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KECK HIRES SPECTROSCOPY OF M92 SUBGIANTS: SURPRISING ABUNDANCES NEAR THE TURNOFF

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ABSTRACT

Using high-resolution, moderate signal-to-noise ratio spectroscopy obtained with the 10 m Keck I Telescope and efficient HIRES echelle spectrograph, we derive abundances of several elements in subgiants near the M92 turnoff. As a consistency check, we also analyze the metal-poor field star HD 140283 and find an Fe abundance in fine agreement with many previous determinations. However, our M92 value ($[\text{Fe}/\text{H}] = -2.52$) is a factor of 2 lower than the abundance derived from its red giant members. Differences in model atmospheres, g_f -values, and instrumental effects might account for this difference, but whether they in fact do so is unclear. We note possible evidence for $[\text{Fe}/\text{H}]$ differences within M92. Our spectroscopic analysis suggests that the M92 reddening, $E(B-V)$, may be 0.04–0.05 mag greater than canonical values, but various uncertainties mean that this conclusion is not definitive; the significant difference in interstellar Na I line strengths in the M92 and HD 140283 spectra may be consistent with an increased reddening. Regardless, the conclusion that either the $[\text{Fe}/\text{H}]$ of M92 has been significantly overestimated from red giants or current reddening/photometry estimates are too small/red is not easily escaped. If the reddening/photometry were in error by this amount, turnoff color-based ages for M92 could be reduced by ~ 4 Gyr. The adjustment to the M92 distance modulus required for a similarly reduced turnoff age that is luminosity-based can be accommodated by increases in extinction and alterations to the metal-poor field star distance scale recently inferred from *Hipparcos* Cepheid and subdwarf data.

Our M92 subgiants demonstrate $[\text{Cr}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, and $[\text{Ti}/\text{Fe}]$ ratios that are unremarkable and essentially identical to the values for HD 140283. $[\text{Ba}/\text{Fe}]$ is 0.45 dex larger for the M92 subgiants than for HD 140283. Surprisingly, we find $[\text{Mg}/\text{Fe}]$ to be 0.55 dex lower in our M92 subgiants than in HD 140283, and $[\text{Na}/\text{Fe}]$ to be 0.76 dex larger in our M92 subgiants than in HD 140283. These differences (and indeed nearly all our abundance ratios) seem immune to various data, analysis, and parameter errors. If real, this striking abundance pattern is suggestive of material in our M92 stars' photospheres that has undergone $\text{Ne} \rightarrow \text{Na}$ and $\text{Mg} \rightarrow \text{Al}$ cycling like that inferred for red giants in M92 and other clusters. While this is generally believed to be an in situ process in cluster giants, the presence of abundant Li in our M92 objects suggests a polluting source acting either primordially or via accretion after cluster star formation. This may be consistent with CN and Na variations on the 47 Tucanae main sequence, recently reported Ba and Eu variations in M15 red giants, possible cluster-to-cluster n -capture abundance differences, and very low $[\text{O}/\text{Fe}]$ ratios observed near the base of the M13 giant branch. We thus suggest that a polluting source of light-element alteration, in addition to the in situ source for more evolved stars, may be required for M92. Comparison of our M92 subgiant abundance ratios with those of M92 red giants may indicate that pollution occurred after the present generation of cluster stars formed, but until the cause or causes of the subgiant versus giant Fe abundance discrepancy are definitively identified, this conclusion is uncertain. A polluting source of our Na and Mg anomalies produced via processing in a previous stellar generation also has complications; namely, how the Mg and Na anomalies arise without apparently any net influence on our subgiants' Li abundances and on the C abundances of other M92 subgiants. A similar quandary may exist in some 47 Tuc turnoff stars. An understanding of cluster abundance variations (by whatever mechanisms) and their behavior with evolutionary state may be needed for a complete understanding of absolute and relative globular clusters ages, and for derivation of the primordial Li abundance.

Key words: globular clusters: individual (M92) — stars: abundances

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1. INTRODUCTION

Spectroscopic abundance determinations in metal-poor halo stars can provide important information about a diverse range of fundamental astrophysical issues, such as Galactic chemical evolution, Galactic formation, stellar structure, stellar evolution, and the age of the Galaxy. Abundances in metal-poor field stars residing in the solar neighborhood have been obtained by numerous investigators to address these important topics. Globular clusters, as archetypal halo components that are believed to be more reliably datable than a given field star, provide a complementary means to address these issues. The advent of modern silicon detectors, 4 m-class telescopes, and efficient echelle spectrographs have resulted in an impressive database of abundances of various elements for numerous individual red giant stars in several globular clusters. Use of current and planned 10 m and 20 m-class telescopes, however, makes it possible to obtain high-resolution, moderate signal-to-noise ratio (S/N) spectroscopy of less evolved globular cluster stars near the main-sequence turnoff.

Abundance determinations of little-evolved stars in globular clusters are of great interest for several reasons. It appears that, in situ, deep mixing and nucleosynthesis have altered the abundances of several light elements (C, O, Na, Al, and Mg) in some globular cluster red giant branch (RGB) stars (see, e.g., the more recent studies of Sneden et al. 1991; Kraft 1994; Pilachowski et al. 1996). For example, in the globular cluster M92, C depletions are seen to begin at the base of the giant branch (if not just above the main-sequence turnoff) and, on average, to increase with evolutionary state up the RGB (Carbon et al. 1982; Langer et al. 1986). These data, the Na abundance distribution with evolutionary state in M13 (Pilachowski et al. 1996), and observations of *n*-capture elements in several globular clusters (Armosky et al. 1994) point to a scenario in which deep mixing and *p*-capture synthesis, the vast extent of which is not predicted by standard stellar models, is operating in situ in globular cluster giants (e.g., Langer, Hoffman, & Zaidins 1997). However, in the globular cluster 47 Tucanae, star-to-star CN and Na variations are observed at the main-sequence turnoff (Briley et al. 1994, 1995). These variations and those in the Eu and Ba abundances of red giants in the metal-poor globular cluster M15 (Sneden et al. 1997) are suggestive of “primordial” (or, perhaps more accurately, non-in situ) mechanisms that have altered the surface abundances of some globular cluster stars. Thus, observational evidence favors in situ processes that alter abundances in some globular clusters and primordial processes that have altered abundances in other clusters. For most clusters, though, the observational evidence needed to infer which (if not both) mechanisms have acted (and when) is unclear or incomplete. For M92, observations of its less evolved stars near the main-sequence turnoff can help address this issue, providing an initial impetus for determining detailed abundances in these objects. The M92 objects considered here have abundant Li at levels grossly comparable to those of metal-poor warm field stars (Deliyannis, Boesgaard, & King 1995; Boesgaard et al. 1998). Thus, abundance signatures of deep mixing seen in such stars would point to a non-in situ mechanism, since Li is destroyed in the interiors of these stars at temperatures lower by an order of magnitude than those where, e.g., $\text{Ne} \rightarrow \text{Na}$ and $\text{Mg} \rightarrow \text{Al}$ cycling

occur.

Second, abundances in lesser evolved stars of M92 are of interest in order to investigate the basic adequacy of determinations made in red giants. While assumptions such as LTE, plane-parallel flux-constant atmospheres, and a host of others seem (at this time anyway) practical simplifications to extract a myriad of valuable information from stellar spectra of metal-poor stars, these assumptions could introduce errors of different magnitudes into abundances derived from dwarfs and red giants (or a metal-poor star versus a more metal-rich analog). For example, dwarf-giant abundance discrepancies have been noted in Population I open clusters (e.g., Griffin & Holweger 1989). In addition, there are also concerns about the adequacy of spectroscopically inferred gravities for Population I clusters and field giants (e.g., Luck & Challener 1995; Trimble & Bell 1981). Uncertainties may exist in the relative adequacy of model atmospheres and of abundance determinations in dwarfs versus giants because of the effects of spherical symmetry assumptions, convection, chromospheric structure, non-LTE (NLTE) and microturbulence (see the review by Gustafsson & Jorgensen 1994). On the other hand, drawbacks to using cluster near-turnoff stars rather than red giants are the lower S/N obtained and that direct comparison of the same stellar and solar spectral features may be impossible or more difficult (though, even if possible, such a comparison is frequently not performed in red giant studies).

Third, spectroscopic parameters and abundances provide necessary ingredients to stellar models used to date globular clusters. To the extent to which (1) abundances in unevolved stars may inherently be more reliably determined than those in red giants and (2) abundances in unevolved stars may be genuinely different than those in more evolved RGB stars as a result of deep mixing, these abundances in stars near the M92 turnoff are of great interest. They can be used to provide observable inputs for the detailed opacity mixture of evolutionary tracks used in computing theoretical isochrones. In addition, spectroscopic constraints may yield information on the relative T_{eff} values of M92 near-turnoff stars and similar field stars. These estimates, in turn, then allow an assessment of the cluster reddening to be made.

Here, we derive abundances of several elements in three subgiants near the M92 turnoff from high-resolution, moderate-S/N spectroscopy carried out with the 10 m Keck I Telescope. Scientifically, M92 is a cluster of great interest because it is believed to be one of the most metal-poor and oldest clusters. From an observational standpoint, M92 is one of the nearest globular clusters accessible from the Northern Hemisphere; this makes the challenging spectroscopy of its near-turnoff stars more feasible than for other clusters. Our analysis emphasizes the consistent determination of solar abundances with which to normalize the stellar results. These results are then discussed in the context of the issues outlined above.

2. OBSERVATIONAL DATA

The observational data analyzed here are those discussed in Deliyannis et al. (1995) and Boesgaard et al. (1998, hereafter BDSK), to which the reader is referred for more details. Briefly, we have obtained spectra of six subgiants between the base of the RGB and turnoff in the old, metal-poor globular cluster M92. The observations were obtained

in 1994 July and 1995 July with the 10 m Keck I Telescope and the efficient HIRES echelle spectrograph (Vogt et al. 1994). The spectra have (incomplete) wavelength coverage from ~ 4430 to ~ 6890 Å (in the atmospheric *B* band) at an inverse resolution of $\sim 45,000$. The photon noise-based per pixel S/N for each of the three main M92 stars discussed here ranges from 25 to 40, with typical values of about 30; for the two additional M92 stars discussed later, the S/N is in the range 10–25. The data quality is similar to the metal-poor field giant study of McWilliam et al. (1995), whose S/N values are, on average, slightly larger than ours, but whose inverse resolution was 18,000–25,000. Various portions of the spectra are displayed in Figures 2–4 of BDSK and Figure 8 below.

We also utilize spectra of the Moon and the metal-poor field subgiant HD 140283 in our analysis. The 30 s lunar spectrum is discussed in King et al. (1997) and was obtained with the same instrumentation and on the same night as our 1994 M92 spectra. The per pixel S/N ranges from ~ 880 to ~ 1500 . The 180 s exposure of HD 140283 was obtained with the same instrumentation and on the same night as our 1995 M92 spectra. The per pixel S/N ranges from ~ 260 to ~ 500 .

3. ELEMENTAL ABUNDANCE ANALYSES

The M92 abundances were derived from the equivalent widths listed in Tables 3 and 4 of BDSK. Continuum rectification and equivalent width measurement for HD 140283 and the lunar spectrum were carried out using the one-dimensional analysis package SPECTRE (Fitzpatrick & Sneden 1987). Uncertainties in the measurements of these low photon noise spectra are dominated by continuum placement; thus, uncertainties were assessed by multiple measurements after plausible adjustments in the continuum location. Abundances for each species were determined from the equivalent widths using the most recent version of the LTE abundance package MOOG (Sneden 1973). We employed the $I/H_p = 1.25$ model atmosphere grids of R. L. Kurucz (1992, private communication). One of the concerns of the present work is the accuracy of spectroscopically constrained stellar parameters. As we argue below, these may depend on sources of atomic data as well as line selection. Thus, the details of our parameters, atomic data, and selection of spectral features are contained in the subsections for each element.

3.1. Iron Abundances

3.1.1. M92 Stars

Because of the metal-poor nature of M92, our incomplete spectral coverage, and only moderate S/N, there are relatively few suitable Fe lines available for measurement in our M92 spectra. BDSK identify and measure 18 Fe I lines. In order to avoid any subjective bias, each of these features was examined prior to any abundance determination to see whether it would be included in the analysis. This examination studied the features in our Keck lunar spectrum and the very high resolution atlas of Kurucz et al. (1984) to check for severe blending or contamination from neighboring lines. Each feature was then also examined in our HD 140283 spectrum. Excluded from the analysis were features for which blending or significant contamination was evident or for which routines in the SPECTRE package indicated significant asymmetries in the HD 140283 spectrum. The

wavelengths and lower excitation potentials of the final selection of 15 Fe I lines are contained in Table 1.

Throughout this work, we have sought to use laboratory oscillator strengths and derive solar abundances (to normalize the stellar abundances) as self-consistently as possible. We also rely on homogeneous sources of atomic data where possible. The decision on the source of *gf*-values is an important one. An example is provided by the recent work of Kostik, Shchukina, & Rutten (1996), who compared the Kiel and Oxford groups' oscillator strengths in deriving an estimate of the absolute solar Fe abundance. Their Figures 5 and 7 indicate that different sets of *gf*-values can introduce trends in abundance versus equivalent width and *gf*-value. Such effects may influence the derived abundances. Moreover, we emphasize that, given the excitation potential versus line strength correlations noted below, trends in abundance with equivalent width suggest that different sources of laboratory oscillator strengths may also yield different spectroscopically derived T_{eff} estimates.

A related but distinct issue is that the selection of Fe lines used in fine analyses may also lead to different abundances and spectroscopically derived stellar parameters. In the case of solar Fe lines, Kostik et al. (1996) note that "suspicious" abundance trends arise when using the Kiel *gf*-values for Fe I lines not in common with those of the Oxford group. Another illustration comes from a recent typical fine spectroscopic analysis of the metal-poor dwarfs HD 25329 and HD 74000 by Beveridge & Sneden (1994). The oscillator strengths that they employ for their assortment of Fe I lines come from the experimental work of O'Brian et al. (1991).

