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Spectroscopic abundances of solar-type dwarfs in open cluster M34 (Ngc 1039)

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SPECTROSCOPIC ABUNDANCES OF SOLAR-TYPE DWARFS IN OPEN
CLUSTER M34 (NGC 1039)

by

Simon Charles Schuler

Bachelor of Science
University of Miami
2001

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Physics
Department of Physics
College of Sciences

Graduate College
University of Nevada, Las Vegas
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ABSTRACT

Spectroscopic Abundances of Solar-Type Dwarfs in Open Cluster M34 (NGC 1039)

by

Simon C. Schuler

Dr. Jeremy R. King, Examination Committee Chair
Assistant Professor of Physics
University of Nevada, Las Vegas

Parameters and relative abundances of Fe, Ni, Ti, Cr, Ca, Si, Al, and Mg have been derived for nine M34 G and K dwarfs from high-resolution, modest S/N, Keck/HIRES spectra. Effective temperatures have been derived spectroscopically and fall in the range $4750 \leq T_{\text{eff}} \leq 6130$ K. Despite modest scatter in Fe, Ti, Cr, Ca, Al, and Mg (none of which is found to be correlated with Li scatter in M34), our two coolest stars are slightly though consistently underabundant in these elements relative to the warmer stars. The two cool stars are slightly overabundant in Si, whose abundances are derived from higher excitation lines. This and our finding that Fe II-based abundances are significantly higher than Fe I-based values in the cool stars seems to point towards the action of NLTE effects (overionization and/or overexcitation), though additional analysis is required to exclude inadequacies in the model atmospheres. Final mean cluster abundances are based on five warm stars, which indicate $[\text{Fe}/\text{H}] = +0.07 \pm 0.04$, and are void of any statistically significant scatter. The other elements scale well with Fe, except for Ni, which appears to be slightly underabun-

dant with respect to Fe. K abundances are derived and show a surprising marked trend with temperature, which further supports our suspicion of the presence of NLTE effects. Moreover, the expected similar spectroscopic behavior of the neutral alkali resonance lines we employ suggests the apparent Li and K underabundances in cool M34 dwarfs are partly related; thus, some portion of the well-known Li- T_{eff} trend in cool M34 dwarfs may be illusory.

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CHAPTER 1

INTRODUCTION

Open clusters and the elemental abundances of member stars have long been known to be of great astrophysical importance. Assuming they are of the same age and formed from a chemically homogeneous gas cloud, open cluster stars can serve as test beds for our understanding of stellar properties which is then incorporated into our stellar models. However, it is apparent that stellar models in their standard form - those not including rotational mixing, magnetic fields, mass loss, or gravitational settling - are incomplete. Evidence for this is copious. For example, the observed Li spread in low-mass ($M \leq 0.9M_{\odot}$) G and K dwarfs in several open clusters - particularly in the Pleiades (Duncan & Jones 1983; Soderblom *et al.* 1993) - cannot be reproduced by standard models, but it has been shown that models including microscopic diffusion and rotational mixing might naturally produce such Li scatter (Chaboyer, Demarque, & Pinsonneault 1995). However, Chaboyer *et al.* (1995) also point out the importance of iron abundance ($[\text{Fe}/\text{H}]$ ¹) to the models. Scaling the relative Fe abundance while still assuming a solar mixture (and using the relation $\Delta Y/\Delta Z = 2.5$ for the helium-to-metal mass ratio) produced considerable changes in their standard model Li depletion predictions for Pleiads with effective temperature (T_{eff}) < 6000 K: $\Delta[\text{Fe}/\text{H}] = 0.05$ dex resulted in a change of ~ 0.4 dex in the predicted Li abundance at $T_{\text{eff}} = 5000$ K. Additionally, Piau & Turck-Chièze (2002) have investigated the effects of altering metallicity and chemical composition on their model Li abundance predictions. They compared models using observed metallicities

¹ $[\text{Fe}/\text{H}] = \log N(\text{Fe})_{\text{star}} - \log N(\text{Fe})_{\odot}$

to models that used the lowest metallicity and highest helium mass fraction allowed within observational errors for both the Pleiades and the Hyades. Specifically for the Pleiades, varying the metallicity from -0.034 dex to -0.058 dex - corresponding to the mean $[\text{Fe}/\text{H}]$ and the lower uncertainty of Boesgaard & Friel (1990) - and altering Y according to $\Delta Y/\Delta Z = 3$ (Fernandes *et al.* 1998) produced a positive change of 0.35 dex in the Li abundance (for $T_{\text{eff}} \sim 5800$ K). Piau & Turck-Chièze also studied more detailed opacity effects on Li depletion, finding that a 1.7 dex (~ 50 times) increase in Li abundance resulted when the O abundance within a Hyades model was changed from 0.127 (scaled to $[\text{Fe}/\text{H}]$) to -0.07 dex (observed $[\text{O}/\text{H}]$ from Garcia Lopez *et al.* 1993) and scaling the rest of the metals (except the iron peak elements) with O.

Interestingly, the ever increasing number of extrasolar planets being discovered may provide a mechanism by which intracluster abundance scatter could arise. Spectroscopic studies have shown enhanced metallicities for stars with planets relative to nearby field stars (*e.g.*, Gonzalez *et al.* 2001). Accretion of high-Z proto-planetary material onto the parent star has been suggested as a possible cause of abundance scatter. However, an alternate explanation for the increased metallicity might be that planetary systems preferentially form in high metallicity environments. Data exist supporting both hypotheses, making accurate *cluster* abundance calculations significant to clarifying the situation.

