusters. The basis for this scale is that of Ridgway et al. (1980), which was established from lunar occultation angular diameters and infrared photometry for K0–M6 giants of approximately solar composition. Toward later spectral types—e.g., the temperature range $T_{\rm eff} = 4000$ K and below—the Ridgway et al. calibration exhibits considerable scatter. Unfortunately, this temperature range is the very same as that of the more luminous giants in globular clusters that are bright enough for high-dispersion studies. Uncertainties in the stellar effective temperature can then induce most undesirable uncertainties in abundance studies: e.g., Pilachowski, Sneden, & Wallerstein (1983) indicate that an uncertainty of 200 K in effective temperature of the globular cluster giants in their study engenders an uncertainty of 50% in the iron abundance.

If it were possible to derive stellar fundamental parameters and abundances accurately for stars in globular clusters using only spectral features, then such a method would be of great value for two main reasons: (1) the analysis would require no a priori assumptions relating to stellar evolution theory, such as the mass and age of the stars in question and the distance to the cluster; and (2) it would enable us to derive abundances which would not rely on currently rather uncertain temperature calibrations for metal-deficient stars, especially around 4000 K, and with no dependence on cluster reddening and extinction.

Such a method, based on the analysis of high-quality recordings of calcium and iron lines, has been developed and applied to the study of solar-type dwarfs by Smith, Edvardsson, & Frisk (1986) and Smith & Drake (1987). Subsequently, Drake & Smith (1991) applied the method successfully in an analysis of the K0 giant Pollux ($\beta$ Gem), accounting for possible departures from local thermodynamic equilibrium (LTE) through detailed radiative transfer and statistical equilibrium calculations involving extensive model calcium and iron atoms. In this paper we demonstrate that, provided high-quality spectroscopic material of sufficient resolution is available, the method can be applied to giant stars in the more metal-rich globular clusters with only a small loss in accuracy. We apply our method to four giant stars in the CN-bimodal intermediate-metallicity globular cluster M4 as part of a wider investigation into abundance inhomogeneities in globular clusters (for recent reviews of abundance variations in globular clusters, see, e.g., G. H. Smith 1987, 1988; Suntzeff 1988; Pilachowski 1988). Our spectroscopic observations of four giants in M4, two of which are "CN-strong" and two "CN-weak," are described in § 2; in § 3 we outline the details of the method of analysis; radiative transfer and statistical equilibrium calculations to assess any likely non-LTE contamination are described in § 4; and in § 5 we discuss our results briefly in the light of some previous work. We demonstrate that the differences between the results obtained in this work and previous high-dispersion analyses can be explained entirely by the choice of stellar parameters.

The abundances of O, Na, and Al in our program stars were presented and discussed in an earlier paper (Drake, Smith, & Suntzeff 1992).

## 2. OBSERVATIONS AND DATA REDUCTION

We list the M4 stars observed in Table 2, together with $V_0$ and $(B-V)_0$ magnitudes from Cudworth & Rees (1990), and CN band strengths, S(3839), from Suntzeff & Smith (1991). We also list the Suntzeff & Smith diagnoses of whether the stars are on the first ascent of the giant branch (RGB), or on the asymptotic giant branch (AGB); a question mark denotes uncertainty between the two. Our observations are briefly described in Drake et al. (1992); we give a more detailed overview here for completeness.

The observations were made with the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope and the facility echelle spectrograph in a single run on 1991 May 19–22 (UT). The 31.6 groove mm$^{-1}$ echelle, 226 groove mm$^{-1}$ cross-dispersing grating blazed at 6300 Å, and blue long camera were used, in conjunction with a 150 $\mu$m slit (1″). The detector was a 1024 × 1024 24 $\mu$m pixel TEK CCD, binned on-chip by a factor of 2 perpendicular to the dispersion. The spectra covered the wavelength range 5480–7080 Å in 23 orders. The CCD read-noise was 4.1 electrons pixel$^{-1}$. Spectral coverage was continuous from 5480–6800 Å. Longward of 6800 Å, there were small gaps in the data because the detector did not cover the full free spectral range. The final resolution was 2.5 pixels (FWHM), which corresponded to $\lambda/\Delta\lambda = 35{,}000$.

Each program object was observed twice with exposure times of typically 1 hr. Because of the large flexure present in the echelle spectrograph (6–12 pixels across the sky), we obtained thorium argon (Th-Ar) comparison exposures after every stellar observation. We also obtained spectra of the quartz continuum lamp at various telescope positions each night. Spectra of the daytime sky, bright field giants ($\epsilon$ Vir, and $\epsilon$ Aqr), and a hot star at extremely high signal-to-noise ratio (S/N) to locate telluric absorption, were also taken.

The data were direct-current–bias corrected, subtracted of bias structure, and trimmed with the usual Image Reduction and Analysis Facility (IRAF) tasks. The normalized two-dimensional quartz frame taken nearest in the sky to the program object was used as the flat field. A smooth two-dimensional polynomial fit to the interorder scattered light was subtracted from each frame. The spectra were then extracted to one dimension using a variance-weighting scheme with no "sky subtraction," since the OH telluric emission was judged to be negligible. The spectra were rebinned onto a linear wavelength scale using the Th-Ar spectra taken throughout the night. The fit to the Th-Ar lines was 0.0045 Å for 500 lines. The data were then edited for cosmic rays and co-added. The final S/N ratio in the continuum on the echelle blaze ranged from 100 to 250, with 200 being typical.

TABLE 2

STARS STUDIED IN THIS PROGRAM

| Star | $V_0$ | $(B-V)_0$ | S(3839) | Type |
|---|---|---|---|---|
| 2519 CN-weak ............. | 10.62 | 1.09 | 0.44 | AGB? |
| 2617 CN-strong ........... | 10.65 | 1.23 | 0.71 | RGB |
| 3612 CN-strong ........... | 10.70 | 1.12 | 0.74 | RGB? |
| 3624 CN-weak ............. | 10.65 | 1.21 | 0.44 | RGB |

## 3. ANALYSIS

The stellar parameters $T_{\rm eff}$, log $g$, and $\xi$, and the abundances of iron and calcium were determined in a completely self-consistent way from the equivalent widths of a limited set of Fe I, Fe II, and Ca I lines and used the wings of the strong, collisionally broadened Ca I 6162 Å line. The method closely followed that described by Drake & Smith (1991) and is summarized below.

### 3.1. *Line Selection*

The calcium and iron lines selected for use in the analysis are listed in Table 3. Stringent criteria were applied to the line selection. As a first step we compiled a list of possible candidates. Iron lines were selected from the set of lines deemed to be "clean" in the solar spectrum by Rutten & van der Zalm (1984). It is known from both theoretical work (Steenbock 1985) and empirical work (e.g., Ruland et al. 1980) that, in giant stars, lines of Fe I that are (1) strong and (2) of low excitation ($\chi \lesssim 3.5$ eV) are subject to significant non-LTE effects. This is demonstrated for the K0 giant Pollux in Figure 3 of Drake & Smith (1991). In order to minimize potential non-LTE contamination in this analysis, only Fe I lines with lower excitation potential $\geq 3.5$ eV and with solar (flux) equivalent width in the range 20–50 mA were considered. The lower equivalent width limit was imposed because weaker spectral features could not be measured in our stellar spectra with such high precision. Since Fe II lines are not expected to be significantly affected by departures from LTE (Steenbock 1985), selection criteria did not include line strength. Calcium lines were chosen from the subset of lines deemed to be unblended in a critical investigation of spectra of the Sun and Procyon by Smith (1981). Of these lines, only those with solar equivalent widths $\lesssim 100$ mA were retained in order to minimize the dependence of derived abundances on rather uncertain collision-broadening parameters. The final subset of lines was chosen from the larger set of candidates by carefully inspecting each line in both the solar flux spectrum, as in the Atlas of the Spectrum of Arcturus (Griffin 1968), and in the stellar spectra themselves; any lines that were judged to be compromised by blending were rejected. As a rough guide, a line was judged to be effectively free from blends if it satisfied three criteria: (1) visible blends must not affect the line profile to a depth greater than 25% of the total line depth, as measured from the continuum; (2) lines appearing clean, must not have anomalously large half-widths or asymmetries; (3) the estimated total combined equivalent width of coincident lines listed by Kurucz & Peytremann (1975) must not exceed 1 mÅ.

An example of a spectral region in one of our program stars exhibiting typical lines of Fe used in the analysis is illustrated in Figure 1.