TABLE 1
M92 DATA AND ABUNDANCES

λ (Å)	χ (eV)	$\log gf$	EW (mÅ)	$\sigma(\text{EW})$ (mÅ)	$\log N$ (dex)	$\sigma(\log N)$ (dex)
Fe I:						
4528.627.....	2.18	−0.887	49.7	3.2	5.25	0.07
4871.325.....	2.86	−0.362	18.5	4.1	4.64	0.12
4890.763.....	2.87	−0.394	23.2	2.0	4.81	0.05
4891.502.....	2.85	−0.111	35.9	5.2	4.80	0.11
4918.998.....	2.86	−0.342	32.4	4.9	4.97	0.10
4920.514.....	2.83	0.068	53.6	3.2	4.97	0.07
5171.610.....	1.48	−1.721	23.4	2.0	4.78	0.05
5232.952.....	2.94	−0.057	44.1	7.4	4.99	0.15
5269.550.....	0.86	−1.333	61.4	2.4	4.61	0.05
5328.051.....	0.91	−1.465	57.0	4.5	4.68	0.10
5328.540.....	1.56	−1.850	26.1	2.0	5.05	0.04
5397.141.....	0.91	−1.982	44.5	3.7	4.93	0.08
5405.785.....	0.99	−1.852	49.0	2.0	4.97	0.04
5434.534.....	1.01	−2.126	52.3	8.1	5.33	0.18
5615.658.....	3.33	0.050	26.4	2.0	4.85	0.05
Mg I:						
4702.995.....	4.35	−0.442	14.7	4.9	4.88	0.15
5172.698.....	2.71	−0.393	90.2	2.7	4.73	0.05
5183.619.....	2.72	−0.171	115.3	6.5	4.97	0.10
Ca I:						
6162.180.....	1.90	−0.090	37.3	2.0	4.23	0.04
Cr I:						
5208.432.....	0.94	0.158	28.6	2.8	2.86	0.06
Na I:						
5889.973.....	0.00	hfs	147.9	4.5	4.38	0.06
Ti II:						
4501.278.....	1.12	−0.86	41.6	3.5	2.65	0.07
4563.766.....	1.22	−0.95	46.1	7.4	2.93	0.14
4571.982.....	1.57	−0.53	46.4	4.3	2.85	0.09
Ba II:						
4554.036.....	0.00	0.163	23.7	5.8	−0.92	0.15
6141.727.....	0.70	−0.077	11.6	3.7	−0.51	0.15

Experimental values for some of these lines are also available from the recent work of Bard, Kock, & Kock (1991) and Bard & Kock (1994). Figure 1 shows the difference between the O'Brian et al. (1991) and the Bard et al. (1991) $\log gf$ -values as a function of lower excitation potential for the lines in common to both studies and utilized in the Beveridge & Sneden (1994) analysis. For $\chi \lesssim 2.5$ eV, the majority of differences are smaller than the mean difference; for $\chi \gtrsim 2.5$ eV, the converse is true. Bard & Kock (1994) note that for 80 Fe I lines with $3 \text{ eV} \leq \chi \leq 7 \text{ eV}$ in common with O'Brian et al. (1991), the mean difference in $\log gf$ is 0.003 dex with a scatter of 0.15 dex. However, Figure 1 suggests that for lines actually utilized in analyses of metal-poor stars, the $\log gf$ difference (translating into an equivalent logarithmic abundance difference) may be larger. Moreover, the trend with excitation potential in Figure 1 illustrates that, despite excellent overall agreement between different sets of gf -values, a subset of such lines actually employed may yield different T_{eff} estimates in the analyses of metal-poor dwarfs. The general stellar parameters (excitation and ionization), data quality (S/N), and instrumentation (resolution and wavelength coverage) all influence the selection of features available for analysis in metal-poor stars like those discussed here. Thus, these factors may affect the resulting abundances and spectroscopic stellar parameters since they may drive the selection of features and the source of oscillator strengths.

Lacking the “definitive oscillator strengths” called for by Kostik et al. (1996), the above difficulties could be avoided by use of solar gf -values (i.e., those deduced from an inverted analysis assuming a specific solar abundance). However, the features we use in our metal-poor M92 stars are very large in the Sun. Thus, small deficiencies in, e.g., the outer layers of model atmospheres or the treatment of damping, introduce significant uncertainties in the derived abundances. Hence, our approach here is to try to use a sole source of laboratory gf -values to determine our stellar abundances and normalize them relative to the Sun by determining solar abundances from different, weaker Fe I features and use of the same gf source. This approach also has its uncertainties. For example, the adequacy of the model atmospheres (particularly the treatment of convection) can affect spectroscopically inferred parameters such as T_{eff} and $\log g$; these, in turn, affect the derived abundances. The consistency of the solar and M92 model atmospheres (e.g., the assumption of identical mixing lengths in the treatment of convection) is another issue that might also affect the derived abundances. While these

FIG. 1.—Difference between Fe I values of $\log gf$ from the work of O'Brian et al. (1991) and the work of Bard, Kock, & Kock (1991) and Bard & Kock (1994) vs. lower excitation potential for features utilized in a typical fine analysis (in this case, Beveridge & Sneden 1994) of little-evolved metal-poor stars.

uncertainties are beyond the scope of the present paper, we favor our approach over the common procedure of merely assuming a solar Fe abundance.

A recent source of experimental oscillator strengths for numerous Fe I lines is the work of O'Brian et al. (1991), which has been utilized by others (e.g., McWilliam et al. 1995; Ryan, Norris, & Beers 1997) in studies of very metal-poor stars. The atomic data for our M92 stars are listed in Table 1. For our M92 abundance analysis, we have utilized the equivalent widths of the three BDSK subgiants (18, 21, and 46) with the highest quality spectra. These have been averaged to treat these stars, which are photometrically virtually identical (with $V \sim 18.0$ and $B - V \sim 0.49$), as a single object. A comparison of the line strengths of Fe I (our most numerous species) indicates that the values for 21 are, on average, $\sim 20\%$ larger than for 18 and 46. The significance of this difference is discussed below. In any case, such a difference will influence the derived mean $[\text{Fe}/\text{H}]$ at a level of only ~ 0.05 dex. Our weighted (by the square of the uncertainties) mean equivalent widths and the estimated errors in the mean are listed in the fourth and fifth columns of Table 1.

The initial T_{eff} value for our M92 stars was taken from Table 2 of BDSK, who calculated color-based temperature estimates using the relations of both Carney (1983) and King (1993). Since BDSK estimate that the three stars differ by only ~ 20 K, we initially adopted an intermediate value of 5950 K on the hotter King (1993) T_{eff} scale. The microturbulence was set at 1.5 km s^{-1} , the average value deduced for a sample of little-evolved metal-poor field stars by Magain (1989). The gravity we adopted was $\log g = 3.75$, a value gauged from comparison with old metal-poor revised Yale isochrones (Green, Demarque, & King 1987) after anticipating the later results. The sensitivities listed in Table 4 below indicate a negligible dependence of our Fe abundance on the choice of $\log g$. In the analyses, we have followed Ryan et al. (1997) in adopting a small enhancement factor of 2.2 for the van der Waals broadening, which was computed according to Unsold (1955).

The resulting absolute logarithmic Fe abundances [by number, on the usual scale with $\log N(\text{H}) \equiv 12.0$] calculated from the equivalent widths using MOOG and the $[\text{M}/\text{H}] = -2.5$ grids of R. L. Kurucz (1992, private communication) and the abundance uncertainties resulting from the equivalent width uncertainties are tabulated in the final two columns of Table 1. The resulting absolute abundances are plotted versus lower excitation potential and the reduced line width in Figure 2. No statistically significant correlations are present in either plot; the small magnitude of the correlation coefficients are significant at only the 16% and 60% confidence levels for excitation potential and line strength, respectively. This was deemed satisfactory, and the above parameters were retained throughout the analysis. One could be tempted to conclude from these results that the adopted color- T_{eff} relation from which the BDSK T_{eff} estimate was derived must therefore be reasonably correct. However, such an inference rests squarely on the M92 photometry, the adopted reddening value for M92, the specific choice of spectral lines, the degeneracy of T_{eff} and ξ (discussed below and alluded to above), the correctness of the gf -values, and the absolute adequacy of the model atmospheres; thus, no such inference can be safely drawn.

The standard deviation around our mean absolute Fe abundance of $\log N(\text{Fe}) = 4.91$ is ± 0.20 dex. Two of the

FIG. 2.—Absolute Fe abundances from each of our 15 Fe I lines for the M92 stars plotted vs. the lower excitation potential of the Fe I features (*top*) and reduced width [$\log (W/\lambda)$] of the Fe I features (*bottom*).

lines, $\lambda 4528$ and $\lambda 5434$, show larger deviations with no clear cause except, perhaps, that the former feature does have the lowest S/N of all our lines. Excluding these two features, the scatter is ~ 0.14 dex. Table 1 indicates that the typical measurement error is ~ 0.08 dex. The uncertainties in the gf -values of our particular lines are among the lowest in the O'Brian et al. (1991) sample and are typically 0.05 dex. The abundance scatter perhaps suggests moderately small underestimates in the uncertainties of the gf -values and/or the equivalent width measurements. Given our mean abundance, current solar estimates of $\log N(\text{Fe}) = 7.5\text{--}7.6$ then suggest $[\text{Fe}/\text{H}] \lesssim -2.6$, which is more than a factor of 2 lower than canonical M92 values near $[\text{Fe}/\text{H}] \sim -2.2$.

3.1.2. The Metal-poor Subgiant HD 140283

Given this rather surprising result, we decided to derive abundances for a similarly metal-poor star using Keck data obtained during the same run. For this purpose, we selected the metal-poor subgiant HD 140283, since it is relatively well studied and was expected, from study of the relevant literature, to have an evolutionary state nearly identical to that of our M92 objects. Equivalent widths were measured for the same features used in the M92 analysis and are presented with their estimated uncertainties in Table 2. The values are compared with values from the literature in Figure 3. The limited comparison suggests fine agreement with extant measurements, except those of Ryan, Norris, & Bessell (1991).⁴

An initial T_{eff} trial value of 5845 K was taken based on the same T_{eff} scale as the M92 stars; this also assumed a small reddening of $E(b - y) = 0.010$ for HD 140283. A gravity of $\log g = 3.5$ was adopted based on literature

TABLE 2
HD 140283 DATA AND ABUNDANCES

Wavelength (Å)	χ (eV)	$\log gf$	EW (mÅ)	$\sigma(\text{EW})$ (mÅ)	$\log N$ (dex)	$\sigma(\log N)$ (dex)
Fe I:						
4528.627.....	2.18	-0.887	52.4	2.0	4.96	0.03
4871.325.....	2.86	-0.362	37.5	1.5	4.83	0.03
4890.763.....	2.87	-0.394	38.2	2.1	4.88	0.04
4891.502.....	2.85	-0.111	52.1	2.4	4.82	0.04
4918.998.....	2.86	-0.342	40.2	2.6	4.86	0.04
4920.514.....	2.83	0.068	61.1	2.0	4.77	0.04
5171.610.....	1.48	-1.721	42.0	1.8	4.84	0.03
5232.952.....	2.94	-0.057	49.3	2.3	4.79	0.04
5269.550.....	0.86	-1.333	95.2	1.9	4.79	0.04
5328.051.....	0.91	-1.465	88.9	1.7	4.83	0.04
5328.540.....	1.56	-1.850	35.7	1.7	4.93	0.03
5397.141.....	0.91	-1.982	65.9	1.4	4.90	0.03
5405.785.....	0.99	-1.852	67.1	1.7	4.87	0.03
5434.534.....	1.01	-2.126	53.3	2.2	4.93	0.04
5615.658.....	3.33	0.050	34.3	1.9	4.79	0.03
Mg I:						
4702.995.....	4.35	-0.442	44.2	1.9	5.38	0.03
5172.698.....	2.71	-0.393	150.1	3.9	5.32	0.05
5183.619.....	2.72	-0.171	172.6	4.3	5.35	0.05
Ca I:						
6102.727.....	1.88	-0.793	12.1	1.0	4.07	0.04
6122.226.....	1.89	-0.316	27.9	1.4	4.04	0.03
6162.180.....	1.90	-0.090	38.5	1.9	4.03	0.03
Cr I:						
5208.432.....	0.94	0.158	44.5	2.8	2.85	0.05
Na I:						
5889.973.....	0.00	hfs	111.5	3.1	3.56	0.05
Ti II:						
4501.278.....	1.12	-0.86	57.5	1.9	2.64	0.03
4563.766.....	1.22	-0.95	50.6	2.1	2.71	0.04
4571.982.....	1.57	-0.53	54.5	2.0	2.72	0.03
Ba II:						
4554.036.....	0.00	0.163	20.8	1.3	-1.32	0.03
6141.727.....	0.70	-0.077	5.4	1.2	-1.14	0.09

FIG. 3.—Our equivalent width measures of HD 140283 compared with those from the literature (ordinate). The references are Norris, Ryan, & Beers (1996; *squares*), Zhao & Magain (1990; *circles*), and Ryan, Norris, & Bessell (1991; *crosses*). The two open stars are from Gratton & Sneden (1990) and Tomkin et al. (1992). The solid line represents perfect agreement.

⁴ Note that (1) the satisfactory agreement with other studies, (2) the Fe abundance for HD 134439 derived by Ryan et al. that is significantly lower than others (see King 1997), and (3) the discussion in Ryan et al. itself all suggest that some of their measurements are likely afflicted by instrumental effects.

studies. While Fe ionization-balance analyses generally yield lower values (e.g., 3.27 according to Axer, Fuhrmann, & Gehren 1995), such discrepancies have been known for some time and may be the result of model atmosphere errors or LTE departures (see, e.g., Edvardsson 1988). Fuhrmann et al. (1997) have derived a T_{eff} -insensitive gravity of $\log g = 3.52$ from profile fitting of the Mg I b features. Such a larger value is also consistent with the recent study of Nissen, Høg, & Schuster (1997), who conclude that spectroscopic gravities are often in error by ~ 0.3 dex, which was deduced by comparison with *Hipparcos* parallax-based values. As for the M92 stars, we assumed $\xi = 1.5 \text{ km s}^{-1}$. The resulting Fe abundances, derived with MOOG using $[\text{M}/\text{H}] = -2.5$ Kurucz model grids, are plotted versus lower excitation potential and reduced width in Figure 4. While any definitive conclusion again rests on the adequacy of the atomic data and the model atmospheres, inspection of Figure 4 indicates that the results are not satisfactory relative to the M92 stars in Figure 2. There are correlations in the abundances with respect to both reduced width and lower excitation potential. Moreover, the figure obviously suggests that for our particular Fe I lines, whose choice is ultimately dictated by the M92 data quality, there is a correlation between line strength and excitation potential. Given the fact that Fe I lines are the only numerous species we have available to study in our M92 stars, the microturbulence and T_{eff} cannot be uniquely determined simultaneously at a fine level.