The importance of opacities has also been exhibited in comparing stellar models and observations of the overall level of Li depletion in cool stars in open clusters of differing age. Swenson *et al.* (1994) showed that increased opacities in Hyades stellar models could produce agreement with the observed Li depletions from standard pre-main sequence (PMS) burning alone. Using $[\text{Fe}/\text{H}] = 0.12 \pm 0.03$ from Cayrel, Cayrel de Strobel, & Campbell (1985) and scaled solar mixtures for the other elements, they

were not able to reproduce the T_{eff} -Li trend observed in cool stars of the Hyades. Because of the lack of knowledge concerning stellar abundances of elements other than Fe and Li, solar mixtures have traditionally been assumed in this way, despite the possibility of non-solar abundances. However, assuming non-solar mixtures, specifically an enhanced abundance of O, Swenson *et al.* found the increased opacity resulted in models that fit well the observed Hyades data. If true, increased opacities and the resulting PMS burning might eliminate the need for main sequence (MS) Li depletion mechanisms in this case (though elevated abundances of the Hyades short-period, tidally locked binaries seem a striking refutation of this; Thorburn *et al.* 1993).

A salient issue, then, is observational guidance in setting model opacities. Unfortunately, substantial information on observed open cluster (or field star) abundances beyond Fe and Li is lacking. In the case of the Hyades, the closest and most-well studied cluster, limited data exist suggesting subsolar, solar, or super-solar [O/Fe] ratios; accounting for study-to-study differences is surprisingly non-trivial (King & Hiltgen 1996). Regardless, Chaboyer *et al.* (1995) and Piau & Turck-Chièze (2002) confirm that metallicity and chemical composition are important to the modelling of Li abundance depletions; that observed intracluster Li dispersions might be related to star-to-star scatter of other elements remains possible. Obviously, knowledge of chemical compositions and any cluster scatter is needed for a more complete understanding of observed Li abundances.

Elemental abundances also play an important role in distances to clusters inferred from MS fitting. This procedure utilizes stars' positions in the H-R diagram, which are specified by their mass, chemical composition (not just [Fe/H] alone), and age. By comparing the MS of a star cluster to an empirical or theoretical MS for which the distance and composition are known, the distance to the cluster can be deduced. The distances as determined by the parallax data of the *Hipparcos* satellite mission are

found to be in good agreement with MS fitting for most of the clusters observed by *Hipparcos*; there are exceptions, however, with much attention given to the Pleiades. Distances are often referenced in terms of the distance modulus ($m - M$), which is defined as the difference of an object's apparent (m) and absolute (M) bolometric magnitudes². The Pleiades distance modulus as determined by MS fitting is found to be 5.60 mag (VandenBerg & Bridges 1984; Pinsonneault *et al.* 1998), while the *Hipparcos*-based distance modulus is 5.36 ± 0.06 mag (Robichon *et al.* 1999). Solar abundances and/or mixtures are often adopted for clusters, which could result in incorrect positions in a model H-R diagram (by as much as 0.20 mag for a $\Delta[\text{Fe}/\text{H}] = 0.15$ dex) and thus incorrect MS fitting-based distance determinations. While Pinsonneault *et al.* (1998) suggest that this is not the cause of the disagreement in the case of the Pleiades, for which limited abundance work has been carried out (*e.g.*, Boesgaard 1989, Boesgaard & Friel 1990, King 1993, and King *et al.* 2000), they remind us that the abundances of Si and Mg, which contribute to atmospheric opacities, are not well known for the Pleiades. Again, proper elemental abundances for clusters are required to help build confidence in the distances derived from MS fitting on a cluster-to-cluster basis. Cognately, these abundances are necessary ingredients for reliable age determinations for open clusters, which are valuable chronometers in the Galactic disk.

Despite the importance of having accurate metal abundances for open clusters, there is limited data other than for Fe and Li; exceptions are detailed abundances for twelve Hyads (Cayrel *et al.* 1985), sixteen Pleiads (Wilden *et al.* 2002), and for a few Pleiads and NGC2264 stars (King *et al.* 2000). While we plan targeted efforts in this regard, it should be noted that the future success of stellar models to match observations (and thus our understanding of stellar properties) undoubtedly lies in

² $m - M = 5 \log(d) - 5$, with d the distance to the object

a combination of accurate abundances and non-standard physics, neither seemingly being a solution to existing discrepancies alone. As such, the present study is an exploratory response to the growing need for accurate open cluster abundances. Using the spectroscopic data from Jones *et al.* (1997, hereafter JFSS), we have analyzed nine solar-type dwarfs in the open cluster M34, deriving abundances for Fe, Ni, Ti, Cr, Ca, Si, and Al. Our goal is to provide initial estimates of mean abundances and to place constraints on intracluster scatter.

CHAPTER 2

OBSERVATIONS AND MEMBERSHIP

Observational Data

Echelle spectra of thirty-four M34 stars were obtained with the HIRES spectrograph (Vogt 1992) on the Keck I 10m telescope with incomplete wavelength coverage from $\sim 6300 \text{ \AA}$ to $\sim 8700 \text{ \AA}$. The data were originally taken by JFSS in 1994 in order to investigate the Li abundances of M34 stars. The spectra presented herein have a resolution of $R \sim 45,000$ with a typical S/N ratio of ~ 70 . The data are more fully described in JFSS.