### 3.2. *Oscillator Strengths*

Oscillator strengths for Fe lines were derived from the Solar Flux Atlas (Kurucz et al. 1984) using the Holweger & Müller (1974) model with a microturbulent velocity of $\xi = 1.5$ km s$^{-1}$ (Smith et al. 1986), assuming a solar iron abundance of Fe/H = 7.50, following Drake & Smith (1991). We emphasize that this value for the solar iron abundance is arbitrary and

TABLE 3

ATOMIC DATA AND EQUIVALENT WIDTHS FOR THE LINES USED IN THIS ANALYSIS

| Multiplet | $\lambda$ (Å) | $\chi$ (eV) | log $gf$ | $\Delta\overline{r^2}$ ($\pi a_0^2$) | Equivalent Width (mÅ) 2519 | 2617 | 3612 | 3624 |
|---|---|---|---|---|---|---|---|---|
| | | | Ca I | | | | | |
| 21 | 5581.97 | 2.51 | −0.555 | 61 | 107 | 117 | 114 | 116 |
| 21 | 5590.12 | 2.51 | −0.571 | 53 | 107 | 115 | 112 | 114 |
| 46 | 5867.56 | 2.92 | −1.57 | 333 | 22 | 36 | 36 | 34 |
| 20 | 6161.29 | 2.51 | −1.266 | 493 | 79 | 88 | 86 | 90 |
| 20 | 6166.44 | 2.51 | −1.142 | 493 | 78 | 93 | 95 | 98 |
| 19 | 6455.60 | 2.51 | −1.34 | 53 | 68 | 84 | 82 | 84 |
| 18 | 6471.66 | 2.51 | −0.686 | 39 | 116 | 126 | 122 | 121 |
| 18 | 6508.84 | 2.51 | −2.41 | 39 | ... | ... | 24 | 18 |
| | | | Fe I | | | | | |
| 1108 | 5652.316 | 4.24 | −1.730 | 86.0 | 19 | 28 | 26 | 28 |
| 1086 | 5793.918 | 4.20 | −1.618 | 74.0 | 29 | 41 | 32 | 34 |
| 1086 | 5814.814 | 4.26 | −1.818 | 74.0 | 18 | 27 | 24 | 23 |
| 1179 | 5855.084 | 4.59 | −1.534 | 158.0 | 12.5 | 15.5 | 17 | 17 |
| 1175 | 5927.785 | 4.63 | −1.042 | 157.0 | 31 | 39 | 34 | 38 |
| 1176 | 6079.013 | 4.63 | −0.993 | 162.0 | 29 | 38 | 37 | 37 |
| 1327 | 6089.570 | 5.00 | −0.846 | 100.0 | 35 | 42 | 39 | 42 |
| 1177 | 6093.647 | 4.59 | −1.325 | 144.0 | 22 | 24 | 26 | 26 |
| 959 | 6096.669 | 3.97 | −1.794 | 121.0 | 40 | 40 | 39 | 41 |
| 1018 | 6165.364 | 4.12 | −1.484 | 10.0 | 39 | 48 | 48 | 51 |
| 959 | 6187.994 | 3.93 | −1.653 | 121.0 | 45 | 54 | 53 | 49 |
| 981 | 6226.740 | 3.87 | −2.064 | 109.0 | 24 | 31 | 29 | 30 |
| 1254 | 6330.852 | 4.71 | −1.154 | 158.0 | 25 | 28 | 19 | 27 |
| 1197 | 6726.671 | 4.59 | −1.045 | 174.0 | 38 | 37 | 36 | 38 |
| 1197 | 6820.373 | 4.62 | −1.131 | 174.0 | 30 | 36 | 38 | 37 |
| 1173 | 6858.154 | 4.59 | −0.950 | 73.0 | 45 | 43 | 44 | 44 |
| | | | Fe II | | | | | |
| 46 | 5991.363 | 3.14 | −3.646 | 14.0 | 31 | 24 | 26 | 23 |
| 46 | 6084.106 | 3.19 | −3.858 | 14.0 | 20 | 18 | 18 | 12 |
| 74 | 6149.249 | 3.87 | −2.824 | 17.0 | 35 | 25 | 22 | 23 |
| 40 | 6369.462 | 2.88 | −4.216 | 13.0 | 19 | 16 | 15 | 16 |
| 74 | 6416.923 | 3.87 | −2.743 | 17.0 | 32 | 26 | 29 | 28 |
| 40 | 6432.683 | 2.88 | −3.671 | 13.0 | 43 | 32 | 35 | 34 |
| 74 | 6456.387 | 3.89 | −2.328 | 17.0 | 56 | 45 | 42 | 44 |

makes no difference to our derived abundances *relative to the Sun*, [Fe/H]. Our reasons for choosing the Holweger & Müller model in order to derive solar *gf*-values are discussed by Drake & Smith (1991). Calcium *gf*-values used were the accurate laboratory values of Smith & Ragget (1981) and G. Smith (1988) except for that for the strong 6162 Å line, which was the laboratory value of Smith & O'Neill (1975).

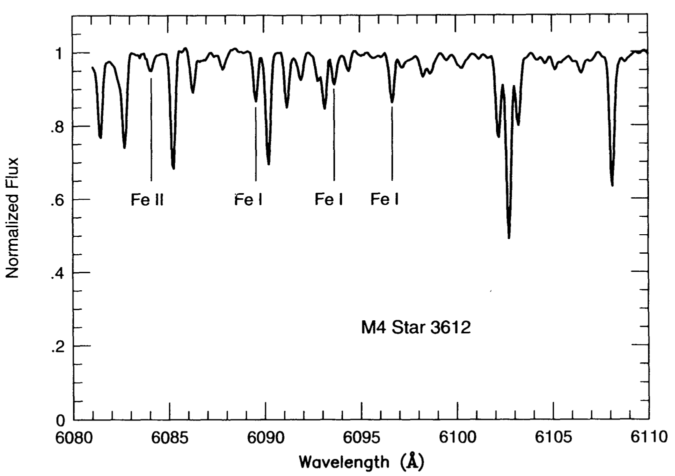


FIG. 1.—6200 Å region in star 3612, illustrating typical Fe lines used in the analysis.

### 3.3. *Collision Broadening Parameters*

In the case of Fe I, broadening parameters for collisional interactions with atomic hydrogen, represented in Table 3 by valence-electronic mean square radii in units of $\pi a_0^2$, were the values calculated by Warner (1969) and scaled by the empirical van der Waals enhancement relation derived from Fe I lines in the solar spectrum by Simmons & Blackwell (1982). This scaling factor is an increasing function of excitation and, for our choice of Fe I lines, amounts to approximately a factor of 2. The mean square radii of Warner (1969) were calculated using scaled Thomas-Fermi wave functions and account for the dependence of the damping constant on the parity of the lower level of the transition.

Broadening parameters for Fe II lines derived from the Unsöld (1955) relation are frequently unrealistically small, and sometimes even negative, because of the inadequacy of the Coulomb approximation for representing Fe II wave functions. Instead, for Fe II lines, we applied the Unsöld formula assuming zero radius for the lower level. In the case of Ca I, we adopted the broadening parameters of Smith & Raggett (1981), and, for the strong 6162 Å line, the semiempirical values of O'Neill & Smith (1980).

### 3.4. *Equivalent Widths*

Stellar equivalent widths were measured by means of Gaussian fitting. This procedure resulted in no loss of accuracy, since at the resolution of our stellar spectra ($\lambda/\Delta\lambda = 35,000$) the combined effects of the instrumental profile and stellar rotation and macroturbulence could be well approximated by a Gaussian function. In the case of the solar spectrum, however, Gaussian profiles are a rather poor approximation to even fairly weak spectral lines. In addition to line asymmetries caused by the granulation contrast, solar line profiles exhibit wings that are slightly broader and cores slightly more narrow than a Gaussian function of the same width at half-maximum. The equivalent widths required to calculate solar oscillator strengths for our set of Fe lines were measured using a more realistic approach. Since our rigorous line selection procedure resulted in a small sample of Fe lines whose solar profiles are generally clean and free from blends, for the majority of the lines we therefore measured solar equivalent widths by means of direct integration. In cases where one of the wings of a line was compromised slightly by a weak blend, the mirror image of the opposite wing served as a guide to remove the blend. In the analyses of solar-type stars and of Pollux, described by Smith & Drake (1987) and Drake & Smith (1991, 1993), solar equivalent widths were measured in a similar manner, except that any weak blends in the line wings were removed by replacing the compromised fraction of the line profile with the corresponding fraction of a synthetic profile, calculated using an appropriate model atmosphere. A comparison of our direct-integration equivalent widths measured here with those of Drake & Smith for the lines common to our and their analyses was gratifying: in no case was the difference between the two methods greater than 2 mÅ. In order to minimize systematic errors in equivalent widths, which might arise as a result of subjective measurement by different workers, all of our equivalent widths were measured by the same person (J. J. D).

