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SODIUM, ALUMINUM, AND OXYGEN ABUNDANCE VARIATIONS IN GIANTS IN THE GLOBULAR CLUSTER M4

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ABSTRACT

Accurate, quantitative abundances are presented for Fe, Ca, Na, Al, and O in four red giants in the bimodal-CN globular cluster M4. Two of the giants are CN-strong and two are CN-weak: all have very similar magnitudes and colors and, thus, have similar effective temperatures and surface gravities. This analysis utilizes high-resolution, high-SN spectra and up-to-date model atmospheres. For the low-ionization element Na, detailed non–LTE calculations demonstrate that, for lines used in the abundance analysis, departures from LTE are small ($\lesssim$0.1 dex). As a group, these four M4 giants have homogeneous Fe and Ca abundances, while Na, Al, and O vary: the CN-strong stars have larger Na and Al but smaller O abundances than the CN-weak stars. When compared to field metal-poor stars, the CN-weak stars resemble the field stars, while the CN-strong stars are Na and Al rich.

Subject headings: globular clusters: individual: M4 — stars: abundances — stars: giant

1. INTRODUCTION

There is a great deal of literature demonstrating that the stars within globular clusters can show a wide range of abundance variations: from large chemical inhomogeneities in virtually all elements (e.g., C, N, O, Na, Al, Ca, Fe, Sr, or Ba) in ω Cen and, perhaps, M22, to only variations in C and N, which may be ubiquitous to all globular cluster giants. Recent reviews of these abundance variations can be found in Smith (1987, 1989), Suntzeff (1989), and Pilachowski (1989). Interesting patterns appear in these abundance variations, such as the bimodal distributions of CN strengths found in many intermediate metallicity clusters ($-0.7 \gtrsim [M/H] \gtrsim -1.6$) which suggest two distinct populations of red giants: "CN-strong" and "CN-weak" stars. The origins of these CN distributions within individual clusters has remained a controversial topic: do these differences in CN band-strengths arise from purely internal stellar evolution within the individual giants (i.e., C and N abundance variations due to convective mixing of CN cycle material on the red giant branch) or do they reflect primordial differences in the C and N abundances in some of the protocluster gas from which a certain fraction of the cluster stars formed. Recent observations of CN and CH variations in main-sequence stars ($M_V \approx +6$) in the globular cluster 47 Yuc (Briley, Hesser, & Bell 1991) and NGC 6752 and 47 Tuc (Suntzeff & Smith 1991) lend some weight to the idea of primordial variations, as it is difficult to mix CN-cycle material to the surface of a low-luminosity main-sequence star (although the picture can always be complicated by other mechanisms such as binary mass-transfer).

An additional pattern associated with the CN variations is the correlation of the strength of Na I and Al I lines with CN band-strength in giants of similar color and magnitude (Peterson 1980; Cottrell & Da Costa 1981; Norris et al. 1981; Norris & Smith 1983; Norris & Pilachowski 1985; Lehnert, Bell, & Cohen 1991). Previous studies of the Na/Al-CN correlations have relied largely upon either empirical indices form ed from the spectra, or LTE analyses of, often, the rather strong resonance Na I and Al I lines. Many of the above-mentioned studies have voiced concern about non–LTE effects being responsible for the strengthened Na I and Al I lines. Campbell & Smith (1987) observed that the K I lines (K I has a similar atomic structure to Na) in CN-strong and -weak giants were of equal strengths and this result supported the hypothesis for abundance variations, although non–LTE calculations are needed to further bolster the argument for abundance variations. Indeed, in a recent study of Na and Mg lines in bimodal-CN globular clusters, Smith & Wirth (1991) state the assumption that the Na, Al, and Mg line-strength variations reflect real abundance differences, although they stop short of a quantitative abundance analysis.

In this *Letter*, we present a quantitative abundance analysis of Fe, Ca, Na, Al, and O (including detailed non–LTE calculations for Na, Ca, and Fe) in four giants in the CN-bimodal globular cluster M4 (Norris 1981) and find anti-correlations of the Na/Al abundances with the O abundance. Our results add definitive evidence to the case that the Na and Al abundance variations (as well as oxygen) reported previously in globular clusters are indeed real and are not the results of non–LTE or atmospheric effects.