Of the thirty-four stars observed, nine G and K dwarfs were chosen for analysis. The criteria used in deciding which stars to examine were low rotational velocities and high membership probabilities, data for which were taken from JFSS. The significance of choosing stars with relatively low rotational velocities is the reduction of blending of spectral lines which increases with increasing rotational velocity and the minimization of photon-noise contributions to the line strength measurement uncertainties. All the stars have rotational velocities $v \sin i \leq 11 \text{ km s}^{-1}$. We also chose stars such that our sample covered a range of effective temperatures, allowing us to consider any abundance spreads in the cool stars with respect to their observed Li abundances. Star identification numbers taken from Jones & Prosser (1996, hereafter JP) are listed in column one of Table 1, JFSS rotational velocities in column five, and JP proper motion-based membership probabilities in column six.

Table 1 Stellar Data

	$(B - V)_0$	T_{eff}	ξ	$v \sin i$	Mem. Prob.
Star	(Mag.)	(K)	(km s ⁻¹)	(km s ⁻¹)	(%)
JP133.....	0.62	5810	1.05	11.0	96
JP199.....	0.80	5173	0.42	9.5	85
JP208.....	0.66	5658	0.90	5.0	98
JP296.....	0.69	5548	0.78	5.0	91
JP298.....	0.92	4814	0.09	8.9	71
JP366.....	0.65	5695	0.94	7.0	94
JP415.....	0.72	5442	0.69	5.0	93
JP489.....	0.89	4899	0.16	7.8	67
JP515.....	0.57	6007	1.26	9.8	98

Membership

Membership was carefully scrutinized when considering the stars to be analyzed. Proper motion-based membership probabilities were calculated by both Ianna & Schlemmer (1993) and JP. Membership agreement was found for most stars; however two exceptions are considered in the present study - JP296 and JP515. Ianna & Schlemmer (1993) found membership probabilities of 20% for JP296 and 38% for JP515, while JP found 91% and 98%, respectively. A cluster color-magnitude (CM) diagram is shown in Figure 1, photometric data for which was taken from JP and JFSS. The JFSS $(B - V)_0$ values were derived by averaging the observed $(B - V)$ and the observed $(V - I)_K$, both from JP, and transforming these to $(B - V)$. The averaged value was then corrected for reddening by $E(B - V) = 0.07$ mag. $(B - V)_0$ colors are listed in column two of Table 1. The placement of JP296 and JP515 on the cluster CM diagram, as with all the stars considered here, is close to the cluster main sequence, suggesting membership. The JFSS radial velocities confirm membership of all the stars considered here except for JP296, for which only one observation had been made. In spite of its disparate radial velocity, the high membership probability

Figure 1 M34 color-magnitude diagram. A reddening of 0.07 mag has been adopted for $(B - V)_0$ colors. Filled squares are the stars considered in the present study and crosses are the remaining stars found in JFSS.

found by JP and its placement on the CM diagram led JFSS to conclude that JP296 is a member of the cluster but may be a single-line spectroscopic binary (SB1). Both $(B - V)$ and $(V - I)$ CM diagrams based on M34 photometry from the WIYN Open Cluster Study (WOCS) also suggest membership for JP296 (C. Deliyannis 2002, private communication). However, they also find that its radial velocity is outside that of the cluster, adding support that it is a SB1. We have adopted JP296 as a member of the cluster.

CHAPTER 3

ANALYSIS

Spectral Lines

Spectral line selection was aided by the solar line list of Thévenin (1990), except for the two Mg lines measured, which were chosen from King *et al.* (2000). Lines in the Thévenin list classified as “case b” (those with errors $\sigma > 0.05$ in the $\log gf$ values) were not considered due to possible blending. Because of the moderate typical S/N ratio, each of the remaining “case a” lines was scrutinized and compared to solar lines found in the Kurucz *et al.* (1984) solar atlas. Any line that was thought to be blended or otherwise unmeasurable was discarded. Due to the wide spectral coverage, we were left with 69 to 118 Fe I lines for all the stars except for JP298 and JP489, which are the two coolest stars and are subject to increased blending effects. For these we relied on a selection of the 26 and 29 cleanest Fe I lines, respectively. Sample spectra are given in Figure 2.

Equivalent Widths and Stellar Parameters

Equivalent widths - measures of absorbing line strengths - of our stellar and solar lines were measured using the one-dimensional spectrum analysis package SPECTRE (Fitzpatrick & Sneden 1987), utilizing gaussian curves for integrations. The LTE stellar line analysis program MOOG (Sneden 1973) was then used to derive abundances, using stellar atmospheres interpolated from the grids of Kurucz (1992, private communication). The solar abundances were obtained in a consistent fashion, using measured equivalent widths, the same $\log gf$ values, and a Kurucz solar model atmo-

Figure 2 Keck/HIRES Spectra of selected M34 stars. The top panel is JP298, the center panel is JP415, and the bottom panel is JP515.

sphere. Line parameters, equivalent widths, and abundances for the Sun and M34 dwarfs are given in Table 2 and Table 3. Initial color-based effective temperatures for the M34 members were taken from JFSS. Surface gravities ($\log g$) were calculated using the polynomial fitted to zero-age main sequence (ZAMS) models found in Gray (1992), $\log g = 4.38 - 0.1371(B - V) - 0.8141(B - V)^2 + 5.5555(B - V)^3 - 6.6815(B - V)^4 + 2.3615(B - V)^5$, which is believed to vary insignificantly for $(B - V) \geq 0.5$ from a polynomial approximation fitted to an observed MS of binary star calibrations (see Gray for references). The reddening-corrected $(B - V)_0$ colors of JFSS were used to calculate the $\log g$ values. Random uncertainties in $\log g$ due to those color indices are below 0.01 dex. The polynomial relation itself is believed to be accurate to within 0.10 dex, which has been conservatively adopted as the $1-\sigma$ level uncertainty in $\log g$.