In principle, these parameters might be solved for in the case of HD 140283 by, e.g., use of Fe II lines to determine the microturbulence. As will be discussed below, it will be of interest to infer the relative reddening differences of M92 and HD 140283 from spectroscopic T_{eff} values. A lower limit to this interesting quantity can be obtained by maximizing the spectroscopically estimated T_{eff} for HD 140283. This, in turn, can be accomplished by maximizing the microturbulence (which mimics a T_{eff} decrease in the $\log N$ vs. χ plane for our set of Fe I lines) with the constraint that

no trend in the abundance with line strengths or excitation potential exists. Experimentation with a number of (T_{eff}, ξ) -combinations indicates that this can be achieved for $T_{\text{eff}} \sim 5650 \text{ K}$ and $\xi = 2.0 \text{ km s}^{-1}$; these constraints cannot be achieved by holding T_{eff} constant and only increasing ξ to arbitrarily large values. While a ξ -value of 2.0 km s^{-1} is larger than that generally adopted in the analyses of little-evolved metal-poor stars, we note that it is not that different from the results of the fine analysis of Axer, Fuhrmann, & Gehren (1994), who found a value of 1.88 km s^{-1} . As can be inferred from Table 4 below, the difference affects the derived Fe abundance by only a few hundredths of a dex. Nor does $T_{\text{eff}} = 5650$ seem unreasonable compared with other studies' values deduced from photometry (e.g., 5640 K by Magain 1989), the IR flux method (e.g., 5691 K by Alonso, Arribas, & Martinez-Roger 1996), and Balmer line profile fitting (e.g., 5814 K by Fuhrmann, Axer, & Gehren 1994).

The values of $T_{\text{eff}} = 5650 \text{ K}$ and $\xi = 2.0 \text{ km s}^{-1}$ are the final ones used for our analysis of HD 140283. The final Fe abundances derived from these parameters are plotted versus excitation potential and reduced width in Figure 5, inspection of which indicates substantial improvement relative to Figure 4. The HD 140283 results are summarized in Table 2. The mean Fe abundance we derive is $\log N(\text{Fe}) = 4.85$, which is 0.06 dex less than our M92 value. The standard deviation is only ± 0.06 dex, which compares favorably with the expected equivalent width uncertainties of 0.03–0.04 dex and expected oscillator-strength uncertainties of ~ 0.05 dex.

3.1.3. Solar Iron Analysis

Computing a final $[\text{Fe}/\text{H}]$ estimate for M92 and HD 140283 requires a solar abundance. While many studies, including the spectroscopic M92 giant analysis of Sneden et al. (1991), adopt solar abundances, such a procedure does have the potential to introduce systematic uncertainties.

FIG. 4.—Same as Fig. 2, but for our HD 140283 Fe I features based on initial trial parameters of $T_{\text{eff}} = 5845 \text{ K}$ and $\xi = 1.5 \text{ km s}^{-1}$.

FIG. 5.—Same as Fig. 4, but using our final parameters of $T_{\text{eff}} = 5650 \text{ K}$ and $\xi = 2.0 \text{ km s}^{-1}$. The trends of abundance with both excitation potential and reduced equivalent width plainly evident in Fig. 4 are now absent.

Estimates of the solar photospheric Fe abundance still yield values disparate by ~ 0.15 dex, and it appears that the “last word” has not been spoken on this interesting quantity (e.g., Kostik et al. 1996). The meteoritic value might be adopted as a solar abundance, but it is conceivable that the meteoritic and photospheric values are not equivalent. Moreover, adoption of a meteoritic or photospheric value implicitly assumes that analysis of solar lines using similar or identical spectroscopic data, atomic data, analysis methods, and model atmospheres would yield this assumed abundance; usually, this remains to be demonstrated.

Here we utilize solar abundances derived from similarly obtained solar proxy data, the same atomic data source, and the same model atmosphere grids as for our M92 stars. Ideally, one would like this abundance to come from the same lines also, but we believe that could well lead to the type of systematic errors we seek to avoid, given that the same moderate-strength lines used for M92 and HD 140283 are exceedingly strong in the Sun. Derivation of accurate abundances from strong features (or, equivalently, determination of solar gf -values from these features to use in the M92 analysis) could be compromised because of, e.g., inadequately precise treatment of damping, line-strength measurement errors and the propagation of these into abundance errors, the increased risk of unnoticed blending features in the line wings, and uncertainties in the outermost layers of model atmospheres.

Our approach is to use the lunar reflectance spectrum acquired with the same instrumentation to measure the equivalent widths of Fe I lines having the same approximate range in excitation potential and reduced width as the M92 features. We selected clean solar Fe features from Rutten & van der Zalm (1984) that have oscillator strengths in O’Brien et al. (1991) and reduced widths similar to our M92 stars. Thirty-five such lines were identified, providing a good range in excitation potential. The reduced equivalent widths are somewhat larger than for M92 and HD 140283, and there are fewer weaker solar lines; we do not believe that this compromises the analysis, however. The O’Brien gf -values for the solar features are more uncertain than for those used in M92 and HD 140283. We expect line-to-line abundance scatter of 0.10–0.15 dex due to this uncertainty alone. Abundances were derived in the same fashion as for M92 and HD 140283—i.e., from the equivalent widths and MOOG computations performed using the Kurucz grid solar model atmosphere. We again use a van der Waals enhancement of 2.2. A solar microturbulent velocity of 1.1 km s^{-1} was employed. The solar features, their atomic data, equivalent widths, the resulting abundances, and equivalent width-based uncertainties are given in Table 3.

Figure 6 plots the equivalent widths of lines of all species we measure from our Keck spectrum versus those measured by Meylan et al. (1993, hereafter MFWK) from Kurucz et al. 1984. While the relative line-to-line agreement of 2–3 mÅ is satisfactory, the MFWK values are systematically larger (typically by 4 mÅ or so) than ours. Of course, as MFWK note, the equivalent width measurements are dependent on systematics of the adopted continuum rectification. We have thus retained our values for consistency with our stellar measures. If the solar differences do represent genuine systematic errors in the present values, then these are a tolerable 0.05–0.10 dex in the sense that our stellar abundances would be too high. Figure 7 illustrates the resulting solar abundances of Fe, as well as (our other

neutral species) Mg, Ca, and Cr, versus excitation potential and line strength; the abundances for Mg, Ca, and Cr are taken from Table 3 and have been offset by a constant such that the mean abundances for each element are equal to the mean Fe abundance. Like the metal-poor star data in Figures 2 and 5, no significant trends are observed in the Fe abundances. This is confirmed by the much larger combined sample of neutral solar Fe, Mg, Ca, and Cr features.

We find a solar iron abundance of $\log N(\text{Fe}) = 7.43$ with a satisfactory standard deviation (given the expected uncertainties in gf) of 0.14 dex. For our M92 stars, this result then yields $[\text{Fe}/\text{H}] = -2.52 \pm 0.06$, where the uncertainty is the 1σ level statistical mean uncertainty. These values are listed in Table 4, which summarizes our results. The final three columns list the sensitivities of our abundances to $\pm 100 \text{ K}$ variations in T_{eff} , ± 0.30 dex changes in $\log g$, and $\pm 0.5 \text{ km s}^{-1}$ alterations in microturbulent velocity; for all our species, the change in abundance from using model grids differing in $[\text{M}/\text{H}]$ by ± 0.5 dex is ≤ 0.01 dex. For HD 140283, our solar Fe abundance yields $[\text{Fe}/\text{H}] = -2.58 \pm 0.03$; final abundance results for this star are also summarized in Table 4.

TABLE 3
SOLAR DATA AND ABUNDANCES

Wavelength (Å)	χ (eV)	$\log gf$	EW (mÅ)	$\sigma(\text{EW})$ (mÅ)	$\log N$ (dex)	$\sigma(\log N)$ (dex)
Fe I:						
4779.441.....	3.42	−2.020	42.2	1.2	7.33	0.02
4788.764.....	3.24	−1.763	68.0	1.9	7.44	0.04
4798.268.....	4.19	−1.174	45.2	1.6	7.25	0.03
4962.577.....	4.18	−1.182	57.0	2.7	7.47	0.05
5141.751.....	2.42	−2.238	89.7	3.1	7.54	0.07
5187.918.....	4.14	−1.371	65.0	5.0	7.77	0.09
5223.188.....	3.64	−1.783	29.3	1.6	6.99	0.04
5250.218.....	0.12	−4.898	71.8	3.0	7.51	0.07
5321.111.....	4.44	−1.089	42.0	1.3	7.31	0.03
5379.579.....	3.70	−1.514	62.0	1.8	7.44	0.04
5464.289.....	4.14	−1.402	37.9	1.9	7.26	0.04
5618.639.....	4.21	−1.275	50.5	2.3	7.44	0.04
5741.853.....	4.26	−1.672	37.7	1.9	7.63	0.04
5775.081.....	4.22	−1.297	60.7	2.4	7.65	0.05
5856.093.....	4.29	−1.327	35.1	1.6	7.25	0.03
5956.698.....	0.86	−4.498	54.2	2.2	7.41	0.04
6027.058.....	4.08	−1.089	65.5	1.6	7.39	0.03
6065.495.....	2.61	−1.410	122.9	2.4	7.31	0.03
6151.623.....	2.18	−3.371	51.1	1.7	7.54	0.03
6165.363.....	4.14	−1.473	45.7	1.0	7.45	0.02
6213.438.....	2.22	−2.481	82.6	1.1	7.32	0.03
6240.651.....	2.22	−3.173	49.3	1.5	7.34	0.03
6252.573.....	2.40	−1.767	124.1	1.9	7.47	0.02
6265.143.....	2.18	−2.540	87.7	1.0	7.43	0.03
6270.233.....	2.86	−2.609	53.4	1.4	7.49	0.03
6322.693.....	2.59	−2.469	77.6	1.3	7.56	0.03
6335.338.....	2.20	−2.177	102.0	2.7	7.34	0.05
6380.749.....	4.19	−1.375	54.3	1.1	7.55	0.02
6393.613.....	2.43	−1.576	134.7	2.9	7.42	0.02
6481.875.....	2.28	−3.010	65.8	2.0	7.54	0.04
6498.942.....	0.96	−4.689	48.0	2.0	7.54	0.03
6518.376.....	2.83	−2.297	60.0	1.8	7.26	0.04
6593.880.....	2.43	−2.366	86.9	1.5	7.46	0.03
6633.753.....	4.56	−0.799	69.2	2.2	7.57	0.04
6750.158.....	2.42	−2.584	75.4	1.0	7.43	0.02
Mg I:						
4730.033.....	4.35	−2.347	71.4	3.8	7.73	0.05
4571.097.....	0.00	−5.557	109.2	2.5	7.52	0.05
6318.716.....	5.11	−1.684	50.8	3.4	7.40	0.05
8712.689.....	5.93	−1.076	59.8	3.2	7.48	0.03
8717.825.....	5.93	−0.854	89.1	3.5	7.53	0.03

TABLE 3—Continued

Wavelength (Å)	χ (eV)	$\log gf$	EW (mÅ)	$\sigma(\text{EW})$ (mÅ)	$\log N$ (dex)	$\sigma(\log N)$ (dex)
Ca I:						
4456.616.....	1.90	-1.662	78.2	1.9	6.56	0.03
6102.727.....	1.88	-0.793	139.4	4.0	6.39	0.04
6122.226.....	1.89	-0.316	217.0	7.0	6.49	0.03
6161.297.....	2.52	-1.266	68.7	2.2	6.43	0.04
6166.439.....	2.52	-1.142	72.1	1.8	6.36	0.03
6169.042.....	2.52	-0.797	96.9	2.0	6.40	0.03
6169.563.....	2.53	-0.478	114.2	2.3	6.33	0.03
Cr I:						
4545.95.....	0.94	-1.370	88.6	1.8	5.65	0.03
4600.75.....	1.00	-1.260	87.0	3.2	5.55	0.06
4616.12.....	0.98	-1.190	90.5	2.8	5.52	0.06
4626.18.....	0.97	-1.320	83.9	2.3	5.50	0.05
4651.29.....	0.98	-1.460	83.1	2.5	5.63	0.05
4964.92.....	0.94	-2.527	40.9	1.9	5.70	0.03
5051.90.....	0.94	-2.985	22.5	2.0	5.73	0.06
5072.93.....	0.94	-2.734	34.8	2.3	5.76	0.05
5247.58.....	0.96	-1.640	83.0	1.9	5.68	0.04
5296.69.....	0.98	-1.400	94.8	2.3	5.69	0.05
5300.74.....	0.98	-2.120	60.4	2.0	5.69	0.04
5345.77.....	1.00	-0.980	117.0	2.7	5.67	0.03
5348.30.....	1.00	-1.290	100.2	2.1	5.69	0.04
Na I:						
6154.23.....	2.10	-1.560	40.1	1.3	6.31	0.02
6160.75.....	2.10	-1.261	59.9	1.7	6.29	0.02
Ti II:						
4028.343.....	1.89	-1.00	91.6	2.8	5.29	0.05
4417.719.....	1.17	-1.42	106.0	2.9	5.23	0.05
4444.558.....	1.12	-2.37	65.2	1.8	5.23	0.04
4464.450.....	1.16	-2.07	80.8	2.5	5.33	0.06
4468.507.....	1.13	-0.77	134.2	3.9	4.95	0.05
4470.857.....	1.17	-2.27	64.6	2.3	5.16	0.05
4583.409.....	1.17	-2.73	32.8	1.8	4.90	0.04
4589.958.....	1.24	-1.78	85.1	1.8	5.19	0.04
4708.665.....	1.24	-2.63	51.5	1.7	5.26	0.03
4779.985.....	2.05	-1.37	66.5	2.4	5.11	0.06
5129.152.....	1.89	-1.39	83.5	2.5	5.30	0.06
Ba II:						
4554.036.....	0.00	+0.163	181.2	3.2	2.19	0.02
6141.727.....	0.70	-0.077	123.7	2.6	2.39	0.02

3.2. Magnesium Abundances

Mean equivalent widths and corresponding uncertainties of the $\lambda 4703$, $\lambda 5172$, and $\lambda 5183$ Mg I features for the M92 stars and HD 140283 are listed in Tables 1 and 2. The very large strength of these features in the Sun presents the same difficulties concerning solar normalization as do the Fe I lines. These difficulties may be worse for Mg I, given the smaller number of available features and the shortfall of consistently derived atomic data. We believed that the most reliable procedure was to derive M92 and HD 140283 Mg abundances using the above lines and the theoretical gf -values from the studies of Chang & Tang (1990) and Chang

FIG. 6.—Solar equivalent width measures compared with those (ordinate) measured from the Kurucz et al. (1984) flux atlas by Meylan et al. (1993). The solid line represents perfect agreement.