### 3.5. *Stellar Parameters*

#### 3.5.1. *Method*

Our procedure for obtaining a self-consistent set of stellar parameters is summarized below:

1. We prepared a set of model atmospheres for conjectured values of surface gravity and metallicity ($\log g = 1.2$ and $[M/H] = -1.2$) and for a range of values of $T_{\rm eff}$ (3800–4500 K). The values of surface gravity and metallicity served as initial estimates of these parameters and were taken from the values listed and derived by Suntzeff & Smith (1991); the range of $T_{\rm eff}$ values was chosen so as to encompass the likely range of temperatures of our chosen stars. For each model atmosphere, we then derived iron abundances, [Fe/H], for the Fe I and Fe II lines listed in Table 3, from their measured equivalent widths for each of the four stars. For each star, the iron abundances derived for an Fe line from the set of model atmospheres with different effective temperatures then define a locus of constant equivalent width in the $T_{\rm eff}$-[Fe/H] plane (e.g., Fig. 2). Loci derived from Fe I lines have a positive slope, and those derived from Fe II lines have a negative slope in this plane; the region of intersection of the set of Fe I and Fe II loci provide initial estimates of [Fe/H] and $T_{\rm eff}$ for each star. The result is fairly insensitive to the value chosen for the microturbulence.

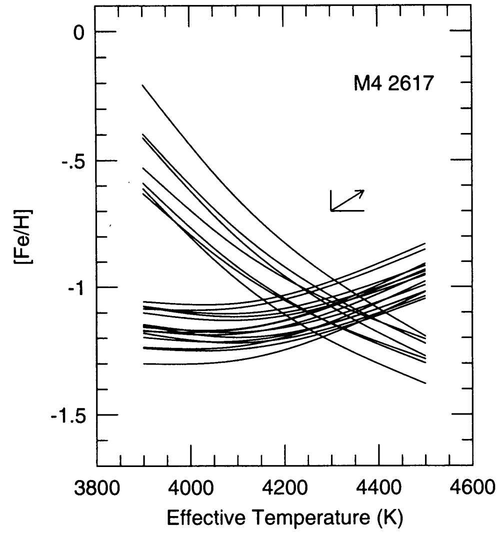


FIG. 2.—Illustration of the determination of the effective temperature and iron abundance for star 2617. The iron abundances were calculated for values of log *g* and microturbulence close to those finally adopted: loci with a positive slope correspond to Fe I lines, those with a negative slope correspond to Fe II.

2. Using model atmospheres corresponding to the initial estimates of $T_{\rm eff}$ and [Fe/H] (initially assuming [M/H] = [Fe/H]) for each of our program stars, we derived calcium abundances, Ca/H, as a function of microturbulence, $\xi$. These abundances define loci of constant equivalent widths in the Ca/H-$\xi$ plane and normally intersect in a narrow region, or "neck," which provides initial estimates for Ca/H and $\xi$ for each star (e.g., Fig. 3).

3. For each star we prepared a set of model atmospheres for a range of values of surface gravity, but with [M/H] and $T_{\rm eff}$ corresponding to the initial estimates. Using these atmospheres, together with the estimates of Ca/H and $\xi$, we synthesized the spectral region in the immediate vicinity of the Ca I

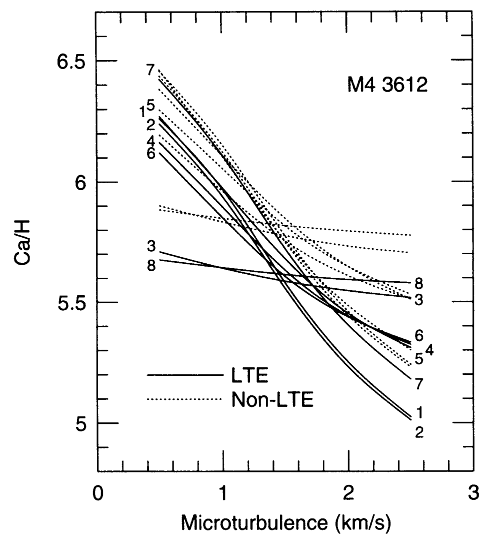


FIG. 3.—Logarithmic abundance of calcium as a function of microturbulence, $\xi$, for star 3612. Key to lines: (1) 5581.97, (2) 5590.12, (3) 5867.56, (4) 6161.29, (5) 6166.44, (6) 6455.60, (7) 6471.66, and (8) 6508.84 Å.

6162 Å line. Smith & Drake (1987) and Drake & Smith (1991) have demonstrated that the strong, collisionally broadening wings of this line provide a sensitive diagnostic of surface gravity in both late-type dwarf and giant stars. Since our program stars are significantly more metal deficient than those considered by Drake & Smith, the Ca I 6162 Å line appears weaker in our stellar spectra. Nevertheless, test calculations indicated that the line wings were still sufficiently sensitive to atmospheric pressure to provide useful observational leverage on the surface gravity. Our spectra are also of lower resolution than those analyzed by Drake & Smith, and we found it necessary to include the strongest of the multiplet 5 Na I lines near 6160 Å, the Ca I line at 6161.3 Å, and the Fe/Ni blend near 6163 Å in our synthesis (the last of which, in our spectra, appeared blended with the weak Ca I 6163 Å line). Comparison between the observed and synthetic spectra, calculated using the different model atmospheres, then yielded an improved estimate of the surface gravity of each star (e.g., Fig. 4, *upper panel*).

4. The spectral indices used to determine $T_{\rm eff}$, log $g$, and microturbulence, $\xi$, described in items 1–3 above are nonorthogonal, and in order to obtain a self-consistent set of parameters, these three stages are iterated to convergence. In the cases of all four stars, convergence was achieved in 3–4 iterations.

### 3.5.2. *Calculations and Results*

Abundance calculations were performed under the conditions of LTE and plane-parallel geometry using the program LINFOR (H. Holweger, M. Steffen, & W. Steenbock, Univ. Kiel). In their analysis of the K0 giant Pollux, Drake & Smith (1991) derived an empirical model atmosphere using the wings of the very strong Ca II infrared triplet line at 8542 Å. The resulting atmosphere was very close to a model with the same parameters generated using the MARCS program. We therefore chose MARCS models as being the best available for the present analysis. The MARCS models are similar to those described by Gustafsson et al. (1975) and published in grid form by Bell et al. (1976).

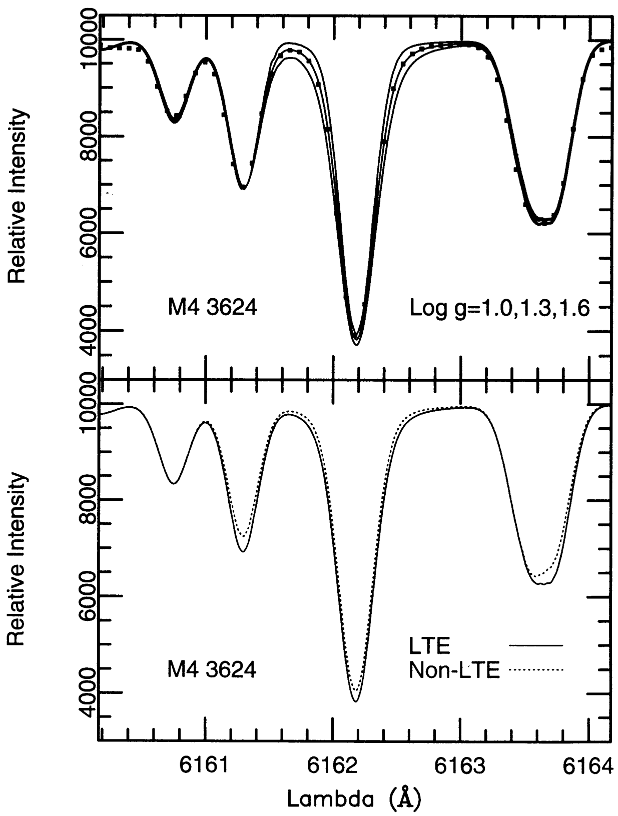


FIG. 4.—Illustration of the 6162 Å region that was used to determine the surface gravity of star 3624. The upper panel exhibits the observed spectrum (*points*) and the LTE syntheses calculated for values of surface gravity (from inside to outside) log $g$ = 1.0, 1.3, and 1.6. The lower panel shows a comparison between the LTE and non-LTE syntheses.