Initial microturbulent velocities (ξ) were calculated using the relation found in Edvardsson *et al.* (1993): $\xi = [1.25 + 8 \times 10^{-4}(T_{\text{eff}} - 6000) - 1.3(\log g - 4.5)] \text{ km s}^{-1}$. This relation was reported to be applicable for stars within the parameter ranges of $5500 < T_{\text{eff}} < 6800 \text{ K}$, $3.8 < \log g < 4.5$, and $-1.1 < [X/H] < 0.3$. While some initial stellar parameters lay outside of these ranges, the calculated ξ values were used only as initial guesses. Initial values for T_{eff} and ξ are listed in columns three and four of Table 1.

Final effective temperatures were derived spectroscopically by utilizing model atmospheres of various T_{eff} and investigating the correlations between the resultant line-by-line Fe I relative abundances (*i.e.*, normalized to the Sun) and the excitation potentials (χ). The final temperature for a given star was achieved when no correlation remained, thus obtaining Fe I excitation balance. Likewise, eliminating correlations between the Fe I relative abundances and reduced equivalent widths ($\log(\text{EW}/\lambda)$) provided the final ξ values.

Table 2. Equivalent Widths and Abundances - Sun, JP133, JP199, JP208, & JP296

	λ	χ		EW		JP133		JP199		JP208		JP296	
Ion	(Å)	(eV)	$\log gf$	($\odot$)	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$
FeI	6311.50	2.83	-3.21	28.6	7.55	...	...	...	...	...	...	...	...
	6315.81	4.07	-1.76	38.5	7.52	...	...	56.0	7.55	52.6	7.63	42.5	7.43
	6322.69	2.59	-2.40	74.7	7.43	100.5	7.52	115.7	7.55	95.1	7.43	114.1	7.81
	6330.85	4.73	-1.32	33.3	7.60	43.0	7.68	53.8	7.74	40.2	7.62	39.4	7.58
	6335.34	2.20	-2.20	102.0	7.36	118.6	7.19	162.0	7.49	119.8	7.20	122.2	7.33
	6336.83	3.69	-0.68	109.8	7.33	139.0	7.36	165.8	7.42	159.6	7.56	116.2	7.15
	6338.88	4.79	-1.06	48.0	7.67	...	...	74.3	7.81	70.2	7.86	...	...
	6344.15	2.43	-2.93	58.1	7.47	94.6	7.79	107.8	7.79	94.3	7.78	87.2	7.75
	6364.37	4.79	-1.35	32.8	7.67	...	...	53.8	7.83	34.4	7.61	40.3	7.69
	6376.20	4.32	-2.98	2.0	7.45	...	...	...	...	...	...	...	...
	6380.75	4.19	-1.44	50.3	7.54	66.7	7.63	74.2	7.61	68.7	7.65	...	...
	6385.73	4.73	-1.96	11.5	7.63	...	...	...	...	18.0	7.80	15.2	7.65
	6392.54	2.28	-4.04	17.1	7.53	...	...	46.0	7.80	15.2	7.37	...	...
	6419.96	4.73	-0.27	82.3	7.41	116.3	7.60	126.7	7.57	116.9	7.60	91.5	7.34
	6421.36	2.28	-2.01	110.5	7.38	139.8	7.36	174.1	7.48	148.2	7.46	147.0	7.49
	6430.86	2.18	-1.98	112.2	7.28	138.2	7.21	173.3	7.35	148.0	7.33	147.2	7.36
	6436.41	4.19	-2.51	9.4	7.56	...	...	16.6	7.66	13.3	7.67	...	...
	6475.63	2.56	-2.97	57.9	7.63	...	...	83.0	7.59	71.6	7.61	75.2	7.70
	6481.87	2.28	-3.01	67.0	7.57	76.8	7.45	94.6	7.51	84.8	7.56	90.4	7.72
	6494.50	4.73	-1.44	39.5	7.84	...	...	65.0	8.01	...	...	...	...
	6494.99	2.40	-1.24	156.3	7.26	191.4	7.23	234.2	7.22	200.7	7.28	175.0	7.05
	6495.74	4.83	-1.11	52.0	7.83	...	...	59.5	7.70	49.5	7.65	45.7	7.57