(1990) and to determine a solar Mg abundance with the sufficiently weak $\lambda 4730$, $\lambda 6318$, $\lambda 8712$, and $\lambda 8717$ Mg I features using gf -values from the same studies. The $\lambda 4571$ Mg I feature is also sufficiently weak to be useful for a secure solar Mg abundance determination, but it does not have a consistently determined gf -value. Therefore, we used the relative differences between the $\lambda 4730$ and $\lambda 4571$ solar gf -values determined by Thevenin (1989) and Fuhrmann, Axer, & Gehren (1995) to estimate one; the two estimates of this difference agree to within a satisfactory 0.06 dex, and their mean was applied to the Chang & Tang (1990) gf -value for the $\lambda 4730$ feature to arrive at a consistent value for the $\lambda 4571$ feature. The two near-IR Mg I lines were measured from a high-S/N Keck daytime sky spectrum, kindly provided by D. Soderblom, obtained with the same instrumentation as the rest of our data.

The atomic data for the Mg I lines are given in Tables 1–3. The latter also lists our measured solar equivalent widths and their uncertainties. Abundances were determined with MOOG using the same model atmospheres and parameters as for the [Fe/H] determinations. For our M92 stars, we find $\log N(\text{Mg}) = 4.86$ with a standard deviation of ± 0.12 dex. For HD 140283, we find $\log N(\text{Mg}) = 5.35$ with a very small scatter of 0.03 dex. Analysis of the different solar Mg I lines yields $\log N(\text{Mg}) = 7.53 \pm 0.12$ (s.d.) dex.

TABLE 4
ABUNDANCE SUMMARY AND SENSITIVITIES

Ratio	M92	σ (dex)	HD 140283	σ (dex)	ΔT_{eff} (± 100 K)	$\Delta \log g$ (± 0.3 dex)	$\Delta \xi$ (± 0.5 km s $^{-1}$)
[Fe/H]	-2.52	0.06	-2.58	0.03	± 0.08	∓ 0.02	∓ 0.07
[Mg/Fe]	-0.15	0.09	0.40	0.07	∓ 0.01	∓ 0.03	∓ 0.04
[Ca/Fe]	0.33	0.11	0.21	0.05	∓ 0.02	± 0.02	± 0.03
[Cr/Fe]	-0.34	0.12	-0.29	0.11	± 0.00	∓ 0.01	± 0.04
[Na/Fe]	0.60	0.09	-0.16	0.06	± 0.03	∓ 0.12	∓ 0.06
[Ti/Fe]	0.15	0.11	0.09	0.06	∓ 0.04	± 0.11	± 0.00
[Ba/Fe]	-0.49	0.13	-0.94	0.08	∓ 0.02	± 0.10	± 0.04

FIG. 7.—Analogous plot to Figs. 2, 4, and 5 for the Sun. The different symbols represent Fe I (stars), Cr I (circles), Ca I (squares), and Mg I (triangles). Like the metal-poor stars, there is no significant trend in the Fe I abundances with excitation potential or line strength; nor are there trends for the combined sample of different elements.

The scatter is satisfactory but perhaps a bit larger than expected. Most of this is due to the $\lambda 4730$ feature, for whose somewhat high abundance we can find no explanation; we suspect a moderate blend exists in the red wing of the profile but believe we have accurately accounted for this in our measurement.

The results lead to estimates of $[\text{Mg}/\text{H}] = -2.67 \pm 0.09$ for the M92 stars and $[\text{Mg}/\text{H}] = -2.18 \pm 0.06$ for HD 140283. The uncertainties are 1σ internal mean errors based on the observed scatter. Using the above Fe abundances, we find $[\text{Mg}/\text{Fe}] = -0.15 \pm 0.11$ (1σ internal error in the mean) for our M92 stars. These results are listed in Table 4. The last three columns again list the sensitivities of our abundance ratio to parameter variations; one can see that these are quite small. For HD 140283, we find $[\text{Mg}/\text{Fe}] = 0.40 \pm 0.07$ dex.

3.3. Calcium Abundances

The $\lambda 6162$ line was the only Ca I feature measurable in our M92 spectra. Thus, the abundance will be more uncertain than for the species considered thus far. In addition, consistent solar normalization presents problems similar to those for Mg I. Table 1 lists the mean equivalent width and uncertainty of the $\lambda 6162$ feature for our M92 stars; the measures in all three stars are in very close agreement. The gf -value for this line is taken from the photoelectric furnace absorption measurements of Smith & O'Neill (1975, hereafter SO75). Table 2 gives our measurement of the line strength in our HD 140283 spectrum. In addition, we also utilized two other Ca I lines ($\lambda 6102$ and $\lambda 6122$), having consistently determined oscillator strengths from SO75, in our HD 140283 spectrum.

While not ideal, we believed the best approach to attain a consistent solar Ca abundance was to use the strong $\lambda 6102$ and $\lambda 6122$ Ca I lines having gf -values from SO75. These two

features were supplemented by the apparently clean $\lambda 4456$ line, which also has an SO75 gf -value. However, we do not have Keck data for this region of the solar spectrum. Thus, while not a wholly ideal approach, we measured the feature from the high-S/N, high-resolution daytime sky spectrum, obtained with the two-dimensional coude spectrograph of the McDonald 2.7 m telescope, described by King (1997). These three features, all with SO75 gf -values like our M92 stars and HD 140283, were further augmented by the weaker $\lambda 6161$, $\lambda 6166$, $\lambda 6169.0$, and $\lambda 6169.5$ Ca I features with furnace absorption gf measures from Smith & Raggett (1981); these should be reasonably consistent with the SO75 study of lower excitation lines. The solar Ca I equivalent width measurements and their uncertainties are listed in Table 3 with the atomic data.

For our M92 stars, we find $\log N(\text{Ca}) = 4.23$. The uncertainty in the abundance estimated from that in the equivalent width measurement is ± 0.04 dex, but we adopt ± 0.10 dex as the 1σ random uncertainty in the absolute Ca abundance; systematic errors are discussed below. For HD 140283, the three Ca lines yield $\log N(\text{Ca}) = 4.05$ with a surprisingly small scatter of only ± 0.02 dex, suggesting that the relative gf -values are quite accurate. The seven solar Ca I lines yield a mean result of $\log N(\text{Ca}) = 6.42 \pm 0.08$ (s.d.). These values, when combined, lead to $[\text{Ca}/\text{H}] = -2.19 \pm 0.11$ for the M92 stars and $[\text{Ca}/\text{H}] = -2.37 \pm 0.04$ for HD 140283; these uncertainties are, again, the 1σ internal mean error estimates.

Our above Fe abundance yields $[\text{Ca}/\text{Fe}] = 0.33 \pm 0.12$ for the M92 stars. Again, this final result is summarized in Table 4. External uncertainties can be gauged from the parameter sensitivities listed in the rightmost columns of the table. For HD 140283, our abundances yield $[\text{Ca}/\text{Fe}] = +0.21 \pm 0.05$. We note that the mean solar abundance of the three lower excitation potential lines having gf -values from SO75 is 0.06 dex larger than the mean abundance we derive from all lines; thus, a systematic error of 0.06 dex in our $[\text{Ca}/\text{H}]$ and $[\text{Ca}/\text{Fe}]$ ratios, in the sense that they are too large by this amount, is possible. However, the mean $[\text{Ca}/\text{H}]$ of HD 140283, computed only from the two lines that were also analyzed for the Sun, is within 0.02 dex of the above value. This, and the very small scatter among all three lower excitation potential lines for HD 140283, may suggest that the systematic errors in $[\text{Ca}/\text{H}]$ for both M92 and HD 140283 are smaller than 0.06 dex, however.

3.4. Chromium Abundances

The mean equivalent width and uncertainty for the $\lambda 5208$ Cr I feature is listed in Tables 1 and 2 for our M92 stars and HD 140283. We take the gf -value of this line from the critical compilation of Martin, Fuhr, & Wiese (1988); this value comes from the furnace absorption measures of Blackwell, Menon, & Petford (1984) and Tozzi, Brunner, & Huber (1985). To derive a consistent solar Cr abundance, we have selected 13 similarly low excitation lines from the Martin et al. (1988) list having gf -values from the same sources. These features, their atomic data, and our lunar reflectance spectrum line measurements are listed in Table 3.

For our M92 stars, we find a mean Cr abundance of $\log N(\text{Cr}) = 2.86$ with an abundance uncertainty of 0.06 dex due to that in the equivalent width. We adopt ± 0.10 dex as a reasonable 1σ internal uncertainty in our absolute abundance to account for uncertainty in the gf -value. For HD 140283, we find $\log N(\text{Cr}) = 2.85$ and again take ± 0.10 dex

as a reasonable internal uncertainty. For the Sun, we find $\log N(\text{Cr}) = 5.65$ with a satisfying standard deviation of 0.08 dex, which is in accord with the line-by-line measurement and gf -value uncertainties. However, a small but statistically significant trend is apparent, in that the stronger lines yield lower abundances. The four Cr I lines having a logarithmic reduced width ≤ -4.94 (equivalent widths ≤ 60 mÅ) yield $\log N(\text{Cr}) = 5.72$ with a scatter of only 0.03 dex. Given the significance of the trend, we have chosen to use this higher abundance (but to retain the higher standard deviation to be conservative) from the four lines most similar in strength to our M92 and HD 140283 Cr I feature. Thus, systematic errors of ~ 0.07 dex may exist in our $[\text{Cr}/\text{H}]$ and $[\text{Cr}/\text{Fe}]$ ratios in the sense that they are too low.

These results lead to $[\text{Cr}/\text{H}] = -2.86 \pm 0.10$ and $[\text{Cr}/\text{Fe}] = -0.34 \pm 0.12$ for our M92 stars, and $[\text{Cr}/\text{H}] = -2.87 \pm 0.10$ and $[\text{Cr}/\text{Fe}] = -0.29 \pm 0.11$ for HD 140283. As before, the uncertainties in the normalized ratios are 1σ internal uncertainties in the mean. The $[\text{Cr}/\text{Fe}]$ ratios and these uncertainties are summarized in Table 4. The final columns again give parameter sensitivities.

3.5. Sodium Abundances

Na abundances were derived from the $\lambda 5889$ Na I D feature; the stellar $\lambda 5895$ Na I lines fall off the CCD. The measured equivalent widths and uncertainties are given in Tables 1 and 2 for our M92 stars and HD 140283, respectively. Abundances were again computed in MOOG using the gf -value from Wiese & Martin (1980) and the hyperfine components from Table 5 of McWilliam et al. (1995). For M92, we find $\log N(\text{Na}) = 4.38 \pm 0.06$, where the uncertainty is that due to the measurement uncertainty. External sensitivities to the adopted stellar parameters can again be found in the final columns of Table 4. For HD 140283 we find $\log N(\text{Na}) = 3.56 \pm 0.05$, where the uncertainty is again that in the line-strength measurement.

Given the great strength of the solar D lines, we used the $\lambda 6154$, 6160 Na I features to attempt normalization. The gf -values were taken from Wiese, Smith, & Miles (1969), and are consistent with the D-line value(s). We find a solar abundance of $\log N(\text{Na}) = 6.30$ with a small equivalent width-based internal uncertainty of ~ 0.02 dex. These results lead to $[\text{Na}/\text{H}] = -1.92 \pm 0.06$ and $[\text{Na}/\text{Fe}] = 0.60 \pm 0.09$ for the M92 stars, and $[\text{Na}/\text{H}] = -2.74 \pm 0.05$ and $[\text{Na}/\text{Fe}] = -0.16 \pm 0.06$ for HD 140283. Uncertainties in the Na gf -values could result in errors ~ 0.10 dex larger than our quoted internal uncertainties. Inasmuch as we are interested in the *relative* M92 versus HD 140283 $[\text{Na}/\text{Fe}]$ values, such errors are disregarded here and in Table 4, but should be kept in mind. Despite possible zero-point errors, the M92 stars appear to be significantly more Na-rich than does HD 140283; our results indicate an $[\text{Na}/\text{Fe}]$ difference (in the sense of M92 minus HD 140283) of $\Delta[\text{Na}/\text{Fe}] = +0.76 \pm 0.11$, where the uncertainty is the 1σ mean uncertainty.

3.6. Barium Abundances

Our stellar Ba abundances were determined from the $\lambda 4554$ and $\lambda 6141$ Ba II features. The $\lambda 4934$ feature measured by BDSK was not considered because of problematic blending concerns. The equivalent width measurements for our M92 stars and for HD 140283 are given in Tables 1 and

2. Solar-normalized abundance measures were formed by analyzing the same, but much stronger, features in the Sun. As for Na, the relative $[\text{Ba}/\text{Fe}]$ values of HD 140283 and M92 are probably more reliable. The solar measurements are given in Table 3. We have taken the Ba II gf -values from Wiese & Martin (1980).