As the analysis proceeded, it became clear that calcium was enhanced relative to iron by about 0.2 dex or so. Calcium is an $\alpha$ element, and such enhancements of the $\alpha$ elements are now commonly observed in metal-deficient stars (e.g., Wheeler, Sneden, & Truran 1989). It is likely, then, that the abundances of the common electron-donor elements Mg and Si (both $\alpha$ elements) are also enhanced relative to Fe by a similar amount as Ca. Indeed, we have confirmed that this is the case in all four stars from a preliminary analysis of Si and Mg lines: these results will form part of a future paper in which we will also present abundances derived for other heavy elements. In the final iteration of our scheme, above, we therefore included enhancements of Mg and Si equivalent to that observed in Ca in our atmospheric models.

The final iteration to determine the effective temperature and iron abundance for star 2617, microturbulence and calcium abundance for star 3612, and surface gravity for star 3624, are illustrated in Figures 2, 3, and 4 (*upper panel*), respectively. The final sets of parameters derived for all four stars are listed in Table 4, together with the standard deviations in derived iron and calcium abundances at the confluence of loci of constant equivalent width, and the formal uncertainties in each quantity, $\sigma_F$, estimated as explained below. Figures 3 and 4 (*lower panel*) also illustrate the non-LTE results which we discuss in the following section.

Estimating the uncertainties of our results is more complex than usual, since each parameter, through our iterative procedure, is somewhat dependent on each of the other parameters. The *experimental* uncertainties, disregarding any systematic effects in our modeling approach, are given by the definition of the convergence of the iterative method.

The accuracy of the effective temperature is essentially determined by the uncertainty in the surface gravity and by the scatter of the [Fe/H]-$T_{\rm eff}$ loci corresponding to the Fe I and Fe II lines. The standard deviation of the abundances derived from the Fe lines corresponds to a spread in effective temperature of about $\pm 60$ K at the intersection of Fe I and Fe II loci. As we explain below, the uncertainty in the surface gravity amounts to about $\pm 0.2$ dex. Such an uncertainty in log $g$ engenders an uncertainty of $\pm 70$ K in $T_{\rm eff}$. Adding the uncertainties in quadrature yields a total uncertainty in $T_{\rm eff}$ of 90 K. The error vector in the [Fe/H]-$T_{\rm eff}$ plane corresponding to an error of $+0.2$ in log $g$ is illustrated in Figure 2.

The uncertainty in the iron abundance, [Fe/H], can be derived in the same way as that in the effective temperature. It is, analogously, almost wholly determined by the uncertainty in the surface gravity and the scatter in the [Fe/H]-$T_{\rm eff}$ loci. An uncertainty of 0.2 in log $g$ implies an uncertainty of 0.08 dex in [Fe/H]; combining this in quadrature with the scatter in the loci yields a total uncertainty in [Fe/H] of approximately 0.1 dex.

The uncertainty in our surface gravity is governed primarily by the resolution of the fit of the synthetic Ca I 6162.2 Å line profiles, which we estimate to be about 0.15–0.2 dex. The

TABLE 4

STELLAR PARAMETERS AND ABUNDANCES DERIVED IN THIS ANALYSIS

| PARAMETER OR ABUNDANCE | STAR 2617 | 3612 | 2519 | 3624 | $\sigma_F$ | WLO[a] |
|---|---|---|---|---|---|---|
| $T_{eff}$ | 4280 | 4350 | 4480 | 4300 | ±100 | 4125 |
| log $g$ | 1.22 | 1.28 | 1.34 | 1.30 | ±0.2 | 1.1 |
| $\xi$ (km/s) | 1.5 | 1.5 | 1.8 | 1.7 | ±0.2 | 3.0 |
| [Fe/H] | −1.08 | −1.02 | −1.07 | −1.04 | ±0.1 | −1.2 |
| $\sigma_{n-1}$ | 0.07 | 0.06 | 0.07 | 0.06 | ... | ... |
| [Ca/H] | −0.80 | −0.74 | −0.92 | −0.86 | +0.2/−0.15 | −0.6 |
| $\sigma_{n-1}$ | 0.02 | 0.04 | 0.06 | 0.07 | ... | ... |
| $\Delta T$ | 237 | 200 | 280[b] | 182 | ... | ... |

[a] Values for star 3624 from Wallerstein et al. 1987.

[b] Value derived from $B-V$ temperature of Suntzeff & Smith 1991; see text.

surface gravity is relatively insensitive to effective temperature: raising $T_{eff}$ by 100 K leads to a value for log $g$ about 0.05 dex lower. The scatter in our Ca abundances from individual Ca lines also affects the surface gravity, corresponding, typically, to an uncertainty of 0.06 in log $g$. Considering these quantities in quadrature leads to a total uncertainty in log $g$ of ±0.2 dex or so.

The microturbulence values are robust and nearly independent from temperature and gravity over their ranges of interest here. Consequently, the uncertainty in $\xi$ is dominated by the scatter of Ca I loci and typically amounts to ±0.1–0.15 km $s^{-1}$. The calcium abundance, Ca/H, has a total uncertainty of 0.1–0.15 dex.

### 3.6. *Relaxing the Assumption of LTE*

In the analysis described above, there might remain some doubt as to whether departures from LTE play a significant role. The effects of departures from LTE on the derivation of fundamental parameters, using a similar method to that described above, for the bright K0 giant $\beta$ Gem were investigated in detail by Drake & Smith (1991). They concluded that their method was relatively insensitive to non-LTE effects, the LTE and non-LTE analyses yielding very similar results. Nevertheless, we thought it worthwhile to undertake a more quantitative estimate of non-LTE effects: our program stars are significantly cooler and more metal deficient than $\beta$ Gem, and it is not yet known whether effects of departures from LTE will be significantly different in the two spectral types. Simultaneous radiative transfer and statistical equilibrium calculations for a model atmosphere representative of our program stars ($T_{eff}$ = 4300 K, log $g$ = 1.3, [M/H] = −1.0) were therefore undertaken.

Model atoms used were updated versions of the Ca and Fe models described in detail by Watanabe & Steenbock (1985) and Steenbock (1985) respectively. The Ca model comprised 16 levels of Ca I, five levels of Ca II, and the Ca III continuum, including 23 bound-bound radiative transitions treated in detail. The Fe model comprised 74 levels of Fe I, 25 levels of Fe II, and the Fe III continuum, including 75 bound-bound radiative transitions treated in detail. The non-LTE code employed was a modified version of the code MULTI (Carlsson 1986). Excitation and ionization by collisions with neutral hydrogen atoms were accounted for according to the scheme suggested by Steenbock & Holweger (1984). The effects of line blanketing on the ionizing radiation field were included using the Kurucz (1979) opacity distribution functions (ODFs).

#### 3.6.1. *Iron*

The results of the non-LTE computations are illustrated in Figures 5 and 6. In Figure 5, the non-LTE abundance corrections for iron, defined here as the correction to be added to the LTE result in order to arrive at the non-LTE result, $[Fe/H]_{NLTE} - [Fe/H]_{LTE}$, is plotted as a function of line equivalent width. The corrections are all small, amounting to an average of about 0.06 dex for the Fe I lines and to about half this value in the case of the Fe II lines. The characteristics of these small departures from LTE are similar to those described by Steenbock (1985), whose radiative transfer and statistical equilibrium calculations for iron, using model atmospheres appropriate to the Sun and to the K0 giant Pollux, uncovered a pattern influenced predominantly by overionization. Overionization of Fe I was found to increase with increasing atmospheric height, echoing the increasing nonlocality of the ionizing radiation field and the decrease in thermalizing collision rates with altitude. The Fe I lines are then weaker than predicted by the LTE approximation—hence the non-LTE corrections are positive—with the departures from LTE increasing with increasing line strength. We have minimized the effects of departures from LTE by using only weak lines that are formed in atmospheric layers deep enough to suffer only very slightly from overionization effects. Applying these results to our ionization balance leads to negligible corrections

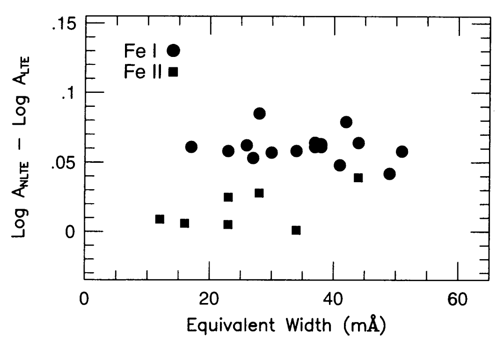


FIG. 5.—Non-LTE abundance corrections for Fe as a function of line equivalent width, calculated for a model with parameters $T_{eff}$ = 4300 K, log $g$ = 1.3, and [M/H] = −1.0.

to the LTE results: [Fe/H] increases by only 0.02 dex, while the effective temperature is increased by about 20 K.