Table 2—Continued

Ion	λ (Å)	χ (eV)	EW	JP133			JP199			JP208			JP296		
				$\log g f$	($\odot$)	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$	EW
	6496.47	4.79	-0.65	63.4	7.53	...	...	...	84.5	7.53	72.9	7.48	70.1	7.47	...
	6498.94	0.96	-4.70	46.3	7.51	...	...	...	78.5	7.52	63.0	7.56	60.9	7.45	...
	6551.70	0.99	-5.82	5.2	7.42	...	...	...	...	...	6.4	7.41	...	...	...
	6556.81	4.79	-1.70	10.0	7.35	...	...	...	19.4	7.53	...	...	26.1	7.74	...
	6574.25	0.99	-5.00	25.9	7.42	48.1	7.70	...	59.1	7.55	44.5	7.61	43.4	7.45	...
	6581.22	1.48	-4.82	20.8	7.61	...	...	...	43.4	7.67	28.6	7.66	29.5	7.52	...
	6591.33	4.59	-2.07	9.6	7.51	...	...	...	...	...	...	...	19.8	7.75	...
	6593.88	2.43	-2.34	86.7	7.42	121.7	7.57	...	129.0	7.47	129.6	7.68	105.9	7.45	...
	6608.04	2.28	-4.02	18.2	7.53	30.1	7.73	...	42.6	7.71	24.3	7.58	32.6	7.63	...
	6609.12	2.56	-2.67	68.0	7.51	89.2	7.56	...	97.0	7.49	102.6	7.76	85.3	7.57	...
	6625.04	1.01	-5.38	15.0	7.51	...	...	...	44.9	7.74	25.8	7.68	24.4	7.46	...
	6627.56	4.55	-1.59	28.0	7.57	...	...	...	43.0	7.65	37.3	7.66	...	...	...
	6663.45	2.42	-2.45	86.2	7.51	147.6	8.01	...	144.6	7.75	113.5	7.55	140.7	7.97	...
	6667.45	2.45	-4.42	5.9	7.54	...	...	...	...	...	9.4	7.67	...	...	...
	6667.74	4.58	-2.18	9.7	7.61	19.3	7.91	...	...	...	13.9	7.73	17.6	7.79	...
	6678.00	2.69	-1.22	129.4	7.20	163.9	7.21	...	193.0	7.21	162.5	7.18	149.3	7.08	...
	6696.32	4.83	-1.65	20.1	7.70	...	...	...	39.8	7.94	19.9	7.63	...	...	...
	6699.14	4.59	-2.22	8.6	7.60	...	...	...	...	...	16.4	7.86	...	...	...
	6703.58	2.76	-3.13	38.3	7.59	...	...	...	52.9	7.49	45.7	7.56	48.9	7.56	...
	6710.32	1.48	-4.90	16.7	7.56	27.4	7.74	...	32.3	7.55	25.9	7.68	20.5	7.38	...
	6713.74	4.79	-1.52	20.7	7.54	...	...	...	45.8	7.86	25.0	7.58	...	...	...

Table 2—Continued

λ	χ	EW	JP133		JP199		JP208		JP296	
			EW	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	EW	$\log N$
Ion	(Å)	(eV)	$\log gf$	($\odot$)	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	$\log N$
	6716.25	4.58	-1.90	16.4	7.60	...	...	...	15.2	7.43
	6725.36	4.10	-2.30	18.7	7.60	...	...	26.2	7.71	24.3
	6726.67	4.61	-1.12	48.8	7.57	62.7	7.64	67.5	7.60	62.3
	6732.07	4.58	-2.17	6.5	7.41	...	...	13.5	7.60	...
	6733.15	4.64	-1.52	28.3	7.59	...	...	42.4	7.66	31.9
	6737.98	4.56	-1.78	22.3	7.63	40.2	7.91	38.3	7.77	27.2
	6739.52	1.56	-4.98	11.9	7.54	...	...	31.6	7.70	23.3
	6745.11	4.58	-2.17	7.7	7.48	5.0	7.25	23.5	7.89	...
	6750.16	2.42	-2.48	73.6	7.28	87.5	7.20	112.0	7.35	7.26
	6752.72	4.64	-1.30	34.9	7.51	37.6	7.47	46.1	7.50	7.56
	6786.86	4.19	-2.01	27.1	7.62	43.4	7.71	...	...	29.6
	6793.27	4.07	-2.48	13.6	7.58	...	...	17.3	7.51	...
	6796.13	4.14	-2.54	15.8	7.79	...	...	...	...	...
	6804.01	4.65	-1.68	24.6	7.67	...	...	...	...	...
	6806.86	2.73	-3.24	34.4	7.58	39.4	7.56	56.4	7.62	39.4
	6810.27	4.61	-1.12	48.8	7.56	62.9	7.64	77.8	7.73	60.3
	6820.37	4.64	-1.27	41.4	7.61	61.3	7.80	61.4	7.69	46.2
	6824.86	4.99	-2.15	4.5	7.60	4.7	7.60	...	...	...
	6828.60	4.64	-0.94	59.2	7.60	78.0	7.69	78.7	7.60	77.7
	6833.25	4.64	-2.07	8.6	7.49	...	...	...	...	...
	6837.01	4.59	-1.81	15.6	7.48	...	...	...	...	14.1
	6839.84	2.56	-3.47	33.8	7.62	58.2	7.90	60.5	7.73	43.7

Table 2—Continued

Ion	λ	χ	EW	JP133		JP199		JP208		JP296	
				EW	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	EW	$\log N$
	(Å)	(eV)	$\log gf$	($\odot$)							
	6841.34	4.61	-0.79	64.8	7.52	89.5	7.67	92.6	7.59	89.5	7.66
	6842.69	4.64	-1.28	37.0	7.53	52.0	7.67	62.8	7.72	52.0	7.66
	6843.65	4.55	-0.98	63.5	7.63	82.9	7.71	78.5	7.54	82.9	7.71
	6851.65	1.61	-5.33	4.7	7.49	...	...	...	...	...	...
	6855.17	4.56	-0.63	77.6	7.53	107.6	7.68	101.8	7.50	107.6	7.68
	6855.72	4.61	-1.83	21.3	7.70	...	...	28.0	7.68	...	...
	6857.25	4.07	-2.21	23.1	7.60	...	...	31.6	7.58	...	...
	6858.15	4.61	-1.09	52.2	7.60	69.6	7.70	73.3	7.65	69.6	7.69
	6860.33	2.61	-4.17	11.8	7.77	...	...	...	...	...	...
	6861.94	2.42	-3.90	20.0	7.59	...	...	37.7	7.65	...	...
	6862.50	4.56	-1.56	30.1	7.59	...	...	39.3	7.56	...	...
	6971.92	3.02	-3.49	16.0	7.65	...	...	22.1	7.55	18.4	7.63
	6976.91	4.58	-1.85	18.4	7.60	...	...	...	...	25.1	7.70
	6978.86	2.48	-2.41	74.7	7.28	...	...	114.2	7.36	98.2	7.32
	6988.53	2.40	-3.56	30.8	7.48	39.1	7.53	60.7	7.64	43.9	7.58
	6999.89	4.10	-1.55	57.5	7.66	65.3	7.60	85.3	7.76	73.2	7.71
	7000.62	4.14	-2.24	18.3	7.56	26.8	7.71	...	...	17.8	7.47
	7007.98	4.18	-1.97	27.0	7.56	29.6	7.53	43.7	7.66	26.9	7.47
	7010.37	4.58	-2.00	11.9	7.52	...	...	...	...	12.8	7.50
	7015.00	2.45	-4.25	8.7	7.53	...	...	...	...	...	...
	7068.42	4.07	-1.41	64.6	7.62	75.6	7.58	88.7	7.63	72.6	7.53
	7071.87	4.61	-1.69	29.1	7.74	...	...	...	...	30.4	7.68
										29.7	7.62