As Tables 1–3 demonstrate, there are significant differences between the *absolute* Ba abundances measured from the two individual lines for M92, HD 140283, and the Sun. However, in forming the normalized stellar abundances, these are greatly reduced, illustrating the value of using consistently derived solar abundances. For our M92 stars, we find $[\text{Ba}/\text{H}] = -3.01 \pm 0.11$, where the uncertainty is that in the mean at the 1σ level calculated from the equivalent width uncertainties. As before, external uncertainties due to parameter errors can be gauged from Table 4. For HD 140283, we find $[\text{Ba}/\text{H}] = -3.52 \pm 0.07$. Combined with our Fe results, we find $[\text{Ba}/\text{Fe}] = -0.49 \pm 0.13$ for M92, and $[\text{Ba}/\text{Fe}] = -0.94 \pm 0.08$ for HD 140283. These results are listed in Table 4.

3.7. Titanium Abundances

Ti abundances for M92 and HD 140283 are based on the Ti II features at 4501, 4563, and 4572 Å measurable in our M92 spectra. While solar spectra reveal possible blending concerns for these lines, our high-quality spectrum of HD 140283 reveals no significant contamination from neighboring features. The measured equivalent widths and their estimated uncertainties are presented in Tables 1 and 2 for M92 and HD 140283.

Because of the large strength of these lines in the Sun, we sought to use other Ti II features to provide consistent normalization. Despite much experimental work and the great astrophysical utility of stellar Ti II features, the atomic data for this important species are of surprisingly modest quality. The Blackwell, Menon, & Petford (1982) Ti II gf -values are of outstanding relative quality, but the uncertainty in their absolute scale is probably $\sim 20\%$; moreover, they do not present gf -values for our M92 and HD 140283 Ti II features. After reviewing the available atomic data, we concluded that two approaches that would yield the most consistent $[\text{Ti}/\text{H}]$ values for our stars were (1) use of the emission arc-based and beam foil-based gf -values of Roberts, Andersen, & Sorensen (1973, hereafter RAS73) with corrections from Roberts, Voigt, & Czernichowski (1975) applied to our stellar Ti II lines and a selection of different weaker solar Ti II features and (2) use of Ti II gf -values from Ryabchikova et al. (1994, hereafter RHLPS94), who combine laboratory, theoretical, and astrophysical data.

For the three Ti II features measured in M92 and HD 140283, these two approaches yield absolute Ti abundances that differ, on average, by 0.19 dex (with the RHLPS94 gf -values yielding smaller abundances). Happily, analysis of 25 other Ti II features in our solar spectra with gf -values from RHLPS94 and a subset of 11 of these with gf -values from RAS73 produces a 0.17 dex solar Ti abundance difference in the same sense. This again illustrates the possible dangers in merely adopting a solar abundance in the analysis of metal-poor stars, and how a consistent solar abundance determination can reduce significant systematic errors. The comparisons also show that the choice of which of the two procedures to adopt is arbitrary, inasmuch as the final stellar $[\text{Ti}/\text{H}]$ values will differ by a scant 0.02 dex. Here, we have simply chosen to use the RAS73 gf -values,

since they produce a smaller scatter for the very securely measured HD 140283 Ti II features; the scatter in the M92 and solar abundances for both sets of *gf*-values is the same.

A few points of possible interest to other workers are as follows: First, the RHLPS94 *gf*-values yield an absolute solar abundance, $\log N(\text{Ti}) = 5.01$, in closer agreement with recent photospheric and meteoritic estimates. Second, there is some evidence, though at low significance, for a trend in the solar Ti abundances with χ (and perhaps wavelength) when the RHLPS94 *gf*-values are employed. Such behavior, possibly attributable to problems with experimental hook measurements, has been noted by Martin et al. (1988). Third, examination of outliers in our solar analysis suggests that the *gf*-values for the Ti II $\lambda 4028$, $\lambda 5129$, and $\lambda 5154$ lines from RHLPS94 are ~ 0.25 dex too small, and the $\lambda 4468$ and $\lambda 4583$ lines from RAS73 are ~ 0.25 dex too large.

The 11 solar Ti II lines having *gf*-values from RAS73 are presented in Table 3 with their equivalent widths and uncertainties. The abundances, also tabulated there, yield a mean absolute solar abundance of $\log N(\text{Ti}) = 5.18$ with a standard deviation of 0.14 dex. From the results in Table 1, we find a mean M92 abundance of $\log N(\text{Ti}) = 2.81$ with a standard deviation of 0.14 dex. From the results in Table 2, we find a mean Ti abundance of $\log N(\text{Ti}) = 2.69$ with a standard deviation of 0.04 dex for HD 140283. These values yield $[\text{Ti}/\text{H}] = -2.37 \pm 0.09$ for our M92 stars and $[\text{Ti}/\text{H}] = -2.49 \pm 0.05$ for HD 140283; the uncertainties are 1 σ mean internal errors. Combined with our earlier Fe results, we find $[\text{Ti}/\text{Fe}] = 0.15 \pm 0.11$ for M92 and $[\text{Ti}/\text{Fe}] = 0.09 \pm 0.06$ for HD 140283. These final ratios are listed in Table 4; again, external errors due to parameter uncertainties can be assessed from the rightmost three columns.

4. DISCUSSION

4.1. Iron Abundance of M92

Our Fe I-based abundance for the M92 subgiants, $[\text{Fe}/\text{H}] = -2.52 \pm 0.06$ (internal), is smaller than the cluster giant-based estimate of Sneden et al. (1991, hereafter SKPL91). The mean abundance of their nine M92 giants is $[\text{Fe}/\text{H}] = -2.26$ with a small internal mean uncertainty of ± 0.03 dex. A more detailed comparison between our subgiant results and their RGB results was made by carrying out abundance calculations for their M92 sample member III-65.

We first adopted their parameters, *gf*-values, and equivalent widths and determined abundances with MOOG using the same family of Kurucz atmospheres employed throughout this work. Adopting the same solar abundance as SKPL91, we find $[\text{Fe}/\text{H}] = -2.27$, which can be compared with their value of -2.21 determined using a different family of model atmospheres. Apparently, we would derive *absolute* Fe abundances for M92 giants that are ~ 0.06 dex lower than SKPL91 simply as a result of model atmosphere differences. Analysis of the SKPL91 data using our Kurucz atmospheres and the *gf*-values (available for seven of the 10 Fe I lines they measure in III-65) yields $[\text{Fe}/\text{H}] = -2.34$, indicating an additional 0.07 dex difference simply due to choice of *gf* source. Kraft et al. (1997) found that higher resolution spectra of M13 red giants yields $[\text{Fe}/\text{H}]$ values that are 0.11 dex smaller than those obtained with lower resolution spectra from the same instrument and analyzed in a similar fashion as the SKPL91 M92 data; the absolute

M92 Fe abundances of SKPL91 could be 0.11 dex too high because of instrumental effects.

Tallying these systematic differences indicates that a lowering of the SKPL91's M92 giants' absolute Fe abundances by 0.24 dex might be easily accomplished. This decrease could essentially account for the 0.26 difference in $[\text{Fe}/\text{H}]$ between our subgiants and their giants without considering systematics exclusive to our analysis. Whether the differences do in fact account for the discrepancy, however, is unclear. For example, if we reanalyze the SKPL91 data using their parameters and equivalent widths and our model atmospheres and *gf*-values *but* adopting our solar Fe abundance derived in a self-consistent fashion, then we find $[\text{Fe}/\text{H}] = -2.25$ for III-65. This is only 0.04 dex lower than their value of $[\text{Fe}/\text{H}] = -2.21$ derived with an assumed solar abundance. A central issue, then, is the solar abundance SKPL91 would derive with their choice of *gf*-values and model atmospheres. This is to say that a rigorous comparison requires knowledge of the internal differences between the M92 giant model atmosphere and the solar model atmosphere for a given model atmosphere family. Since SKPL91 do not conduct a solar analysis, this is difficult to address.

Thus, while the disagreement between our subgiant $[\text{Fe}/\text{H}]$ value and SKPL91's giant $[\text{Fe}/\text{H}]$ value may be accounted for by *gf*-values, model atmospheres, and instrumental effects, possible differences between SKPL91's solar normalization and our own also make conceivable a substantial offset (e.g., ≥ 0.15 dex) of indefinite origin. This could arise from sources like (1) under- or overcorrection for background light in either or both data sets, (2) differential NLTE effects on the Fe I lines in M92 red giants and our subgiants, and (3) relative inadequacies in giant and subgiant model atmospheres. The difficulty in even determining whether there is a genuine or illusory difference between our $[\text{Fe}/\text{H}]$ values and those of SKPL91 may also serve as a cautionary note in trying to conduct precise comparison or fitting of abundances from heterogeneous studies.

Hypothetical errors in our equivalent width measures can also be explored as a source of the discrepancy between giant and subgiant Fe abundances. If our line strengths were errantly low by an amount corresponding to the 0.25 dex Fe discrepancy, then presumably our Li abundances would be similarly low; this would then lead to an unexpectedly large average Li abundance for our M92 stars. Our measures of the $\lambda 6707$ Li I features give abundances (BDSK) that are similar to those observed in field subgiants. As an experiment, though, we increased the M92 Fe I line strengths in Table 1 by 50%. The resulting straightforward abundance increase is 0.45 dex, which more than makes up for the difference between our low $[\text{Fe}/\text{H}]$ and the higher value from SKPL91. However, such a (contrived) error in our line strengths also leads to substantial trends in our abundances with both excitation potential and line strength that need to be remedied by lowering T_{eff} and raising the microturbulence. Lowering T_{eff} by 200 K to 5750 K and increasing the microturbulence to 2.2 km s^{-1} removes the trend with excitation potential; the trend with line strength remains somewhat large ($\sim 85\%$ confidence level), though tolerable. Regardless, the resulting $[\text{Fe}/\text{H}]$ is only a modest 0.08 dex greater than our current value of -2.52 based on the original line strengths. This indicates the enormity of line-strength errors we need to reach agreement with the

SKPL91 Fe abundance. As reiterated below, this experiment also indicates that it is quite difficult to make *simultaneous* substantial revisions in the T_{eff} and $[\text{Fe}/\text{H}]$ of our stars.

4.2. M92 Intracuster Abundance Differences?

We noted previously that star 21 apparently exhibits, on average, larger line strengths of Fe I, which is the most numerous species in the analysis. Assuming identical stellar parameters, the differences result in a mean Fe abundance offset of ~ 0.15 dex with respect to stars 18 and 46. As can be judged from Table 4, such an abundance difference would also result from a T_{eff} difference of roughly 200 K, but individual Fe I analyses of each star yield no spectroscopic evidence that the individual T_{eff} values of the three stars differ; i.e., the optimum (though uncertain) T_{eff} values are essentially identical for the three stars. At the same time, we emphasize that the Fe I analysis does *not* exclude at high confidence level the required large T_{eff} differences leading to line-strength differences from excitation differences rather than abundance differences.

If large T_{eff} differences were the culprit, though, they should manifest themselves in the stars' color indices. Three different measures argue against this. The difference in the $B-V$ index of stars 18 and 21 according to the photometry of Stetson & Harris (1988) is $\Delta(B-V) = +0.004$ (21 – 18). The unpublished photometry of L. E. Davis quoted in Deliyannis et al. (1995) yields $\Delta(B-V) = +0.009$. Furthermore, the difference from Davis' VI photometry is $\Delta(V-I) = -0.004$. Thus, the color differences of our stars appear to be very small. The photometric constraints suggest T_{eff} values for our stars that are identical to within 50 K or so. If, despite these photometric arguments, a T_{eff} difference is responsible for the apparent Fe line-strength differences, then the large 0.5 dex Li abundance difference between these stars (BDSK) would *increase* by an additional 0.15–0.20 dex. We further note that a T_{eff} for star 21 that is 200 K lower would then lead to an $[\text{Mg}/\text{H}]$ value that is 0.44 dex lower than that for star 18. Such a difference is not removed by simply altering the microturbulence. For example, invoking 1.5 km s^{-1} differences between stars 21 and 18 would lower the $[\text{Mg}/\text{H}]$ difference to a still sizable 0.25 dex, leads to clear and opposite trends in the Mg abundance with line strength for stars 18 and 21, and *reintroduces* an inferred 0.2 dex $[\text{Fe}/\text{H}]$ difference between stars 21 and 18, which provided the original impetus for investigating a lower T_{eff} for star 21. Processing or measurement errors would seem to work the same way; errors leading to errantly large Fe line strengths for star 21 would presumably also afflict the Li and Mg measurements. If such errors are the source of the Fe line-strength differences, then Li and any Mg differences between M92 stars 21 and 18 would be more robust.

If real, genuine star-to-star abundance variations could be the result of self-enrichment or primordial differences in the material out of which the cluster stars formed. The 0.15 dex Fe abundance difference between star 18 and stars 21 and 46 that we infer from our data is larger than the Stetson & Harris (1988) “soft” photometric-based (presumably 1σ level) upper limit of 0.10 dex on metallicity dispersion within M92. However, that one given star (21) may exhibit an Fe abundance 0.15 dex larger than two others (18 and 46) is not that statistically remarkable. Given the astrophysical importance of intracuster Fe abundance varia-

tions, it would be of interest to verify the present measurements and improve on the analysis with even higher quality data.

4.3. Reddening of M92

The $B-V$ values of our three M92 subgiants and HD 140283 are indistinguishable at a value of 0.49 (Table 1 of Deliyannis et al. 1995). The reddening of HD 140283 derived from Strömgren photometry by Schuster & Nissen (1989) is $E(b-y) \sim 0.020$, which corresponds to $E(B-V) \sim 0.028$. Though many values are not independent and have unclear origins, the majority of quoted M92 reddenings (e.g., Table 1 of Buonanno, Corsi, & Fusi Pecci 1985) are $E(B-V) \sim 0.02$. Therefore, the T_{eff} values of HD 140283 and our M92 stars are then expected to be similar to within ~ 100 K. At face value, however, our spectroscopic results suggest a much larger difference of ~ 300 K, which would correspond to a *differential* reddening⁵ of ~ 0.07 mag (based on the slopes of extant color- T_{eff} relations such as Carney et al. 1994), with the M92 stars being more heavily reddened.