#### 3.6.2. *Calcium*

In the case of calcium, we see a trend of *decreasing* non-LTE abundance correction (defined in the same way as for iron, above) with *increasing* equivalent width. This effect was discussed by Watanabe & Steenbock (1985) and by Drake (1991). It results, in essence, from a combination of the effects of overionization and, for these particular multiplets, source function depletion: weak lines formed entirely in deep atmospheric layers, beyond the line thermalization depth, are subject to overionization and consequent depletion in line strength; stronger lines whose cores are formed above the thermalization depth are both depleted by ionization and enhanced by source function depletion. The other obvious trend in Figure 6 is the increase in abundance correction with increasing microturbulence for the lines with equivalent width >40 mÅ. The increase in line equivalent width due to microturbulent broadening occurs predominantly in the atmospheric layers where overionization, rather than nonthermal line source functions, dominate the departures from LTE. A higher microturbulence thus leads to larger abundance corrections.

The results of applying the non-LTE analysis to the set of Ca I lines is illustrated in Figures 3 and 4. The positive corrections due to the overionization predicted by the model calculations lead to a calcium abundance that is higher by 0.18–0.19 dex. The microturbulence remains more or less unaltered at 1.5 km $s^{-1}$. Departures from LTE affect the surface gravity estimate through the modification of the 6162 Å line itself and through the calcium abundance used to calculate its line profile. Figure 4 (*lower panel*) illustrates the LTE and non-LTE syntheses of the 6162 Å line region, calculated for LTE parameters and abundances, including calcium, appropriate to star 3624. In the deeper layers, where the line wings are formed, overionization affects the 6162 Å line and the Ca I lines used to determine the calcium abundance to a similar extent. The theoretical non-LTE 6162 Å line wings are weaker than in the LTE case, but this is partially compensated for by the increase in calcium abundance required by the weaker Ca I line equivalent widths: the surface gravity derived is not drastically affected. Using the LTE calcium abundance for each star, results in a surface gravity approximately 0.2 dex higher in non-LTE than in LTE. However, increasing the calcium abundance by 0.2 dex, as required by the non-LTE abundance analysis, then yields a gravity 0.05 dex *lower* than in LTE.

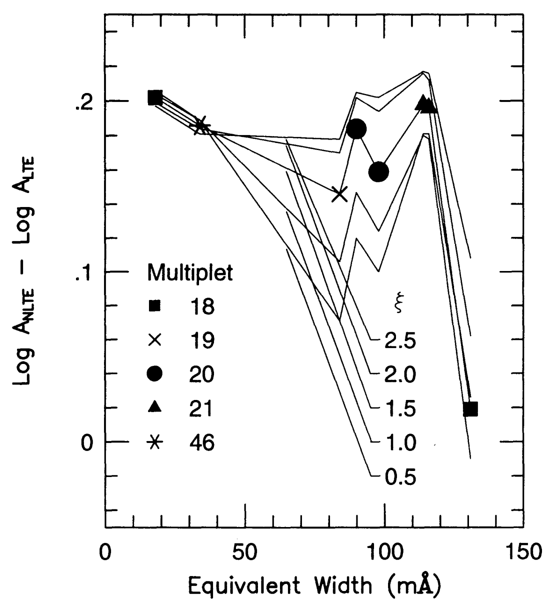


FIG. 6.—Non-LTE abundance corrections for Ca as a function of line equivalent width; the thin solid lines join points corresponding to the same microturbulent velocities.

We conclude that the only significant result of relaxing the LTE assumption in our analysis is a calcium abundance that is higher than in LTE by slightly less than 0.2 dex. It is, however, possible that even this effect is somewhat of an overestimate. In a non-LTE study of calcium using essentially the same model Ca I/II/III atom, Drake (1991) suggested that the effects of overionization might be overestimated due to the incomplete line list in the Kurucz (1979) ODFs and to the neglect of excited levels in the model Ca atom. The Kurucz (1979) model atmospheres are known to be too blue due to the omission of some molecular absorption and to excited transitions in iron group elements (Kurucz 1990). Neglect of high-excitation Rydberg levels in the model atom inhibits the collision-driven flow of electrons between lower levels and the continuum. Consequently, the influence of the radiation field on the ionization balance through bound-free transitions is overestimated, and a non–local radiation field can give rise to spurious non-LTE overionization effects (e.g., see Gigas 1986; Carlsson, Rutten, & Shchukina 1992). A spuriously high radiation field obviously compounds this problem. For these reasons we consider our final non-LTE abundance correction for Ca of 0.2 or so to be an upper limit. We therefore retain our final LTE value for Ca/H but increase the uncertainty in Table 4 to take into account the non-LTE results.

## 4. DISCUSSION

### 4.1. *Effective Temperatures*

Glancing through the literature, it is noticeable that the effective temperatures derived here are higher, perhaps significantly, than those of previous studies. Without exception, the earlier studies used temperatures based on photometric material—indeed, possibly all previous studies of globular cluster stars have relied on photometrically derived temperatures.

We should point out here that, as has been discussed in the literature on previous occasions (e.g., Gustafsson & Gråe-Jørgensen 1985), a spectroscopic effective temperature such as ours is based on a model atmosphere label temperature and is not strictly related to the stellar integrated flux. Our iron ionization balance method using solar *gf*-values ensures that, for spectral types very similar to the Sun, the label temperature will be identical to the true effective temperature. For spectral types differing significantly from solar, it is possible that systematic differences between the label and true effective temperatures might arise. Of course, even if this should be the case, the spectroscopic label temperature would be the appropriate quantity to use in model atmosphere analyses. However, the trend in previous studies of this nature (e.g., Smith & Drake 1987; Drake & Smith 1991, 1993) is for our spectroscopically derived effective temperatures to agree with the most recent and reliable photometric determinations—see Smith (1992) for a discussion.

#### 4.1.1. *Photometry*

The photometry most often cited for M4 is that of Frogel et al. (1983) who derived $(V-K)$ temperatures for stars in several different clusters. Their temperature scale is essentially that of Ridgway et al. (1980). The differences, $\Delta T$, between our temperatures and those of Frogel et al. are listed in Table 4. They amount to approximately 200 K, with ours being the higher values. Star 2519 was not studied by Frogel et al.; instead the difference, $\Delta T$, we have listed is based on the temperature of Suntzeff & Smith (1991). These latter authors used the $(B-V)_0$ colors of Cudworth & Rees (1990) for stars in common with the sample of Frogel et al. and established a $T_{\rm eff}$-$(B-V)_0$ scale for M4 based on the Frogel et al. calibration.

Since the uncertainties in our own effective temperatures are much less than $\pm 200$ K, and the uncertainty typically cited for photometric calibrations is $\pm 100$ K, we must conclude that our temperatures are not in good agreement with those of Frogel et al.

One possible reason for the discrepancy in effective temperatures is that for late K giants the temperature calibration is simply not very accurate. Bell & Gustafsson (1989, p. 653) wrote, "It is obvious from the recent literature ... that the problem of determining red-giant temperatures is an important one that has still not been satisfactorily solved." While the recent work of Di Benedetto (1993) and Di Benedetto & Rabbia (1987), based on Michelson interferometric stellar angular diameters, has considerably improved matters for the solar metallicity giants, in the case of metal-deficient globular cluster red giants this is still true. Based on our own temperatures, we suggest that the Frogel et al. temperature scale could be too cool by perhaps 150 K. Some support for this view can be found in the recent infrared flux calibrations of Blackwell, Lynas-Gray, & Petford (1991) and Bell & Gustafsson (1989): within our temperature range (4000–5000 K), the Bell & Gustafsson calibration is about 100 K hotter than that of Ridgway et al.; whereas Blackwell et al. arrive at a calibration approximately 65 K hotter. These calibrations are for stars of approximately solar composition. Although the $(V-K)$ index is relatively insensitive to metallicity, in the Bell & Gustafsson calibration, for the temperature and gravity appropriate to our program stars, a metal deficiency of 1.0 dex with respect to solar corresponds to a temperature higher by about 30–40 K. For globular cluster giants, then, it is straightforward to see that the Ridgway et al. scale could be too cool by 100–150 K. Such a systematic error is not inconsistent with the uncertainties in the Ridgway et al. analysis: they emphasize that these uncertainties will lead to underestimated effective temperatures.