Table 2—Continued

Ion	λ	χ	EW	JP133			JP199			JP208			JP296		
				log gf	($\odot$)	log $N_{\odot}$	EW	log N	EW	log N	EW	log N	EW	log N	EW
	7083.39	4.91	-1.39	21.1	7.52	20.3	7.45	43.1	7.80	22.0	7.48	19.6	7.37		
	7090.39	4.23	-1.18	63.5	7.52	77.8	7.53	97.0	7.66	89.6	7.68	87.9	7.72		
	7093.09	4.56	-2.05	14.1	7.63	...	...	...	...	25.6	7.89	...	...		
	7112.17	2.99	-3.12	32.5	7.66	...	...	46.5	7.60	42.8	7.72	41.3	7.62		
	7114.57	2.69	-4.05	7.0	7.46	11.5	7.64	10.2	7.37	...	...	...	...		
	7125.02	3.69	-3.48	5.0	7.72	6.5	7.80	...	...	...	...	...	...		
	7127.57	4.99	-1.23	28.9	7.63	29.1	7.56	40.7	7.68	32.3	7.62	...	...		
	7130.93	4.22	-0.72	90.0	7.49	115.4	7.54	116.0	7.42	118.2	7.58	105.3	7.48		
	7132.98	4.07	-1.77	42.3	7.56	53.1	7.61	54.1	7.50	53.9	7.61	51.2	7.56		
	7142.52	4.95	-1.08	37.4	7.62	61.3	7.88	50.4	7.64	45.9	7.66	38.5	7.51		
	7151.46	2.48	-3.71	25.0	7.57	44.6	7.84	40.9	7.56	32.7	7.62	29.7	7.44		
	7155.63	5.01	-1.08	37.8	7.68	...	...	50.8	7.70	39.2	7.60	37.5	7.55		
	7212.44	4.95	-1.20	36.0	7.71	...	...	50.0	7.75	29.0	7.48	22.2	7.28		
	7213.85	4.26	-2.64	8.6	7.68	...	...	...	...	...	...	10.7	7.65		
	7219.68	4.07	-1.69	48.1	7.59	81.9	7.93	63.9	7.56	48.6	7.45	50.0	7.46		
	7221.20	4.56	-1.37	38.7	7.56	...	...	68.5	7.80	44.4	7.54	45.3	7.54		
	7228.70	2.76	-3.38	24.3	7.50	30.9	7.55	67.6	7.93	32.0	7.55	32.6	7.46		
	7256.14	4.95	-1.60	15.0	7.58	...	...	...	...	20.7	7.69	...	...		
	7284.84	4.14	-1.75	40.0	7.56	...	...	60.9	7.64	47.2	7.55	51.5	7.61		
	7285.30	4.61	-1.71	25.8	7.67	...	...	39.3	7.75	26.3	7.60	28.3	7.60		
	7288.74	4.22	-1.33	71.1	7.79	...	...	102.3	7.86	82.1	7.71	...	...		
	7351.52	4.95	-0.90	44.4	7.56	...	...	...	...	51.6	7.55	48.0	7.49		

Table 2—Continued

Ion	λ	χ	EW	JP133		JP199		JP208		JP296	
				EW	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	EW	$\log N$
	7353.51	4.73	-1.57	31.1	7.76	...	...	...	...	25.4	7.51
	7359.98	4.99	-1.89	6.9	7.52	10.3	7.68	...	...	15.6	7.81
	7366.37	4.64	-1.90	14.7	7.57	...	...	20.2	7.67	...	...
	7401.69	4.19	-1.69	41.8	7.58	...	...	59.2	7.60	50.0	7.57
	7411.16	4.28	-0.33	111.0	7.43	136.1	7.42	162.6	7.50	124.1	7.34
	7418.67	4.14	-1.59	51.6	7.61	71.1	7.74	72.6	7.64	76.7	7.86
	7421.56	4.64	-1.80	21.7	7.68	...	...	...	...	26.2	7.66
	7430.55	2.59	-3.87	18.6	7.65	...	...	43.7	7.86	...	...
	7440.92	4.91	-0.77	55.1	7.58	...	...	79.7	7.67	62.6	7.55
	7443.03	4.19	-1.83	39.3	7.67	47.0	7.68	51.3	7.62	43.9	7.60
	7445.76	4.26	-0.02	131.8	7.33	165.6	7.37	202.0	7.44	158.6	7.31
	7447.40	4.95	-1.14	36.4	7.64	...	...	54.1	7.74	44.4	7.67
	7447.91	5.52	-0.95	20.4	7.62	21.0	7.59	...	...	...	...
	7454.00	4.19	-2.42	12.3	7.56	11.8	7.49	...	...	16.7	7.57
	7511.03	4.18	0.32	167.0	7.22	214.2	7.30	258.4	7.31	172.7	7.00
	7531.15	4.37	-0.59	96.4	7.56	134.2	7.73	132.7	7.58	106.6	7.48
	7540.44	2.73	-3.90	9.5	7.47	12.2	7.54	...	...	14.5	7.46
	7547.90	5.10	-1.26	21.0	7.55	23.4	7.56	...	...	34.1	7.74
	7551.11	5.08	-1.64	9.8	7.52	...	...	...	...	...	...
	7568.91	4.28	-0.99	84.0	7.69	124.7	7.94	121.6	7.78	101.4	7.73
	7582.12	4.95	-1.77	11.5	7.60	...	...	...	...	16.2	7.67
	7583.80	3.02	-1.96	87.0	7.53	107.8	7.50	107.7	7.33	106.2	7.56