This spectroscopically inferred differential reddening is uncertain because of uncertainties in T_{eff} and the partial correlation between lower excitation potential and reduced width for our Fe I lines. For HD 140283, the adopted ξ -value was made as large as possible in order to force a large spectroscopically inferred T_{eff} ; this was a conservative approach so as not to overestimate the differential reddening. For our M92 stars, however, we merely adopted a value (1.5 km s^{-1}) that is typically assumed (and derived) in spectroscopic analyses of metal-poor stars. We now consider an M92 star with lower spectroscopically inferred T_{eff} , which would reduce the differential reddening with respect to HD 140283.

The T_{eff} reduction needed to realize a differential reddening concordant with expectations can be achieved by assuming (a tolerable) $E(B-V) = 0$ for HD 140283. The canonical M92 value of $E(B-V) = 0.02$ would thus imply a T_{eff} some 80 K greater than for HD 140283. The latter value used here was 5650 K, so we now ask whether the spectroscopic constraints allow a T_{eff} for our M92 stars of $5650 + 80 = 5730$ K, which is 220 K less than our value of 5950 K. Using $T_{\text{eff}} = 5730$ K and $\xi = 1.5 \text{ km s}^{-1}$ results in a larger correlation coefficient in the abundance versus χ plane than for $T_{\text{eff}} = 5950$ K, but the (one-sided) significance of the correlation coefficient is only at the 70% confidence level. In addition, the abundance versus line strength trend is slightly reduced with respect to the case of $T_{\text{eff}} = 5900$ K. Assuming zero reddening of HD 140283, we cannot exclude an M92 subgiant T_{eff} low enough to imply a small differential reddening (~ 0.02 mag) relative to HD 140283 that is in accord with canonical estimates.

We also note the following: The surprises in our M92 abundances motivated the analysis of HD 140283, and during this consistency check we noted the degeneracy of T_{eff} and ξ . Thus, a more detailed examination of the complicated phase space of abundance, T_{eff} , ξ , and the respective correlation coefficients for our M92 stars was necessary. We

⁵ We cannot distinguish between the effects of reddening and errors in the photometric colors. Therefore, any suggested revisions in “reddening” could wholly or in part be due to revisions in the photometry.

find that the statistically optimum parameters (i.e., those establishing zero correlation abundance and excitation and line strength) are a microturbulent velocity of $\sim 2.0 \text{ km s}^{-1}$ (essentially identical to the value we have used for HD 140283) and an even higher T_{eff} value near $\sim 6020 \text{ K}$.⁶

In sum, the stellar parameters cannot be simultaneously determined in a unique sense because of the partial correlation between our Fe I lines' excitation potential and line strength. Instead, more general indications of the parameters are prescribed. For M92, our optimal estimates of T_{eff} and ξ lead to $[\text{Fe}/\text{H}]$ values near our estimate of -2.52 and differential reddening values with respect to HD 140283 of $0.06\text{--}0.07 \text{ mag}$. However, depending on various assumptions, the spectroscopic constraints may not allow us to exclude at high confidence levels the lower reddenings consistent with current estimates. Higher quality spectroscopic data, analysis of a larger number of lines, and independent determinations of the microturbulence and T_{eff} will be needed to address further these interesting and important issues.

4.4. Reddening versus Metallicity

In the meantime, the fundamental cluster properties of reddening (color) and $[\text{Fe}/\text{H}]$ remain linked in our analysis. When viewed together, the interplay of reddening and abundance should lead to conclusions free from various uncertainties. For example, if one desired a low spectroscopically inferred M92 reddening in line with canonical values, this could be achieved by lowering the T_{eff} . We found before that this yields a tolerable correlation coefficient between the Fe abundance and excitation potential that is only significant at the 70% confidence level. While not statistically optimal, the lower T_{eff} choice is not excluded given the significance levels. However, such a procedure then yields an even *lower* Fe abundance of $[\text{Fe}/\text{H}] = -2.71$. Alternatively, one might try to reconcile the subgiant and giant $[\text{Fe}/\text{H}]$ values by raising T_{eff} . Again, these adjustments may not be optimal, but are also difficult to exclude. Regardless, such a procedure would then imply an even *larger* differential $E(B-V)$ value (with respect to HD 140283) near 0.13 mag . Thus, while the spectroscopic estimates of $E(B-V)$ and $[\text{Fe}/\text{H}]$ are not unique, our results seem to imply that either the currently accepted M92 reddening/photometry is too low/red or that the currently accepted M92 $[\text{Fe}/\text{H}]$ estimate is too high.

4.5. Age of M92

Because our best, though uncertain, estimate of the M92 reddening is significantly larger than that employed in other studies, it seems to necessitate a cursory reexamination of the cluster age. This can be done by using isochrone properties, such as those in the classic M92 study of Stetson & Harris (1988, hereafter SH88), and turnoff-based ages of $\sim 16 \text{ Gyr}$ derived from comparison of the SH88 M92

photometry with theoretical isochrones in SH88 and Bolte & Hogan (1995, hereafter BH95). Our differential reddening estimate between M92 and HD 140283 of $0.06\text{--}0.07 \text{ mag}$ becomes a conservatively small estimate of the absolute M92 reddening by assuming a zero Strömgren-based reddening for HD 140283. Given SH88's and BH95's assumption of $E(B-V) \sim 0.02$ for M92, our optimum spectroscopic results suggest an increase of $\sim 0.04\text{--}0.05 \text{ mag}$.

Based on the age sensitivity of the isochrone turnoff color in § 5g of SH88, such a color shift (whether viewed as altering the cluster reddening or photometric colors) would lower the turnoff color-based age by $\sim 6\text{--}7 \text{ Gyr}$; according to SH88's color-metallicity sensitivity, this reduction would be reduced by $\sim 2\text{--}3 \text{ Gyr}$ (to $\sim 12 \text{ Gyr}$) given the lower $[\text{M}/\text{H}]$ from the present results. SH88's stated age sensitivity of the turnoff luminosity indicates that a total $3\text{--}4 \text{ Gyr}$ age reduction requires a turnoff M_V adjustment of $\sim 0.20\text{--}0.25 \text{ mag}$ for consistency. The metallicity sensitivity of the turnoff luminosity (not luminosity at fixed color) gauged from several sets of different isochrones (e.g., Green et al. 1987; Chieffi & Straniero 1989) indicates that an additional correction of 0.10 mag is needed because of our lower M92 metallicity; thus, a total adjustment in M_V of $0.30\text{--}0.35 \text{ mag}$ is required. Our increased reddening and standard reddening laws provide $\sim 0.13 \text{ mag}$ of this amount via extinction. The remaining $\sim 0.20 \text{ mag}$ adjustment could come from fundamental revisions in metal-poor field star distances, which enter the SH88 and analysis via main-sequence fitting to field subdwarfs. Indeed, Feast & Catchpole (1997) infer a 0.3 dex adjustment in RR Lyrae absolute magnitudes from *Hipparcos* Cepheid data and suggest ages of 11 Gyr for the oldest globular clusters (such as M92). Moreover, the M92 distance moduli inferred by Reid (1997) from main-sequence fitting to subdwarfs with accurate *Hipparcos* parallaxes is some $0.20\text{--}0.25 \text{ mag}$ larger than the SH88 and BH95 values; he suggests typical globular ages of $11\text{--}13 \text{ Gyr}$.

Evaluating whether the M92 turnoff and horizontal-branch (HB) magnitude difference corroborates such a substantial age revision hinted at by our results and the *Hipparcos*-based results is hampered by disparate sources of the requisite precision photometry (photographic photometry for the M92 HB and CCD photometry for the turnoff), by the modest number of genuine M92 RR Lyrae members from which to assess the HB level, and by possible concerns about evolution of elemental abundances between the turnoff and the HB. Obviously, $\sim 12 \text{ Gyr}$ ages for the very *oldest* globular clusters would have a variety of interesting ramifications. Besides consistent HB and turnoff photometry, rigorously dismissing such a possibility would seem to require more and higher quality spectroscopic data of near-turnoff and evolved cluster stars, so accurate parameters and abundances can be deduced.

4.6. Abundance Ratios in M92: Some Surprises

The abundance ratios of our M92 stars and HD 140283 are summarized in Table 4. We find $[\text{Fe}/\text{H}]$ values differing by only 0.06 dex for our M92 stars and HD 140283. Similarly, the $[\text{Cr}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, and $[\text{Ti}/\text{Fe}]$ ratios of our M92 stars and HD 140283 are in very good agreement; indeed, they are identical within the internal uncertainties alone. Comparison of these ratios with, e.g., the various results contained in Figures 2 and 4 of Ryan et al. (1997) indicates that our values are unremarkable compared with other

⁶ Rather than repeat the entire analysis with the fully optimized parameters, we simply note for the record that (as can be gauged from simple inspection of Table 4) the refined M92 parameters would lead to very small changes in the abundances summarized in Table 4. Our $[\text{Fe}/\text{H}]$ value is not affected by more than a hundredth of a dex or so. Our low value of $[\text{Mg}/\text{Fe}]$ would decrease even further by a modest 0.05 dex (the largest change of all our ratios); $[\text{Na}/\text{Fe}]$ would decrease by a scant 0.02 dex .

stars of similar $[\text{Fe}/\text{H}]$. In sum, the abundances of the Fe peak elements Cr and Fe and of the α -elements Ca and Ti are very similar in the M92 stars and HD 140283 and are essentially those expected on the basis of extant data.

The $[\text{Ba}/\text{Fe}]$ ratio of the M92 stars and HD 140283 differ by 0.45 dex, which is substantially larger than expected from the internal uncertainties and plausible parameter variations. Ba is known to exhibit significant star-to-star scatter in metal-poor stars, so the difference is not very surprising. Comparison with the field star data in Figure 5 of Ryan et al. (1997) indicates that neither value can be said to be wildly deviant from other field stars of similar $[\text{Fe}/\text{H}]$. Our M92 $[\text{Ba}/\text{Fe}]$ ratio lies near the upper envelope of most field star data near $[\text{Fe}/\text{H}] = -2.5$, while our HD 140283 $[\text{Ba}/\text{Fe}]$ ratio lies near the lower envelope. The $[\text{Ba}/\text{Fe}]$ difference, however, still remains significant.

We find that the $[\text{Mg}/\text{Fe}]$ ratio of the M92 stars and HD 140283 differ by a substantial 0.55 dex, which is much larger than the internal uncertainties (0.09 and 0.07 dex). We emphasize that the Mg and Fe abundances are derived from the same lines using the same atomic data for both stars. The fine agreement for the Cr, Ca, and Ti abundances also lends confidence to the reality of the $[\text{Mg}/\text{Fe}]$ difference we see. However, the two redder Mg I lines are strong, and this could raise possible concerns about the reliability of our $[\text{Mg}/\text{Fe}]$ values. We note, though, that the Mg abundance difference between the M92 stars and HD 140283 deduced from the weaker $\lambda 4703$ Mg I line alone differs by only 0.02 dex from the difference deduced using all three lines. We also note the outstanding line-to-line Mg abundance agreement for HD 140283 and the entirely satisfactory agreement for the M92 stars; this suggests that, for both HD 140283 and the M92 stars, the line measures are internally consistent and that the damping has been handled reasonably well. Finally, Table 4 indicates that the $[\text{Mg}/\text{Fe}]$ difference is very robust to even absurdly large parameter errors. For example, even if both the *relative* values of $\log g$ and ξ for HD 140283 and the M92 stars were in error by an enormous 1.5 dex and 2.0 km s^{-1} , this would still leave a ~ 0.25 dex difference in $[\text{Mg}/\text{Fe}]$. Comparison of our $[\text{Mg}/\text{Fe}]$ ratios with the extant field star $[\text{Mg}/\text{Fe}]$ data near $[\text{Fe}/\text{H}] = -2.5$ displayed in Figure 2 of Ryan et al. (1997) indicates that our value of $[\text{Mg}/\text{Fe}] = 0.40$ for HD 140283 is unremarkable, whereas $[\text{Mg}/\text{Fe}] = -0.15$ for our M92 stars is anomalously low.

A similarly intriguing difference is observed in the $[\text{Na}/\text{Fe}]$ ratio, which we find to be 0.76 dex larger in our M92 stars than in HD 140283. Figure 8 compares our co-added spectrum of M92 stars 21 and 46 (18 is excluded to avoid any influence from a hot column) with the spectrum of HD 140283. No radial velocity corrections have been applied in order to demonstrate that the blueshifted stellar $\lambda 5889.9$ features are influenced by neither telluric emission nor lower velocity interstellar absorption. The M92 feature is stronger than the HD 140283 line despite the larger T_{eff} and smaller ξ -values assigned to the M92 stars; these would lead us to expect a smaller M92 feature for equal Na abundances. Like Langer, Prosser, & Sneden (1990, hereafter LPS90), we observe two clear interstellar Na I components for M92. The velocity separation is $\sim 18 \text{ km s}^{-1}$, which agrees with LPS90's assessment. The components' strengths appear slightly stronger in star 46, not inconsistent with the variations on even small spatial scales seen by LPS90, but the significance is marginal given the data quality. The

FIG. 8.—Co-added spectrum of M92 stars 21 and 46 compared with HD 140283 in the $\lambda 5889.9$ (rest) Na I region. No radial velocity correction has been applied, in order to demonstrate that the stellar lines in both spectra are well removed from telluric emission and lower velocity interstellar components (at -14.5 and -32.5 km s^{-1}) seen in the M92 spectrum. The M92 stellar feature is stronger than that in HD 140283 despite the larger T_{eff} values and smaller ξ -values we assign to the M92 stars; i.e., we expect the M92 lines to be weaker for identical Na abundances.

absence of a visible interstellar Na I component in HD 140283 versus the interstellar M92 features may provide corroborating evidence for our inferred reddening difference between HD 1482038 and M92.