2. OBSERVATIONS AND DATA REDUCTION

The spectral observations of the giants were made with the CTIO 4 m telescope and the facility echelle spectrograph, in a single run on 1991 May 19–22 (UT). We used the 31.6 groove mm^{-1} echelle, the 226 groove mm^{-1} cross-dispersing grating blazed at 6300 Å, and the blue long camera. The detector was a TEK CCD with 1024 × 1024 μm pixels with on-chip binning by a factor of 2 perpendicular to the dispersion. The spectra

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covered the wavelength range 5480–7080 Å in 23 orders. The final resolution was 2.5 pixels (FWHM), which corresponded to $\lambda/\Delta\lambda = 35{,}000$.

Each program object was observed twice with exposure times of typically 1 hr. We obtained thorium argon (Th-Ar) comparison exposures after every stellar observation and also obtained spectra of the quartz continuum lamp at various telescope positions each night. Spectra of the daytime, bright field giants (ϵ Vir and ϵ Aqr), and a hot star at extremely high S/N, to locate telluric absorption, were also taken.

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

In Figure 1, we illustrate sample spectral regions for two of our program stars: star 3624 (which is CN-weak) and star 2617 (CN-strong). Both of these stars have very similar $T_{\rm eff}$ and surface gravity and, by-and-large, their spectra are extremely similar *except* for the lines illustrated in the figure. The top panel shows the region near the Na I line at 6160 Å: note the similarity of these spectra for the Ca I lines and the Ni/Fe/Ca blend, while the Na I line differs by almost a factor of 2 (as does the 6154 Å Na I line)! In the middle panel we illustrate the difference in the 6300 Å [O I] line, with the CN-strong star having an [O I] line that is some 40% weaker than the CN-weak star. Finally, we show the same effect for the Al I doublet near 6698 Å: note the similarity of the Fe I line, with the other small differences in the spectra being due to CN lines.

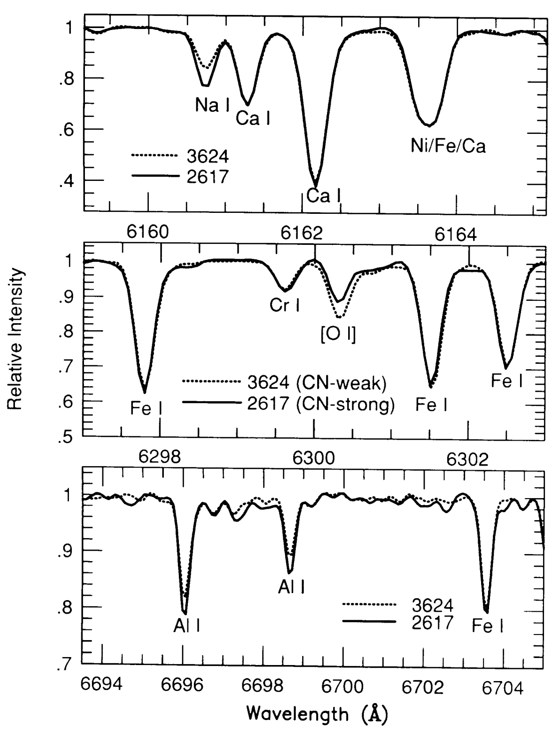

FIG. 1.—The spectral regions illustrating the Na I, [O I], and Al I lines. The top panel shows λ6162 Å in the CN-strong star 2617 and CN-weak star 3624 illustrating the great similarity in the Ca I lines, but large difference in the Na I line. In the middle panel we show the weakened [O I] line in the CN-strong star 2617 relative to the CN-weak star 3624. The bottom panel demonstrates differences in the Al I doublet near 6698 Å (note the similarity in the Fe I lines, while the differences in the weak features are due to CN).

3. STELLAR PARAMETERS AND ABUNDANCES

In Table 1 we list the M4 stars observed along with V_0 magnitudes from Cudworth & Rees (1990) and CN band-strengths, S(3839), from Suntzeff & Smith (1991). The extensive wavelength coverage and high signal-to-noise ratio of the spectra obtained provided a sufficient quantity of good quality spectral lines to enable accurate determinations of the fundamental stellar parameters $T_{\rm eff}$, log g, and microturbulence (ξ), in addition to element abundances. Stellar parameters were determined in a self-consistent way using the equivalent widths of a limited set of Fe I, Fe II, and Ca I lines, and using the wings of the strong, collisionally broadened Ca I λ6162 line. The procedure is outlined briefly below: the method is similar to that applied to the K0 giant Pollux by Drake & Smith (1991), and will be described in more detail in a forthcoming paper (Drake 1992).