Table 2—Continued

Ion	λ	χ	EW	JP133		JP199		JP208		JP296	
				EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$
	7586.03	4.31	-0.18	121.5	7.41	159.6	7.51	217.0	7.71	163.8	7.54
	7588.31	5.03	-1.26	26.7	7.63	...	...	49.0	7.86	37.0	7.75
	7710.37	4.22	-1.22	71.9	7.66	87.5	7.65	90.5	7.58	78.8	7.53
	7719.05	5.03	-1.18	23.0	7.45	...	...	41.5	7.66	26.3	7.46
	7723.21	2.28	-3.59	48.9	7.70	...	...	74.2	7.69	62.5	7.72
	7742.72	4.99	-0.47	96.9	7.96	123.5	8.02	120.1	7.88	112.4	7.90
	7745.52	5.08	-1.29	23.6	7.62	...	...	26.4	7.54	...	...
	7746.60	5.06	-1.39	19.8	7.60	...	...	24.7	7.58	21.9	7.60
	7748.28	2.95	-1.74	98.6	7.42	122.8	7.39	151.1	7.53	118.4	7.33
	7751.12	4.99	-0.90	43.1	7.55	...	...	60.6	7.62	59.6	7.68
	7780.57	4.47	-0.09	120.3	7.43	167.5	7.61	197.9	7.64	183.1	7.71
	7844.57	4.83	-1.82	10.4	7.47	...	...	41.9	8.10	...	...
	7855.40	5.06	-1.22	29.6	7.67	...	...	...	...	35.0	7.69
	7869.64	4.37	-1.89	28.2	7.64	...	...	42.6	7.71	35.1	7.69
	7912.87	0.86	-4.90	51.3	7.60	...	...	109.1	7.92	70.8	7.66
	7941.10	3.27	-2.57	41.4	7.52	61.9	7.70	69.0	7.63	49.9	7.51
	7945.86	4.39	0.26	144.8	7.24	168.4	7.18	221.7	7.34	166.8	7.16
NiI	6327.60	1.68	-3.23	38.2	6.36	40.1	6.27	57.7	6.38	46.4	6.36
	6339.12	4.15	-0.70	47.9	6.43	...	...	52.6	6.33	60.3	6.49
	6370.36	3.54	-2.02	14.6	6.38	14.5	6.34	...	...	15.6	6.36
	6378.26	4.15	-1.00	31.4	6.40	...	...	45.4	6.52	38.1	6.44
	6424.86	4.17	-1.55	12.6	6.44	...	...	...	...	...	...
										17.1	6.52

Table 2—Continued

Ion	λ	χ	$\log gf$	$(\odot)$	$\log N_{\odot}$	JP133		JP199		JP208		JP296	
						EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$
TiI	7748.89	3.70	-0.18	86.7	6.10	102.5	6.04	112.2	6.10	109.4	6.13	...	...
	7917.43	3.74	-1.55	34.1	6.54	...	...	...	...	18.3	6.10	42.0	6.60
	6336.11	1.44	-1.68	10.2	5.18	8.3	5.01	25.0	5.23	8.3	4.98	8.3	4.77
	6508.15	1.43	-2.03	2.7	4.90	...	...	...	...	...	...	...	...
	6554.24	1.44	-1.16	18.6	4.96	...	...	...	...	...	...	...	...
	6556.08	1.46	-1.10	23.4	5.05	...	...	53.3	5.15	33.1	5.12	36.4	5.01
	6599.11	0.90	-2.06	9.8	4.99	...	...	...	...	24.8	5.34	19.7	5.00
	6745.55	2.24	-1.10	4.1	4.94	...	...	...	...	...	...	...	...
	7069.06	3.18	-0.27	6.5	5.23	...	...	...	...	...	...	...	...
	7138.93	1.44	-1.72	7.2	5.01	...	...	23.3	5.19	...	...	13.4	5.00
CrI	7216.19	1.44	-1.30	22.6	5.17	19.6	5.01	49.3	5.22	27.0	5.14	26.7	4.95
	7251.72	1.43	-0.86	36.7	5.03	46.6	5.06	69.4	5.06	43.9	4.99	90.5	5.65
	7352.14	2.49	-0.83	2.3	4.63	...	...	...	...	...	...	...	...
	7357.74	1.44	-1.10	24.5	5.01	...	...	54.9	5.10	29.2	4.98	33.5	4.89
	7364.11	1.43	-1.25	19.5	5.02	...	...	...	...	...	...	...	...
	7440.58	2.25	-1.08	10.3	5.33	...	...	...	...	...	...	...	...
	7580.28	2.23	-1.69	1.4	5.00	...	...	...	...	...	...	...	...
	7949.15	1.50	-1.43	14.2	5.07	...	...	...	...	17.4	5.06	21.0	4.96
	6330.10	0.94	-2.99	27.4	5.77	...	...	73.9	6.04	44.1	5.92	40.5	5.68
	6501.20	0.98	-3.66	10.6	5.95	...	...	15.5	5.69	7.2	5.65	...	...
	6605.57	4.14	-0.81	8.5	6.07	...	...	...	...	...	...	...	...
	6661.08	4.19	-0.24	14.0	5.79	...	...	...	...	...	...	18.3	5.77