It should be noted that the work of Di Benedetto (1993) probably supercedes in accuracy that of Ridgway et al. but largely vindicates the Ridgway et al. calibration. While the metallicity dependence of the $(V-K)$ index certainly will introduce systematic errors in the Frogel et al. temperatures, as noted above, it is also possible that the model atmospheres we have adopted introduce a systematic bias in our spectroscopic effective temperatures. Atmospheric models become increasingly unreliable toward the cooler end of the temperature scale, predominantly as a result of the increasing importance of molecular blanketing, whose complexity is not easy to model with high accuracy. We will discuss the globular cluster temperature scale in more detail in future papers: similar analyses of stars with different parameters in different clusters will certainly provide further insight into these problems.

#### 4.1.2. *Reddening*

In the case of M4, as we mentioned briefly in § 1, the rather uncertain reddening caused by the interposing Sco-Oph nebulosity also conspires to degrade the precision of photometric endeavors. Cacciari (1979) painted a rather gloomy picture, pointing out that the existing estimates of reddening covered the range $0.27 \le E(B-V) \le 0.55$. The situation has been discussed by several authors in the past (e.g., Alcaino 1975; Lloyd Evans 1977; Lee 1977; Sturch 1977; Cacciari 1979; Sandage 1981; Frogel et al. 1983; Liu & Janes 1990; Cudworth & Rees 1990). A fairly complete, but probably not exhaustive, list of the reddening determinations that have appeared in the literature is reproduced in Table 5.

The highest of these reddening values is from Alcaino (1975) and was adopted from a combination of a literature cull and his own *B* and *V* photometry. The integrated colors of Racine (1973) yielded the lowest value. For our stars, the whole range of reddening values, $0.27 \le E(B-V) \le 0.55$, corresponds to a $(V-K)$ temperature uncertainty of approximately $\pm 250$ K. However, the two extreme reddening values are responsible for a large fraction of this range, and uncertainty in temperature due to the $(V-K)$ uncertainty is likely to be considerably smaller than this. The unweighted mean of all the values in Table 5 is 0.39 with a standard deviation of 0.06. This standard deviation corresponds to an uncertainty in $(V-K)$ temperature of approximatly $\pm 120$ K; we therefore suggest that there is an uncertainty in the photometric temperature scale for M4, due to reddening, of about 120 K.

Additional, slightly smaller photometric uncertainties possibly arise as a result of differential reddening. The issue of possible significant differential reddening for M4 remains controversial. Newell (1970) was one of the first proponents of patchy reddening, finding values of $0.37 \le E(B-V) \le 0.63$ from the observed distributions of blue horizontal branch stars. Crawford & Barnes (1975) also noted that they could not obtain a consistent reddening across the field of M4. Considering the rather large angular size of M4 and its galactic location,

TABLE 5

REDDENING VALUES FOR M4 FOUND IN THE LITERATURE

| Source | $E(B-V)$ |
|---|---|
| Greenstein 1939 | 0.42 ± 0.09 |
| Kron & Mayall 1960 | 0.39 |
| Newell 1970 | 0.45 ± 0.03 |
| Eggen 1972 | 0.36 |
| Phillip 1973 | 0.34 |
| Racine 1973 | 0.27 ± 0.05 |
| Harris & van den Bergh 1974 | 0.30 |
| Kukarkin 1974 | 0.36 |
| Alcaino 1975 | 0.55 |
| Burstein & McDonald 1975 | 0.37 ± 0.04 |
| Kron & Guetter 1976 | 0.49 |
| Lee 1977 | 0.40 ± 0.03 |
| Sturch 1977 | 0.34 |
| Cacciari 1979 | 0.36 ± 0.02 |
| Harris & Racine 1979 | 0.35 ± 0.04 |
| Zinn 1980 | 0.37 ± 0.03 |
| Sandage 1981 | 0.36 |
| Frogel et al. 1983 | 0.36 |
| Alcaino & Liller 1984 | 0.44 ± 0.03 |
| Richer & Fahlmann 1984 | 0.37 ± 0.06 |
| Alcaino et al. 1988 | 0.41 ± 0.03 |
| Cudworth & Rees 1990 | 0.40 ± 0.04 |
| Mean ± $\sigma_{n-1}$ | 0.39 ± 0.06 |

these results cannot be entirely unexpected. Unfortunately, the conclusion of Geisler (1986, p. 851), that the long-standing debate on the existence of differential reddening in M4 "appears to have been settled in favor of a uniform value," was perhaps premature, as the recent detective work of Cudworth & Rees (1990) suggests. These authors appealed to differential reddening to explain the rather poor separation of the RGB and AGB in their M4 color-magnitude diagram and the rather large width of the subgiant branch. These effects were considerably larger than their photometric accuracy allowed through observational uncertainties. Cudworth & Rees found that an east-west gradient in reddening of $83 \pm 10$ m mag per kiloarcsec could largely account for these effects. They attributed a residual scatter of individual stars about this linear reddening gradient to a possible patchiness in the reddening. Again, translating these effects into $(V-K)$ temperature uncertainties, this gradient corresponds to approximately 170 K per kiloarcsec, or to a temperature difference of about 90 K across the 9′ span of the central three regions designated by Lee (1977). Now, of our four stars, two lie westward and two eastward of the cluster center. In particular, star 2519 lies the farthest westward from the cluster center, where the reddening should be higher. If there is indeed significant differential reddening across the face of M4, then we might expect a trend in the difference, $\Delta T$, in effective temperatures derived using our reddening-independent method and those derived by Frogel et al. from $(V-K)$ colors. Note that Frogel et al. did not take into account any differential reddening in their temperatures for M4; $\Delta T$ should, therefore, be larger for the two stars to the west of the cluster than for the two stars to the east, and especially for star 2519. This is exactly the pattern we observe in $\Delta T$. Our differences in temperature, $\Delta T$, are 280 K and 237 K for stars 2519 and 2617, respectively, whereas for stars 3612 and 3624, they are 200 K and 182 K. This result provides further convincing evidence for the presence of a nonuniform reddening in the field of M4.

#### 4.1.3. *Summary*

In summary, accurate photometric temperatures for stars in M4 appear to be foiled by uncertain reddening. The uncertainty in the mean value of the reddening leads to a temperature uncertainty of $\sim 100$ K, and the to-date rather poorly defined differential reddening leads to uncertainties of $\sim 50$ K. Since the differential reddening is most probably partially responsible for the scatter in reddening measurements themselves, we estimate the total uncertainty to be of the order of $\pm 100$ K. As a result of these uncertainties, and of the relatively uncertain temperature scale for metal-poor giant stars, the Frogel et al. photometric temperatures for M4 giants are too cool by an average of approximately 200 K.

### 4.2. *Metallicity*

At the beginning of the last decade, there was considerable disagreement between metallicity determinations of globular clusters using high-resolution spectroscopy and those using low-resolution or photometric material, in the sense that the high-resolution studies generally yielded lower abundances. The disagreement was largest for the "metal-rich" clusters, with, in some cases, spectroscopic abundances being a factor of 3 or more smaller than abundances determined using the broadband techniques. The status of globular-cluster metallicity determinations prior to the widespread use of CCD detectors is nicely summarized in the critique of Gratton et al. (1986) and in the discussion by Pilachowski et al. (1983).

The great majority of globular clusters, including M4, appear to be homogeneous in their distributions of Fe peak elements, in that the abundances of these elements are generally found to be the same, within the experimental uncertainties, in different individual member stars of any given cluster. Two notable exceptions are $\omega$ Cen and M22. See, for example, the review by Smith (1987) for an overview. In the case of M4, this picture has been challenged, albeit unsuccessfully: Lambert, McWilliam, & Smith (1992) raised the interesting question of whether blue horizontal-branch stars might be significantly more metal rich than stars on the red giant branch. This conjecture was based on the work of Kodaira & Philip (1984), who obtained [Fe/H] = −0.4 for stars just to the blue of the RR Lyrae gap in M4 (and [Fe/H] = −1.4 for NGC 6397) from 2.5 Å mm$^{-1}$ image tube spectra. Lambert et al. suggested that the apparent metal enrichment could be the result of element diffusion on the blue horizontal-branch, or, possibly, a manifestation of photospheric He enrichment provoked by the He core flash. Lambert et al. dismissed their own conjecture through an observational study of two stars in M4 (and one in NGC 6397) in common with the sample of Kodaira & Philip, obtaining a mean of [Fe/H] $\sim -1.1$. A formal uncertainty is not stated, although from the stated standard deviations of abundances from individual Fe lines, this is likely to be of order $\pm 0.25$ dex.