Stringent criteria were applied to the line selection; iron lines were selected from the set of lines deemed to be "clean" in the solar spectrum by Rutten & van der Zalm (1984). It is known from both theoretical (Steenbock 1985) and empirical work (e.g., Ruland et al. 1980) that, in giant stars, lines of Fe I which are (1) strong and (2) of low excitation ($\chi \lesssim 3.5$ eV) are subject to significant non–LTE effects. In order to minimize potential non–LTE contamination, only Fe I lines with lower excitation potential ≥ 3.5 eV, and with solar (flux) equivalent widths in the range 20–50 mÅ, were considered. The lower equivalent width limit was imposed because weaker spectral features could not be measured in our stellar spectra with such high

TABLE 1

STELLAR PARAMETERS AND DERIVED ABUNDANCES

STAR	CN STRONG 2617	CN STRONG 3612	CN WEAK 2519	CN WEAK 3624
V_0	10.65	10.70	10.62	10.65
CN S(3839)	0.71	0.74	0.44	0.44
$T_{\rm eff}$	4280 K	4350 K	4480 K	4300 K
log g	1.22	1.28	1.34	1.30
ξ (km s^{-1})	1.5	1.5	1.8	1.5
[Fe/H][a]	−1.08	−1.02	−1.07	−1.04
[Ca/H][b]	−0.80	−0.74	−0.92	−0.79
[Na/H][c]	−0.74	−0.70	−1.12	−1.03
[Al/H][d]	−0.46	−0.46	−0.73	−0.60
[O/H][e]	−0.84	−0.80	−0.67	−0.61

[a] The *gf*-values derived using solar equivalent widths and the Holweger & Müller 1974 model with $\xi = 1.5$ km s^{-1} and log ϵ(Fe)$_\odot$ = 7.50.

[b] The *gf*-values were laboratory values from Smith & O'Neill 1975 or Smith & Ragget 1981 with log ϵ(Ca)$_\odot$ = 6.36.

[c] The *gf*-values from Lambert & Luck 1978 with log ϵ(Na)$_\odot$ = 6.32.

[d] Solar *gf*-values as in footnote a with log ϵ(Al)$_\odot$ = 6.49.

[e] The *gf*-value from Lambert 1978 with log ϵ(O)$_\odot$ = 8.92.

precision. The remaining subset of 39 lines was eventually whittled down to 15 by carefully inspecting each line in both the solar flux spectrum and in the Arcturus Atlas (Griffin & Griffin 1968) and rejecting any which were judged to be compromised by blending. Since Fe II lines are not expected to be significantly affected by departures from LTE (Steenbock 1985), selection criteria did not include line strength. Calcium lines were chosen from the subset of lines deemed to be unblended in a critical investigation of spectra of the Sun and Procyon by Smith (1981). Of these lines, only those with solar equivalent widths $\lesssim 100$ mÅ were retained in the Ca abundance determination in order to minimize the dependence of derived abundances on rather uncertain collision broadening parameters.

Unfortunately, in the case of O, Na, and Al, there are very few lines to choose from in our wavelength interval. However, the lines which are available are of sufficiently high quality to allow accurate abundance determinations. The only useful oxygen line is the [O I] line at 6300 Å, as the weaker line at 6363 Å is heavily contaminated by a CN blend. Test calculations demonstrated that contamination of the 6300 Å line by a weak Ni I blend, and by several very weak CN and TiO features was negligible (see also Lambert 1978). In the case of Na, only the 6154 and 6160 Å lines (multiplet 5) were retained. The other potentially useful subordinate line at 5688 Å was eschewed because, recent detailed non–LTE calculations (Drake 1992) suggested that this line could be strongly contaminated by non–LTE effects. The Na I doublet lines at 6154 and 6160 Å were found to be virtually free from non–LTE effects ($\lesssim 0.1$ dex, see below) for these giants and, as these lines are also weak, they provide accurate measures to the Na abundance. The Al I lines at 6696 and 6698 Å were used to determine the Al abundance. Line profiles were clean in all the program stars and could be measured with good accuracy using Gaussian approximations to measure equivalent widths.