Like the two redder Mg I features, our Na I feature is strong. There is thus greater gravity (i.e., pressure) and damping sensitivity than for the other features, and this may raise concerns about the reliability of the Na abundances. First, we recall that the HD 140283 and M92 analyses use the same feature, atomic data, and model atmosphere grids. This should help suppress any systematic errors in the *relative* Na abundances. Second, we recall the indications from the Fe I and, more importantly, from the Mg I analysis that we have apparently handled the damping reasonably well. Even if this were not the case, Table 4 indicates that a huge 2.0 km s^{-1} relative error in the ξ -values of HD 140283 and our M92 stars would still leave a ~ 0.50 dex difference in their $[\text{Na}/\text{Fe}]$ values. Third, the pressure sensitivity given in Table 4 (which, to be conservative, has been purposefully overestimated by treating the D line as a single feature) indicates that enormous errors of 1.0 dex in the relative gravities of HD 140283 and our M92 stars would still leave a ~ 0.35 dex difference in the $[\text{Na}/\text{Fe}]$ values. While larger uncertainties in the Mg and Na abundances exist because of greater sensitivity to pressure, damping, and line strength, the plausible uncertainties seem much smaller than the $[\text{Mg}/\text{Fe}]$ and $[\text{Na}/\text{Fe}]$ differences between HD 140283 and our M92 stars. Higher quality spectra of other stars observed on the same nights indicate that two telluric H_2O absorption features may cause our M92 equivalent widths to be overestimated by $\leq 10 \text{ mÅ}$, but this amounts to a 0.11 dex effect.

The M92 Na I features do reside ~ 100 pixels from the order edge. Because the background light levels in our spectra are inferred to be quite small (perhaps of order 1% or so), and inasmuch as continuum rectification errors would have to be very large (some 25% of the stellar continuum level) and consistently afflict all three of our subgiants plus the two additional ones discussed below, there is no evidence that the Na I lines' placement on the CCD affects our measurements. The red wing of the Na feature for star 18 is contaminated by a hot column. However, because its estimated line strength is intermediate to that for stars 21

and 46, we have no reason to believe that our equivalent width is in significant error. Of course, independent observations would certainly be welcome.

4.7. Abundances in Two Additional M92 Subgiants

Given some of our unexpected results, confirmation from other M92 stars became of considerable interest. We therefore summarize the results for two slightly cooler M92 subgiants (34 and 350) that have data from BDSK of lower S/N than the three “primary” stars that are the basis for our preferred abundances. The lines analyzed were the measurable subset of the same features used for the three primary objects. The atomic data, analysis method, and solar abundances were identical to those employed before. We took the hotter T_{eff} values for each star from Table 2 of BDSK for consistency with the three primary objects, and again utilized a microturbulent velocity of 1.5 km s^{-1} . As before, no significant trends in the Fe I abundances with either excitation potential or line strength are found. The resulting mean iron abundance of $[\text{Fe}/\text{H}] = -2.51$ is in near exact agreement with that (-2.52) of our three primary M92 subgiants. We find $[\text{Ca}/\text{Fe}] = 0.35$, which is also in excellent agreement with the value of 0.33 from our primary M92 subgiants. The $[\text{Ti}/\text{Fe}]$ value of 0.24 is not significantly larger than our previously derived value of 0.15. A Ba abundance could only be derived from one line in star 34 alone; we find $[\text{Ba}/\text{Fe}] = -0.01$, consistent with our previous conclusion of a significantly larger ratio than that for HD 140283. The two additional M92 subgiants have $[\text{Mg}/\text{Fe}] = 0.09$, which is still 0.4 dex below the HD 140283 value. Finally, the Na overabundance with respect to HD 140283 persists; we find $\Delta[\text{Na}/\text{Fe}] = +0.58$, which compares well with the value of $+0.76$ from the three primary M92 subgiants. Except for $[\text{Fe}/\text{H}]$, the 1σ mean internal uncertainties alone among these ratios are probably no better than 0.15–0.20 dex. All the abundance patterns we identified in the primary M92 analysis are confirmed by the supplemental results.

4.8. Deep Mixing or Primordial Effects Near the M92 Turnoff?

The Mg deficiency and Na overabundance of our M92 stars relative to HD 140283 are reminiscent of the behavior observed in the evolved red giants of M92 and other globular clusters (e.g., SKPL91; Pilachowski et al. 1996; Shetrone 1996a; Kraft et al. 1997). In recent years, these investigations and many others have revealed deficiencies of O and Mg and enhancements of Al and Na in globular cluster giants but not in field giants. The observed star-to-star abundance variations on cluster giant branches, the observed “universal” star-to-star correlation between the Mg, O deficiencies and Na, Al enhancements (Kraft 1994) on cluster giant branches, and the constancy of other light metals (Fe, Ni, Sc, and V) and α -elements (Si, Ca, and Ti) on cluster giant branches point to the action of deep mixing and proton-capture nucleosynthesis via $\text{Ne} \rightarrow \text{Na}$, $\text{Mg} \rightarrow \text{Al}$, and $\text{O} \rightarrow \text{N}$ cycling. With assumptions of initial $[\alpha/\text{Fe}]$ enhancements of $+0.4$ dex and scaled solar abundances for other metals, recent modeling by Langer et al. (1997) of such processing yields stunning agreement with observed abundances in M13, the cluster for which the most numerous and highest quality red giant data exist. These results suggest that $\sim 90\%$ of the envelope material

in M13 giants has been processed at a temperature of $\sim 70 \times 10^6 \text{ K}$.

Several factors point to such nonstandard processing occurring within the globular cluster red giants themselves. The observed $[\text{Na}/\text{Fe}]$ ratios near the red giant branch tip in M13 are exclusively high, in contrast to the lower giant branch, which shows a wide range (~ 1 dex) in Na abundance (Pilachowski et al. 1996). If “primordial” abundance variations (i.e., those resulting earlier from an exterior source) were responsible, it is difficult to imagine why only the currently most evolved giants would have formed from Na-enriched material. The lack of any correlation between the abundances of the n -capture elements Y, Ba, Ce, and Nd and the Na/Fe and O/Na ratios in the red giants of several globular clusters (Armosky et al. 1994) is also at least consistent with an in situ mixing site, since if n -capture synthesis was responsible for Na variations (presumably also leading to [unobserved] variations in the above very heavy elements), then a neutron source would be required; it is believed that such a source could only come from a previous generation of stars.

Might the striking Mg-Na pattern we observe be the result of surprising in situ mixing in our M92 subgiants, or the result of mixing in a previous generation of stars that has contaminated the material in our subgiants’ envelopes? The $[\text{C}/\text{Fe}]$ ratio in M92 is observed to drop (though with substantial star-to-star scatter) by roughly an order of magnitude from near or above the turnoff to the tip of the giant branch (Carbon et al. 1982; Langer et al. 1986). This pattern is entirely consistent with in situ internal mixing and $\text{C} \rightarrow \text{N}$ processing, a portion of which is in fact predicted by standard stellar models of the more evolved stars. However, as emphasized by Langer et al. (1986), this behavior does not prove that in situ mixing alone is responsible. Such mixing and internal processing might be expected to be less vigorous in more metal-rich stars because of the effects of molecular weight gradients. In the relatively metal-rich globular cluster 47 Tuc, though, it has been known for some time (e.g., Norris & Freeman 1979) that C, N, and Na variations occur in its RGB stars. Moreover, marked CN and Na variations persist all the way to the main-sequence turnoff (Briley et al. 1994, 1995). These observations are highly suggestive of a mechanism that contaminates the photospheric material of globular cluster stars prior to the subgiant and RGB phase. While the latter authors were not able to exclude a remarkable in situ process as responsible for the observed main-sequence 47 Tuc abundances, the detection of Li in substantial and apparently equal amounts in a weak-CN/weak-Na and strong-CN 47 Tuc turnoff star by Pasquini & Molaro (1997) may suggest this possibility is unlikely.

Similarly, the presence of abundant Li in our M92 stars (BDSK) seems to conflict with in situ $\text{Mg} \rightarrow \text{Al}$ and $\text{Ne} \rightarrow \text{Na}$ processing. As also noted in § 6 of Shetrone (1996b), Li burning occurs at temperatures of a few MK, while Na and Mg synthesis/processing occurs at significantly higher interior temperatures near 30 and 70 MK. Therefore, if in situ Ne, Na and Mg, Al processing has occurred, all the Li should be destroyed. If, on the other hand, interior processing in a previous generation of stars (whether internal or external to the [proto-] cluster) is responsible for the striking Mg/Na pattern we see in M92, then the Li constraint could, in principle, be relaxed. For example, if there were interior processing in a previous

stellar generation that (1) depleted Li and C, (2) cycled Ne, Na and Mg, Al, and (3) then later produced Li and C, the observed abundance patterns might be explained; general examples of Li production in other stellar populations are noted at the end of this subsection. Besides a remarkable conspiracy resulting in final Li and C abundances that are very close to those observed in little-evolved halo field stars, there are still worrisome complications (e.g., ^3He sources) that remain to be explored.

A possible modest $[\text{Ba}/\text{Fe}]$ enhancement in our M92 stars relative to many field stars of similar $[\text{Fe}/\text{H}]$ could result from some degree of n -capture processing. Since no neutron source is known in the interiors of stars having the evolutionary status of our M92 objects, this would also implicate a source of abundance anomalies which is not operating in situ. We thus suggest that, if real, our Mg and Na results argue for a non-in situ source (usually referred to as “primordial”) of contamination in M92 stars in addition to in situ mixing in more evolved M92 stars pointed at by other observations (e.g., Carbon et al. 1982; SKPL91). Suggested nonexplosive candidate primordial mechanisms are stellar wind pollution from massive main-sequence stars having convective cores (e.g., Denissenkov & Weiss 1996), mass loss from intermediate mass ($5\text{--}10 M_{\odot}$) stars having undergone thermal pulses during the asymptotic giant branch (AGB) (Cottrell & Da Costa 1981), and enrichment from low-mass to intermediate-mass ($1\text{--}5 M_{\odot}$) stars (Norris & Da Costa 1995). Whether any of these mechanisms are in fact plausible, however, is unclear. It would seem that detailed element-by-element calculations that consider explosive and nonexplosive pollution before and after cluster formation, and that simultaneously consider the detailed gas (thermo)dynamics, star formation physics, and stellar evolutionary models are lacking.

A primordial source has other attractive features. First, it may be consistent with the remarkable main-sequence abundance patterns in 47 Tuc. Second, a primordial component involving n -capture processing may be responsible for the apparent 0.3 dex difference in the $[\text{Ba}/\text{Fe}]$ and $[\text{Nd}/\text{Fe}]$ ratios between the M92 and M15 giants in the analysis of Armosky et al. (1994). Third, a primordial component involving n -capture processing may be responsible for the significant star-to-star Ba and Eu abundance differences recently reported in M15 red giants (Snedden et al. 1997). Fourth, primordial phenomena might explain the surprisingly low $[\text{O}/\text{Fe}]$ ratios, $\lesssim -0.4$, determined for stars near the base of the giant branch in M13 by Pilachowski & Armandroff (1996); such a low initial $[\text{O}/\text{Fe}]$ would be in conflict with the assumptions in the model studies noted at the beginning of this subsection.

Comparison of our M92 subgiant Na and Mg abundances with those of M92 RGB tip stars from Shetrone (1996a) indicates that our subgiant $[\text{Na}/\text{Fe}]$ value is larger than all the giant values and that our $[\text{Mg}/\text{Fe}]$ value is lower than all the giant values summarized in his Table 4. In particular, the two M92 giants, B-95 and VII-122, have significantly lower $[\text{Na}/\text{Fe}]$ (-0.28 and -0.55) and higher $[\text{Mg}/\text{Fe}]$ (0.43 and 0.30) ratios than do our subgiants. These differences raise the possibility of “primordial” contamination in the form of accretion of processed material by the current M92 stars after they had formed. In this scenario, the amount of accreted Na and Mg needed to alter the surface abundances of stars near the M92 turnoff might not be very large given their shallow convection zones. As such

a polluted star later evolved up the giant branch its convection zone would deepen, and this might dilute the polluted Na and Mg content to the minimum (Na) and maximum (Mg) abundances seen in the two M92 giants. While this dilution occurs for polluted Mg and Na, shallow in situ mixing is presumably lowering the M92 carbon abundances as observed. Then, at some point on the giant branch, some of the giants undergo deep in situ mixing, which reverses the pollution dilution and begins to raise the Na and lower the Mg surface abundances. We have noted the difficulties in performing detailed comparisons between our M92 subgiant abundances and M92 giant abundances in the literature. Specifically, we noted the systematic differences between the subgiant and giant $[\text{Fe}/\text{H}]$ values. Comparison of $[\text{Na}/\text{Fe}]$ and $[\text{Mg}/\text{Fe}]$ ratios may conceivably exacerbate any systematic analysis differences. Thus, the above interpretation is surely speculative, since it is motivated by comparisons whose reliability is uncertain at present.

This scenario of pollution by Na- and Mg-altered material processed in a previous stellar generation is rather complex, not very aesthetic, and harbors the difficulty noted above: if products of $\text{Ne} \rightarrow \text{Na}$ and $\text{Mg} \rightarrow \text{Al}$ cycling in a previous generation of stars have polluted the photospheres of present-day M92 subgiants, one expects Li and C (which are destroyed at even shallower depths than Ne and Mg) to be affected. However, the Li abundances of our stars (BDSK) are within roughly ± 0.3 dex of the value observed in warm metal-poor field stars with normal Mg and Na abundances. In addition, while we are not aware of any C abundance determinations in our subgiants, other M92 stars of similar or lesser evolutionary status exhibit C abundances (Carbon et al. 1982; Langer et al. 1986) that are not depleted with respect to field stars having normal Mg and Na. How might the Li and C abundances (if indeed our objects have C abundances similar to other M92 subgiants) remain unaffected even in a previous generation of stars that had undergone deep mixing and processing to alter Mg and Na? While not clear, we suggested above the possibility of (perhaps AGB) production of C and Li (and maybe Ba) in just the amounts needed to pollute M92 subgiants so that they show apparently normal abundances of C and Li; this would certainly be a remarkable circumstance. Our new M92 abundances seem to raise more questions regarding the chemical history of globular clusters than they answer. An important first step at addressing these would be verification of our results.