#### 4.2.1. *This Work*

Lacking any further evidence to the contrary, if we assume that the iron content of our program stars is representative of that of M4 as a whole, then we obtain for the cluster [Fe/H] = $-1.05 \pm 0.03$, where the uncertainty here is combined from our individual results using the usual relation, $\sigma^2_{\rm total} = 1/\sum (1/\sigma_i)^2$. This uncertainty is too small but does demonstrate the remarkably low scatter in our results. Further systematic errors which might occur as a result of inadequacies in our model atmospheres and radiative transfer, as we discussed previously, could affect the analysis. As usual, the inscrutability of such effects necessitates adopting a somewhat arbitrary additional uncertainty in compensation. We adopt for our final result

$$[{\rm Fe/H}]_{\rm M4} = -1.05 \pm 0.15$$

for the *iron abundance* of M4.

This result is unremarkable in that it lies close to the mean of the values listed in Table 1. However, we feel that this result represents a large increase in accuracy over existing measurements; our *total* uncertainties are most probably a factor of 2 or more lower than those of comparable studies.

Our calcium results suggest that this element might be slightly more abundant in the CN-strong stars than in the CN-weak stars, by about 0.1 dex or so. This result is rather marginal though, and we defer a full discussion of such a possibility to a future paper. Consequently, our mean Ca abundance, [Ca/H] = $-0.83 \pm 0.08$, has rather more scatter than the mean Fe abundance. We adopt for our final calcium abundance

$$[{\rm Ca/H}]_{\rm M4} = -0.85 \pm 0.2 .$$

Our mean enhancement of Ca relative to Fe is then [Ca/Fe] = 0.2.

#### 4.2.2. *Previous Studies*

We feel that the high quality of our spectroscopic material, combined with a careful method of analysis, has enabled us to place tighter constraints on the metallicity of M4 and on the fundamental stellar parameters of our program stars than previous studies have allowed. Since high-dispersion abundance studies are the only way to calibrate with any certainty the extremely useful, though intrinsically less discriminating, low-resolution and photometric indices, it is, therefore, most important that we understand any differences between our results and previous ones obtained using high-dispersion spectroscopy.

We limit our comparative discussion to those studies that are based on CCD high-dispersion spectroscopy. A literature search uncovered the following: Gratton et al. (1986), Wallerstein et al. (1987), Brown et al. (1990), and Lambert et al. (1992). Since the work of Lambert et al. concerns blue horizontal-branch stars and is not directly comparable to the study in hand, we also omit a discussion of their results.

#### 4.2.3. *Gratton et al. (1986)*

These authors published what appear to be the first high-dispersion CCD studies of five different globular clusters, including M4. From spectra with resolution $\lambda/\Delta\lambda = 15{,}000$ and S/N ratio of 50 or better, they obtained $[\mathrm{Fe/H}] = -1.32 \pm 0.15$, this being the average value obtained for three different K giants. Their spectroscopic material is comparable to our own, although the resolution is significantly lower. Lower resolution necessitates the use of stronger lines, which are more sensitive to the microturbulence parameter. From a similar choice of target stars, our iron abundance is only marginally in agreement with theirs. Since we have no stars in common with their sample, a direct comparison of results is not possible. However, it appears that the reasons the agreement is not better are straightforward and can be attributed entirely to the choice of stellar parameters and *gf*-values.

Gratton et al. used the temperature of Frogel et al. which we believe are too cool. Their analysis suggests that raising their effective temperatures by 200 K—roughly the increase required for consistency with our results—would raise the derived iron abundance by about 0.15 dex. The effect of such an increase in $T_{\mathrm{eff}}$ on the values of surface gravity taken from Frogel et al. and derived from an assumed stellar mass of $M/M_{\odot} = 0.8$ would not be significant.

The *gf*-values used were those of Gurtovenko & Kostyk (1981), which were based on the analysis of line central depths, measured from the star flux spectrum, using the Bell et al. (1976) solar model. Since our solar *gf*-values were derived using the Holweger & Müller (1974) model, small systematic differences in derived [Fe/H] will result. Blackwell et al. (1987) have quantified these effects in detail for Ti I and Cr I (the effects are almost identical in the case of Fe I): for weak lines of medium to high excitation, the Holweger & Müller model yields log *gf* values approximately 0.08 dex larger than does the Bell et al. model (see also Drake & Smith 1991). Pilachowski et al. (1983) derived a larger effect; this was probably a result of the stronger lines used in their analysis. Contrary to the effects of effective temperature and microturbulence discussed above, the use of *gf*-values derived using the Bell et al. model conspires to increase the iron abundance derived from Fe I lines, by slightly less than 0.1 dex.

The net effect of these systematic differences is to raise the Gratton et al. iron abundance relative to our own by approximately 0.1 dex, bringing the two analyses into slightly better agreement.

It is possible that there is a systematic difference between the microturbulent velocities derived in their study and in ours. The average microturbulence for the three stars in their sample is 1.9 km $s^{-1}$. For our four stars, the average is 1.6 km $s^{-1}$. Since the stars of both samples are very similar in temperature and luminosity, we would suppose that their microturbulent velocities should be very similar. Unfortunately, Gratton et al. do not give a detailed account of the method used to determine their listed values of microturbulence, and it is difficult to assess their likely accuracy. Since their abundances are fairly sensitive to microturbulence—they suggest that decreasing the microturbulence by 0.5 km $s^{-1}$ would imply an iron abundance which is higher by $\sim 0.18$ dex—a small overestimate in $\xi$ would have lead to a lower Fe abundance. It is possible that the Gratton et al. iron abundance could have been underestimated by an additional 0.1 dex or so, because of an overestimate in $\xi$.

Gratton et al. also derived Ca abundances for their M4 stars: they obtained an average of $[\mathrm{Ca/H}] = -1.24$, or $[\mathrm{Ca/Fe}] = 0.08$—much lower than our average of $[\mathrm{Ca/H}] = -0.81$ (relative to a solar calcium abundance of Ca/H = 6.36) or $[\mathrm{Ca/Fe}] = 0.24$. Why should the Ca abundances differ more than the Fe abundances? The answer most probably lies in the corresponding abundance uncertainties Gratton et al. cite for uncertainties in the stellar parameters $T_{\mathrm{eff}}$ and $\xi$: in their study, Ca I is more sensitive to changes in both $T_{\mathrm{eff}}$ and $\xi$ than is Fe I, such that application of the "corrections" to the Gratton et al. parameters advocated above to explain the different Fe abundances results in a Ca abundance that is higher by 0.35 dex or so. This result reinforces our diagnosis that the Gratton et al. adopted effective temperatures are slightly too low and microturbulent velocities slightly too high.

#### 4.2.4. *Wallerstein et al. (1987)*

These authors obtained CCD spectra with a resolution of 0.6 Å, used the Frogel et al. photometry and an assumed mass of $M = 0.8\ M_{\odot}$ to estimate effective temperatures and gravities, and obtained abundances for Fe and other elements based on *gf*-values derived from the Bell et al. (1976) solar model. Their value for the metallicity of M4 is [Fe/H] $-$ 1.2—on the face of it a value in reasonable agreement with our own. They estimated the formal uncertainty in this value to be $\pm 0.09$ dex, but also admitted the possibility of a further systematic error of $\pm 0.1$ dex or so because of the model atmosphere modeling technique.

Taking into account the different set of solar *gf*-values used by Wallerstein et al., the comparison between our result and theirs is less gratifying: these authors note that the use of *gf*-values derived using the Holweger & Müller (1974) solar model would result in an iron abundance that is lower by about 0.25 dex (though this difference is considerably larger than that found by Drake & Smith 1991 and by Blackwell et al. 1987). There is one star, star 3624, common to both analyses that permits a direct comparison of results: the comparison is shown in Table 4 (the original results from Wallerstein et al. are quoted, rather than those corrected for the *gf*-value choice). However, if we take into account the values of effective temperature and microturbulence used by Wallerstein et al., the comparison looks less gloomy: raising their effective temperature scale (based on that of Frogel et al. 1983) by 200 K, as suggested in our discussion above, would raise their iron abundance by 0.2 dex.

Another source of discrepancy most probably lies in the rather large value for the microturbulence, 3 km $s^{-1}$, adopted by Wallerstein et al. for all of their stars. The method used to derive this value is not clear, and we find no evidence for such a large microturbulent velocity in any of our stars. It would seem unlikely that the stars in our sample and in the sample of Wallerstein et al. are fundamentally different in some respect—indeed, star 3624 is common to both analyses. A lower microturbulence would raise the Fe abundance, though there is insufficient information to make a qualitative estimate. Gratton et al. suggest that for their Fe lines a microturbulence lower by 1 km $s^{-1}$ would result in [Fe/H] being higher by over 0.3 dex, though this is very sensitive to line strength. Suffice it to say that taking into account the discrepancy in microturbulent velocity between our analysis and that of Wallerstein et al. is easily enough to explain the differences in Fe abundances obtained.