Before discussing the abundance determinations, we describe, in some detail, the non–LTE calculations; the effects of departures from LTE on the derivation of fundamental parameters (which rely on Fe I, Fe II, and Ca I lines), using a similar method as used here, but for the K0 giant β Gem, were investigated in detail by Drake & Smith (1991). They concluded that their method was relatively insensitive to non–LTE effects, with the LTE and non–LTE analyses yielding similar results. Due to the fact that the cluster giants studied here are cooler and metal-poor relative to β Gem, we investigated non–LTE effects using a representative model atmosphere ($T_{\rm eff} = 4300$ K, $\log g = 1.3$, $[{\rm M/H}] = -1.0$). Model atoms used were updated versions of the Ca and Fe models described in detail by Watanabe & Steenbock (1985) and Steenbock (1985), respectively. The Ca model comprised 16 levels of Ca I, 5 of Ca II, and the Ca III continuum, including 20 bound-bound radiative transitions treated in detail. The Fe model included 74 levels of Fe I, 25 of Fe II, and the Fe III continuum, including 75 bound-bound radiative transitions treated in detail. The non–LTE code used was a modified version of MULTI (Carlsson 1986), with collisional excitation and ionization by neutral H accounted for according to the scheme suggested by Steenbock & Holweger (1984). The effects of line blanketing on the ionizing radiation field were included using the Kurucz (1979) opacity distribution functions. We note, that, as with β Gem, departures from LTE had only small effects on derived LTE parameters, and we will therefore retain our LTE parameters with confidence.

Departures from LTE for Na were investigated using a model atom from Drake (1992) which comprised 47 levels of Na I, plus the Na II continuum, and included 65 *b-b* radiative transitions treated in detail. This model atom will be described in more detail in Drake (1992) which discusses Na abundances in a large sample of Galactic G and K supergiants. However, the data for this model atom are available upon request from the authors. We illustrate the non–LTE calculations in Figure 2 for the multiplet 5 doublet of Na I (6154 and 6160 Å) that was used in the abundance analysis; the contribution functions, C_I, for both lines are shown (*top panel*), as well as the departure coefficients, B_i, for the first three energy levels of Na I (3*s*, 3*p*, and 5*s*), both as functions of the continuum optical depth, τ_{5000}. The ^2P–^2S transition of multiplet 5 consists of the 3*p* to 5*s* transitions. The contribution function here is defined as in Gray (1978), with each curve representing the depth of formation at a specified wavelength from line center, $\Delta\lambda$, with $\Delta\lambda = 0.00$ being the line center. The departure coefficient, B_i, is defined as the ratio of LTE to non–LTE population. It is found that the non–LTE corrections to the LTE abundances are small for multiplet 5: the non–LTE abundances are lower than in LTE by 0.07 dex. This is well shown in Figure 2 where we note that virtually all of the contribution function to the absorption for both lines comes from below optical depths of $\log \tau_{5000} \sim -1.4$ (even at line center), while non–LTE effects only become apparent ($\log B_i$ differs from 0) above $\log \tau_{5000} \sim -2$. These results are not surprising, as the absorption lines used here from Na I (5) are weak and are formed relatively deep in the atmosphere where LTE is a good approximation. We conclude, therefore, that departures from LTE on our derived Na abundances for these four M4 giants are small, although it is possible that the LTE results are too large by ~0.05–0.1 dex. Unfortunately, we have not yet compiled sufficient atomic data to perform similar calculations for Al, but we would anticipate that, as in the case of Na, departures from LTE will not be large for these weak lines.

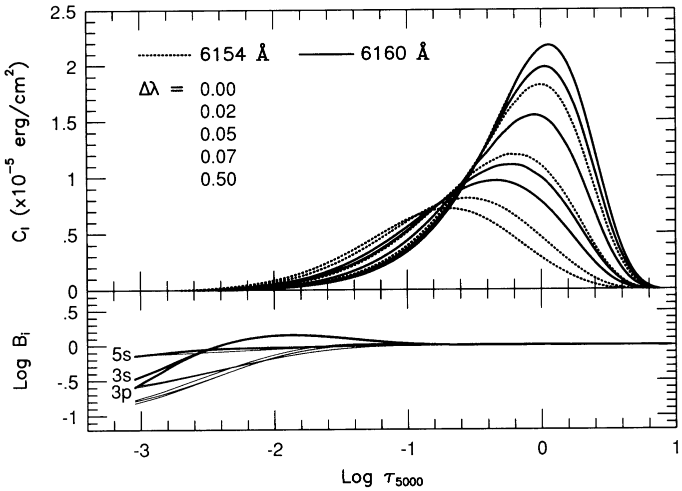

FIG. 2.—The contribution functions, C_I (see text), for the Na I (5) multiplet and non–LTE departure coefficients, B_i, as a function of continuum optical depth, τ_{5000}, for a $T_{\rm eff} = 4300$ K, $\log g = 1.3$, $[{\rm M/H}] = -1.0$ model atmosphere. The contribution functions for this weak Na I doublet are formed almost completely below layers where non–LTE effects on the population levels ($\log B_i \neq 0.0$) become important. This figure shows that these particular Na I lines are formed close to LTE and that the differences observed in the Na I equivalent widths are due to abundance differences.