For the time being, though, we suggest that the difficulty of the Li, C and Mg, Na abundances in our M92 objects may not be unique. An analogous abundance quandary in the context of processing in a prior generation of stars may be evident in, e.g., the globular cluster 47 Tuc. Pasquini & Molaro (1997) find that the 47 Tuc turnoff stars BHB 5 and 7 have similar Li abundances that are possibly only slightly larger than the value in warm metal-poor field stars. However, Briley et al. (1994) find significant differences in their (anticorrelated) CH and CN indices. The CH-CN behavior and the correlation of 47 Tuc turnoff stars' CN and Na line strengths (Briley et al. 1995) suggest that the mechanism that produced 47 Tuc turnoff abundance variations was some form of in situ mixing in a previous generation of stars. Thus, on the 47 Tuc turnoff, it appears that $\text{C} \rightarrow \text{N}$ (and possibly $\text{Ne} \rightarrow \text{Na}$) processed material, rather than material affected by primary N production variations alone, has contaminated stars without leading to Li abun-

dance alterations. This is despite the fact that $C \rightarrow N$ (and $Ne \rightarrow Na$) processing occurs at depths at which significant Li destruction is expected.

Another curiosity may be found on the 47 Tuc giant branch. Brown & Wallerstein (1992) have determined spectroscopic abundances for the two 47 Tuc red giants 3501 and 4418. Star 3501 has a significantly higher CN index (Norris & Freeman 1979) than does 4418. That this is related to CN(O) processing rather than differences in N produced in a primary sense is supported first by the fact that the lower $^{12}C/^{13}C$ ratio of 7 for star 3501 versus 12 for star 4418 (Table 2 of Brown & Wallerstein 1990), and secondly, that Brown & Wallerstein's (1992) finding that giant 3501 has $[Na/Fe] = 0.28$, while 4418 has $[Na/Fe] = -0.12$. These values imply that 3501 has the greater content of processed material in its photosphere. Despite these differences in processed content, Brown & Wallerstein (1990) derive a CH-based C abundance that is 0.1 dex larger for star 3501 than for 4418. As we suggested for M92, these results might be explained by both depletion and production of C in a prior generation of stars or a combination of primordial and in situ star-to-star abundance variations.

An example seeming to require Li production in evolved Population I stars is provided by Li-rich field K giants. There are a number of very Li-rich Population I K giants that have $^{12}C/^{13}C$ measures (see, e.g., de la Reza & da Silva 1995; da Silva, de la Reza, & Barbuy 1995). HD 787, 19745, 39853, and 95799 all have C isotope ratios in the range 6–15, which indicates that these giants have undergone internal mixing to an extent greater than predicted by standard stellar models. Stellar models also suggest significant Li destruction—more so for models that incorporate extra mixing to satisfy the isotopic ratios. However, these stars' NLTE Li abundances are in the range $\log N(Li) = 3.1\text{--}4.75$, values that are near or exceed estimates of the present-day Galactic Li abundance. Presumably because of Li enrichment, these metal-rich objects apparently have undergone deep mixing without net loss of Li.

A similar example is provided by giants in the open cluster NGC 7789. Pilachowski (1986) determined the Li abundances of giants in this cluster to be larger than average for Population I low-mass giants. The LTE Li abundances of her three “group IV” ($T_{\text{eff}} = 4600$ K, $\log g = 2.5$) giants are 1.3, 1.5, and 2.5, which are larger than the higher mass Hyades giant Li abundances of ~ 0.9 . While the Hyades giants have C isotope ratios in accord with standard model predictions, the lower mass NGC 7789 giants have values below such predictions, again necessitating some sort of extra mixing mechanism in this cluster. It is rather striking that the NGC 7789 Li abundances are larger than the Hyades values despite this additional mixing. Indeed, in terms of standard stellar models, it is curious that the NGC 7789 giant with the largest Li abundance of 2.5 also has the *lowest* $^{12}C/^{13}C$ ratio (~ 10 ; Sneden & Pilachowski 1986) observed in the cluster. Again, the simplest explanation would appear to be Li production in these giants.

We call attention to the fact that the Population I field and cluster giants with high Li have C isotope ratios that are low but not at the equilibrium value of ~ 4 . Thus, total destruction of 3He —critical for Li production via a 7Be transport mechanism—has presumably not occurred. If the low Mg in our M92 stars is a product of very deep mixing, then 3He may have also been destroyed. This is a possible

complication, as it would mean no conventional source of 7Be for Li production needed to balance the Li depletion preceding very deep mixing.

4.9. Final Comments

This paper provides some of the first detailed abundances for globular cluster stars near the main-sequence turnoff. Given the modest S/N of the spectra and the implications of the abundances, the results for these very faint stars need confirmation with even higher quality data. In particular, our Mg and Na results are important to verify. Photospheric contamination by deep mixing products might also be investigated by very challenging determinations of Al and O abundances. Additional valuable future efforts would be (1) reexamination of the M92 reddening and photometry; (2) homogeneous abundance determinations in globular cluster giants and dwarfs so that a direct comparison can be made; and (3) investigation of model atmosphere uncertainties on dwarf *versus* giant abundances in globular clusters.

If confirmed, our results might also raise concerns about globular cluster photometric dating, which requires accurate $[Fe/H]$ values. Given our deficient $[Mg/Fe]$ ratio but unremarkable $[Ca/Fe]$ ratio, opacity mixtures assuming either solar ratios or constant enhancements of α -elements may not be applicable. We also draw attention to M13, where Pilachowski & Armandroff (1996) find low ($\lesssim -0.1$ at the 1σ level) values of $[O/Fe]$ from the $\lambda 7774$ O I triplet near the base of the giant branch. However, the analysis of similarly evolved metal-poor field stars by Cavallo, Pilachowski, & Rebolo (1997) suggests that such abundances are spuriously high by ~ 0.5 dex in such stars. If true, this would indicate that $[O/Fe]$ really is $\lesssim -0.6$, which conflicts with Kraft et al.'s (1997) conclusion that $[O/Fe]$ in lower luminosity M13 stars is consistent with that of higher luminosity giants as inferred from the O-Na anticorrelation. Indeed, it may suggest that $[O/Fe]$ is “unusually low” at the turnoff of M13. Other issues such as the consistency of differing spectroscopic analyses and the adequacy of model atmospheres may also be important considerations in such differences.

Additional complications are the possibilities that the values of $[O/Fe]$ and/or $[Mg/Fe]$ could vary with evolutionary state within a globular cluster and the effects of primordial or in situ processing on helium abundance. In principle, any deep mixing necessary to explain the abundance patterns in globular cluster red giants or in our M92 stars might also affect the value of Y , which is a key ingredient in stellar evolutionary calculations. Furthermore, one again might wonder what the behavior of any such Y variations with evolutionary state within a globular cluster is. Until some of these issues can be addressed with observational spectroscopic constraints, the adequacy of stellar models of globular cluster stars, and hence accurate absolute and relative cluster ages, must remain uncertain by an uncertain amount. With the construction of very large aperture telescopes and efficient echelle spectrographs, detailed spectroscopic information should become available for more globular clusters in the near future.

5. SUMMARY AND CONCLUSIONS

We have used high-resolution, modest-S/N spectra obtained with the Keck I HIRES spectrograph to derive abundances of Na, Mg, Ca, Ti, Cr, Fe, and Ba for subgiants

near the M92 turnoff. Using a high-S/N spectrum from the same instrument, we derive abundances of the same elements in a similar fashion for the metal-poor field subgiant HD 140283. Our Fe abundance for HD 140283, $[\text{Fe}/\text{H}] = -2.58$, is in fine accord with determinations in the literature. Our M92 abundance of $[\text{Fe}/\text{H}] = -2.52$ is about a factor of 2 lower than that derived from spectroscopic analyses of evolved cluster giants (e.g., SKPL91) and horizontal-branch stars (Cohen & McCarthy 1997). We find that differences in model atmospheres, atomic data, and possible instrumental effects are large enough to explain the difference. However, a current unknown is the consistency of the red giant analyses' adopted solar abundances with their derived stellar values; the search for such consistency has been emphasized in this analysis.

We have noted possible evidence for an Fe abundance difference between M92 subgiants 21 and subgiant 18 and 46. We find a mean Fe abundance for the former star that is 0.15 dex larger than the latter two stars. This is larger than the Stetson & Harris (1988) "soft" statistical limit of 0.10 dex for the abundance spread in M92; however, a 0.15 dex difference would not be very shocking for any given star such as 21. While the abundance difference might also be due to an errant T_{eff} value for star 21 versus stars 8 and 46, two independent $B-V$ values and a $V-I$ measurement indicate that the stars' colors are identical to within 0.01 mag. This suggests that T_{eff} differences are not the culprit; yet regardless we would then infer an Mg abundance difference in the opposite sense between the stars.

The stellar parameters, T_{eff} and ξ , deduced from a straightforward Fe I line analysis, suggest temperature differences of ~ 300 K between HD 140283 and our M92 stars; this value was much larger than anticipated, since the field and cluster stars have identical colors. If correct, these T_{eff} differences would suggest that the M92 reddening, $E(B-V)$, is some 0.04–0.05 mag larger than currently assumed values, or that the $B-V$ photometry is in similar error; a larger reddening may be consistent with the interstellar Na I features present in our M92 spectra but absent in our HD 140283 spectrum. This significant revision to the M92 colors would reduce the inferred turnoff ages to values near 12 Gyr. Consistent revisions to the M92 turnoff luminosity appear possible as a result of extinction and new *Hipparcos*-based distances. Such a young age would be of great astrophysical significance, as M92 is assumed to be among the very oldest Galactic globular clusters. However, our spectroscopic parameter estimates are not very stringent. Specifically, excluding relative T_{eff} values for our M92 stars that would result in a reddening identical to current estimates *cannot* be done at a significant confidence level. If such agreement is indeed achieved with lower M92 T_{eff} values, this would only serve to lower further our already surprisingly low M92 $[\text{Fe}/\text{H}]$ value. Hence, it is difficult to escape the conclusion (from the present data anyway) that either the canonical Fe abundance of M92 has been overestimated or canonical reddening/color estimates are too low/red.

The $[\text{Fe}/\text{H}]$, $[\text{Cr}/\text{Fe}]$, $[\text{Ca}/\text{Fe}]$, and $[\text{Ti}/\text{Fe}]$ ratios of our M92 objects and HD 140283 are the same to within the errors and are unremarkable compared with the values for field stars of similar $[\text{Fe}/\text{H}]$. The $[\text{Ba}/\text{Fe}]$ ratios of both HD 140283 and our M92 objects cannot be said to deviate greatly with respect to extant field star data, which show large scatter. However, the two values differ by 0.4 dex, with

our M92 objects demonstrating a larger ratio.

A surprisingly large difference is seen in both the $[\text{Mg}/\text{Fe}]$ and $[\text{Na}/\text{Fe}]$ ratios. The $[\text{Mg}/\text{Fe}]$ value for our M92 objects is some 0.55 dex lower than that for HD 140283, while our M92 $[\text{Na}/\text{Fe}]$ value is 0.76 dex higher than that for HD 140283. The M92 stars, and not HD 140283, are clearly the anomalous objects with respect to extant field star data for Mg and Na. We use moderately strong lines to derive the stellar Mg and Na abundances. There is thus larger uncertainty in these measures, but the plausible uncertainties seem much smaller than the derived abundance differences.

This Mg/Na abundance pattern is reminiscent of that seen in evolved giants of several globular clusters and suggests that material in the photospheres of our near-turnoff M92 objects has undergone $\text{Ne} \rightarrow \text{Na}$ and $\text{Mg} \rightarrow \text{Al}$ cycling. The higher $[\text{Ba}/\text{Fe}]$ ratio in our M92 stars could mean that some portion of this was accomplished via processing involving n -capture. The abundant Li content of our little evolved M92 stars, the near-normal C abundance in *other* M92 stars of similar evolutionary state, and the lack of an internal neutron source (if indeed n -capture is responsible for any of the M92 abundance anomalies) would all seem to indicate that this processing does not have an in situ source like that inferred for evolved giants in some globular clusters such as M13 and M92. Rather, we suggest that our M92 objects' photospheres must have been polluted by material processed at an earlier time by another source. We cannot, however, exclude the possibility that our M92 objects have undergone some degree of shallower in situ mixing; indeed, we have proposed (BDSK) that this may explain the substantial star-to-star Li abundance variations between our M92 objects.

There is good evidence that such "primordial" (though, in principle, they may have occurred after cluster star formation) variations have occurred in some globular clusters such as 47 Tuc (e.g., Briley et al. 1995) and ω Centauri. Such primordial effects seem attractive in explaining, e.g., the star-to-star n -capture abundance variations in M15 (Snedden et al. 1997) and possible cluster-to-cluster differences in n -capture abundances (Armosky et al. 1994). In sum, our near-turnoff results, coupled with previous red giant data, would indicate that the detailed abundances of M92 stars may be a complex result of both "primordial" and in situ processes.

The large difference between our M92 subgiant $[\text{Mg}/\text{Fe}]$ and $[\text{Na}/\text{Fe}]$ values and those in at least some M92 red giants may indicate that pollution of the subgiants' photospheres occurred after the present generation of cluster stars had formed. In such a scenario, less material is required to alter the surface abundances due to the stars' shallow convection zones. As the stars evolve and their convection zones deepen, these polluted abundances could be diluted to the nearly normal values seen in some M92 giants. Subsequent deep in situ mixing could then alter these diluted polluted abundances, resulting in the abundance patterns seen near the tip of the M92 RGB. Admittedly, this picture is not a simple one. An additional complication is that the source of polluting material, having suffered severe Na and Mg alterations but not gross Li or C alterations, is unclear. However, one may face a similar puzzle in explaining the abundance patterns of some 47 Tuc main-sequence stars. Whatever the source of the odd abundance ratios we find in our M92 subgiants, a more confident determination of the

abundances of several elements and delineation of any variation in these abundances with evolutionary state may be needed to derive relative and absolute globular cluster ages with greater confidence.

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NOTE ADDED IN PROOF.—We should like to point out that R. C. Peterson, R. L. Kurucz, & B. W. Carney (*ApJ*, 350, 173 [1990]) have found a low value for $[\text{Fe}/\text{H}]$ from two M92 giants from CCD spectra from the KPNO 4 m telescope. Their value, $[\text{Fe}/\text{H}] = -2.5 \pm 0.2$, is the same as ours.