More striking, however, are the relative calcium and iron abundances, which amount to [Ca/Fe] = 0.6, compared to our value of 0.25. A Ca enrichment of 0.6 dex (a factor of 4) relative to Fe would have serious consequences for metallicities derived using photometric or spectrophotometric indices that are sensitive to the Ca abundance, such as $\Delta S$ (Butler 1975) and $Q_{39}$ (Zinn 1980b)—see Pilachowski et al. (1983) for a critical discussion. We find no support in our Ca results for the larger Ca abundance of Wallerstein et al. Gratton et al. (see above) obtained [Ca/Fe] = 0.08; Lambert et al. (1992) obtained [Ca/Fe] = 0.45 and 0.07 from their two blue horizontal-branch stars.

#### 4.2.5. *Brown et al. (1990)*

Brown et al. obtained spectra for four giants in M4 at a resolution of $\lambda/\Delta\lambda \approx 20{,}000$ and with S/N $\sim 100$ or so. Unfortunately, none of their stars are in our sample. They derived abundances of Fe and C, N, and O using models from the Bell et al. (1976) grid, with stellar parameters (see Brown & Wallerstein 1989) estimated using the same prescription as Wallerstein et al. (1987). Oscillator strengths were calculated using equivalent widths measured from the Kurucz et al. (1984) solar flux spectrum and the Holweger & Müller (1974) solar model. Their average iron abundance for the four stars of their sample is [Fe/H] = −1.34, a factor of 2 lower than our value. The maximum uncertainty for each star is estimated to be approximately 0.3 dex, so that the uncertainty for the four-star average is probably 0.15–0.2 dex. They also derived an iron abundance of [Fe/H] = −0.68 for Arcturus to provide an [Fe/H] calibration point.

Within experimental uncertainties, our results and those of Brown et al. are in marginal agreement. Part of the small differences between the two can be explained by the different temperature scale. Brown et al. note that increasing their temperatures by 100 K leads to a 0.05 dex increase in [Fe/H], so that a 200 K increase can account for 0.1 dex. The values of microturbulence used also have a small effect. First, the solar microturbulence used by Brown et al., 0.85 km $s^{-1}$, to calculate solar *gf*-values is rather low for the integrated disk spectrum from which their equivalent widths were measured and is more appropriate for the disk center (e.g., Blackwell et al. 1987); values about 0.3–0.6 km $s^{-1}$ higher have generally been found to be appropriate for the integrated disk (e.g., Holweger, Gehlsen, & Ruland 1978; Smith 1981; Simmons & Blackwell 1982; Blackwell et al. 1987). A solar microturbulence higher by 0.3 km $s^{-1}$ would lower the derived *gf*-values by up to 0.1 dex or more, depending on line strength, thereby yielding higher stellar Fe abundances. Brown et al. (1990, p. 1563) note that their *gf*-values were "systematically higher than the lab values by $\lesssim 0.1$ dex," which could be explained by their adopted solar microturbulence. However, they also claim that "no trend with excitation or line strength is apparent in the comparison," which suggests otherwise; although the effect could be masked somewhat by scatter in the results.

The microturbulence values derived by Brown et al. from the Fe abundances for their M4 stars are generally slightly larger than our own: they average to 2.0 km $s^{-1}$ if the more luminous star of their sample, identified as a possible post–asymptotic giant-branch star, is excluded. Unfortunately, the uncertainty in, or the sensitivity of [Fe/H] to, their microturbulence values is not clear. Since random uncertainties in equivalent width tend to lead to an overestimate in microturbulence when using the abundance–equivalent width correlation technique (Magain 1984), perhaps the Brown et al. values are slightly overestimated, by up to 0.5 km $s^{-1}$. If so, lowering the microturbulence by a few tenths of a km $s^{-1}$ could raise the iron abundance by a further 0.1 dex or so.

Finally, Brown et al. note in their Table VII that at least two of their M4 stars show some emission in the wings of H$\alpha$. Such emission in globular cluster red giants was first recorded by Cohen (1976) and is a common feature in the spectra of luminous cool stars. In a survey of H$\alpha$ emission in globular cluster giants, Cacciari and Freeman (1983) found emission in about one-third of their sample of 143 stars in 12 different clusters. Looking carefully at the H$\alpha$ profiles in our four stars, it seems likely that at least two of them (2617 and 3624) show very weak emission in the blue wing amounting to 2%–3% or so of the continuum. Such emission is almost certainly a result of mass loss rather than chromospheric activity. A very large H$\alpha$ emission flux could indicate potential problems arising from contamination of the spectrum by either line filling or enhanced absorption caused by a circumstellar shell or wind. Our marginal detection of H$\alpha$ emission is consistent with the assumption that our spectra do not suffer from such effects.

### 4.3. *Microturbulence*

In the discussions above, a large part of the possible uncertainties in the iron abundances derived in the different studies relates to the microturbulent velocity. The microturbulence parameter is often the least well constrained parameter in abundance analyses of relatively bright, nearby stars and can contribute a large fraction of the total abundance uncertainties. The exhortation of Griffin & Holweger (1989, p. 253)—"This seemingly innocent but potent parameter deserves more respect than it usually gets, as its abuse can produce drastic effects on abundance results"—rings even more true in the case of globular cluster stars. In globular cluster analyses, the attendant uncertainties connected with microturbulence are compounded further: the stars are rather faint, and the spectral material, being of consequently poorer quality, forces the use of stronger lines, which are more sensitive to microturbulence. Overestimating the microturbulence results in *underestimated* abundances.

Comparing our microturbulence results to those of previous studies, it would appear that the tendency in the latter is to overestimate the microturbulence. This could be due partly to the systematic error which is induced in microturbulence values derived from nonideal data using the traditional [Fe/H]–equivalent width plot, first pointed out by Magain (1984). In their study of seven globular clusters at high resolution, Pilachowski et al. (1983, p. 254) state, "We found that a microturbulent velocity of 3 km $s^{-1}$ was a good choice for all the stars in our sample and could find no compelling evidence in the data to use another value for any star." They indicate that decreasing the microturbulence by 1 km $s^{-1}$ would result in an iron abundance derived from Fe I lines that is lower by 0.26 dex. They do, however, state that the uncertainty in the microturbulence is slightly lower—0.75 km $s^{-1}$. Nevertheless, if the microturbulent velocities we have found in M4 are typical for globular cluster giants, then it is possible that the metallicities derived by Pilachowski et al., and consequently the Pilachowski (1984) globular cluster metallicity scale, were underestimated by 0.3 dex or so—a factor of 2.

The Pilachowski et al. data was obtained using plates with an image intensifier—a combination which did not yield spectra of the quality available subsequently with CCD detectors. A careful analysis of high-quality CCD data should, in principle, yield more accurate microturbulence values. It is interesting to note that the Gratton et al. (1986) analysis of CCD spectra of stars in five different clusters yielded, on average, slightly lower microturbulent velocities than found by Pilachowski et al.: the average velocity for the 14 cluster stars in the analysis is 2.2 km $s^{-1}$. The average microturbulence for the 15 stars in three different clusters studied by Brown et al. is also 2.2 km $s^{-1}$.

Clearly, constraining the microturbulence parameter is an essential step toward defining a more accurate metallicity scale for the globular clusters.

## 5. CONCLUSIONS AND IMPLICATIONS FOR THE GLOBULAR CLUSTER METALLICITY SCALE

Using a 4 m telescope and CCD detector it is possible to obtain spectral data for stars in globular clusters with sufficient resolution and S/N to enable precision model atmosphere analyses to be undertaken with an accuracy commensurate with that to which we are accustomed for much more bright, nearby stars. Using the same combination of LTE and non-LTE modeling applied to the K0 giant Pollux by Drake & Smith (1991), we have determined a self-consistent set of parameters for four giants in the intermediate-metallicity globular cluster M4.

Our result for the iron abundance of M4 is higher by 0.2–0.3 dex than those of previous high-dispersion CCD studies. We conclude that the reasons for this lie primarily in the values used for the stellar effective temperatures and microturbulent velocities. Our spectroscopic temperatures suggest that the photometric temperatures based on the temperature scale of Ridgeway et al. (1980) commonly used for globular clusters are too cool by 100–150 K. In the case of M4, uncertainties in the reddening conspire further to degrade the accuracy of photometric temperatures. Our microturbulent velocities suggest that values for this parameter used in previous studies have been too high, leading to underestimated abundances.

Based on these results, we suggest that globular cluster metallicities derived in previous high-dispersion studies could be too low by 0.2–0.3 dex.

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