As the non–LTE effects were found to be small, abundance calculations were performed under the conditions of local thermodynamic equilibrium and plane-parallel geometry using the program LINFOR (H. Holweger, M. Steffen, and W. Steenbock, Universität Kiel). For this purpose, a three-dimensional grid of model atmospheres, each dimension corresponding to one of the parameters $T_{\rm eff}$, log g, and global metallicity (represented by the abundance of iron relative to the Sun, [Fe/H]), was generated using the MARCS program. These models are similar to those described by Gustafsson et al. (1975) and published by Bell et al. (1976). The ranges of the stellar parameters were chosen so as to encompass the likely values of these quantities possessed by our program stars.

The effective temperature and iron abundance were determined simultaneously using the iron ionization balance, employing the usual method whereby the Fe I and Fe II lines are forced to yield the same abundance. In a similar way, the microturbulence and calcium abundance were determined by forcing Ca I lines of varying strength to yield the same abundance in the Ca-ξ plane. Smith & Drake (1987) and Drake & Smith (1991) have demonstrated that, provided the calcium abundance is known, the pressure sensitive, collision-broadened wings of the Ca I λ6162 line can provide a sensitive diagnostic of surface gravity in both late-type dwarfs and giants. Using spectrum synthesis, the surface gravity was determined by varying this quantity until the synthetic spectrum matched the observed spectrum in the regions of the 6162 Å line wings.

In practice, the spectral indices used to determine $T_{\rm eff}$, log g, and microturbulence (ξ) described above are nonorthogonal and the entire process proceeds by iteration until a self-consistent set of parameters is obtained. In the cases of all four stars, convergence was achieved in 3–4 iterations with uncertainties of ± 80 K in $T_{\rm eff}$, ± 0.2 in log g, ± 0.2 km s^{-1} in ξ, and ± 0.1 dex in the abundances. The derived stellar parameters and abundances are presented in Table 1: the abundances are measured with respect to solar.

4. DISCUSSION

An inspection of the abundance results presented in Table 1 shows clearly that the CN-strong and -weak giants segregate in terms of their Na, Al, and O abundances. The differences in the mean abundances between the CN-strong and -weak pairs, when defined as $\bar{\Delta} = \log \epsilon_{\rm CN\text{-}strong} - \log \epsilon_{\rm CN\text{-}weak}$, are listed as follows: $\bar{\Delta}$(Fe) = +0.01, $\bar{\Delta}$(Ca) = +0.08, $\bar{\Delta}$(Na) = +0.36, $\bar{\Delta}$(Al) = +0.21, and $\bar{\Delta}$(O) = −0.18. The Fe abundances are extremely homogeneous, while the Ca abundances show a larger dispersion, yet, even this difference in $\bar{\Delta}$ is less than 0.1 dex and could not be claimed to be significant. The Na, Al, and O abundances, on the other hand, show much larger differences which reflect real abundance variations. As low-mass stars are not expected to alter their Na or Al abundances, these abundance variations probably result from primordial differences in the gas from which these stars formed. A comparison of the $\overline{\rm [Na/Fe]}$ abundances in the CN-strong and -weak giants ($\overline{\rm [Na/Fe]}$ = +0.33 and +0.02, respectively) with field stars of similar metallicity (François 1986; Gratton & Sneden 1987) reveals the CN-weak giants to agree with the general trend of [Na/Fe] versus [Fe/H] found for the field stars: the CN-strong pair is "Na-strong" relative to the field. This agrees with the results from a much larger sample of field and globular-cluster giants by Kraft et al. (1992).

The main result here is that a thorough analysis of the Na/Al/O line-variations in pairs of CN-strong and -weak giants in M4 reveals significant Na, Al, and O abundance variations: a non–LTE analysis of Na demonstrates that the Na line variations observed so extensively in many globular cluster stars cannot be dismissed as a "non–LTE effect," but must reflect real Na abundance variations (and almost certainly Al and O also). These Na, Al, and O abundance differences probably originated in the gas from which the globular-cluster stars formed (i.e., primordial differences).

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