Table 2—Continued

λ		χ	EW	JP133		JP199		JP208		JP296	
Ion	(Å)	(eV)	$\log gf$	($\odot$)	$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	EW	$\log N$
CaI	6680.15	4.16	-0.52	9.1	5.83	...	...	11.5	5.89	7.7	5.59
	6729.74	4.39	-0.66	2.0	5.50	...	...	...	...	...	...
	6978.48	3.46	0.01	60.3	5.84	...	6.13	...	...	68.2	5.73
	6979.81	3.46	-0.46	38.4	5.91	52.9	6.03	61.3	5.94	57.7	6.08
	6980.91	3.46	-1.12	10.2	5.81	...	...	...	...	...	...
	7355.89	2.89	-0.28	67.3	5.69	110.9	6.05	115.7	5.88	95.6	5.84
	7400.19	2.90	-0.08	74.4	5.62	104.7	5.78	120.3	5.73	105.4	5.78
	6417.69	4.44	-0.75	14.3	6.61	...	...	...	...	14.7	6.57
	6455.60	2.52	-1.50	57.4	6.46	64.0	6.39	93.1	6.56	76.8	6.55
	6464.68	2.52	-2.53	13.8	6.54	...	...	...	...	...	...
SiI	6499.65	2.52	-1.00	86.1	6.43	106.1	6.44	129.9	6.49	116.7	6.56
	6572.80	0.50	-3.97	30.0	6.43	58.3	6.77	91.1	6.90	57.4	6.73
	6798.47	2.71	-2.72	9.0	6.69	...	...	...	...	...	...
	7148.15	2.71	-0.08	137.2	6.27	175.8	6.35	223.2	6.39	185.9	6.41
	7202.21	2.71	-0.34	100.7	6.10	134.1	6.23	162.7	6.26	145.4	6.33
	6555.47	5.98	-1.00	40.5	7.44	78.8	7.85	43.8	7.52	50.6	7.56
	6741.63	5.98	-1.62	13.4	7.48	...	...	...	...	22.7	7.74
	6848.57	5.86	-1.74	18.8	7.66	...	...	...	...	...	...
	7003.57	5.96	-0.86	61.1	7.58	61.3	7.54	60.7	7.59	55.7	7.48
	7005.90	5.98	-0.68	77.9	7.60	83.9	7.61	80.6	7.63	79.7	7.57
	7226.21	5.61	-1.50	37.8	7.59	...	...	51.1	7.82	37.2	7.56
	7235.34	5.61	-1.50	40.4	7.64	43.0	7.65	...	...	42.3	7.64

Table 2—Continued

Ion	λ (Å)	χ (eV)	$\log gf$	EW ($\odot$)	JP133		JP199		JP208		JP296		
					$\log N_{\odot}$	EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	
	7235.82	5.61	-1.72	28.6	7.64	...	...	...	...	33.2	7.71	...	...
	7289.19	5.62	-0.62	98.0	7.54	...	...	...	...	...	...	...	...
	7405.79	5.61	-0.57	91.9	7.41	106.1	7.45	85.9	7.30	95.7	7.36	111.9	7.59
	7409.10	5.61	-1.04	85.4	7.80	...	...	...	...	89.0	7.76	...	...
	7415.96	5.61	-0.63	90.6	7.45	99.5	7.45	88.1	7.38	91.3	7.37	107.0	7.61
	7849.98	6.19	-0.80	53.6	7.59	...	...	...	...	52.3	7.55	53.2	7.61
	7912.38	6.10	-1.66	13.7	7.61	...	...	...	...	...	...	36.7	8.18
	7918.38	5.95	-0.59	83.1	7.57	84.9	7.51	99.2	7.71	92.5	7.60	90.7	7.65
	6696.03	3.14	-1.65	40.7	6.62	...	...	63.7	6.69	46.8	6.62	52.8	6.63
	6698.67	3.14	-1.95	24.1	6.60	...	...	42.5	6.71	27.7	6.61	23.7	6.43
MgI	7362.29	4.02	-1.00	36.9	6.65	...	...	42.4	6.57	24.4	6.38	53.1	6.74
	6318.71	5.11	-1.68	46.8	7.34	47.2	7.28	59.7	7.32	42.8	7.21	42.7	7.15
	7691.57	5.75	-0.78	100.4	7.44	120.1	7.53	125.2	7.44	106.3	7.42	95.2	7.26

Table 3. Equivalent Widths and Abundances - JP298, JP366, JP415, JP489, & JP515

Ion	λ	χ	$\log gf$	JP298		JP366		JP415		JP489		JP515	
	(Å)	(eV)		EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$
FeI	6311.50	2.83	-3.21	59.1	7.57	...	...	39.6	7.52	51.3	7.57	...	...
	6315.81	4.07	-1.76	41.9	7.26	45.6	7.58	53.3	7.63	44.8	7.39	...	...
	6322.69	2.59	-2.40	...	...	87.0	7.44	98.4	7.59	...	...	...	...
	6330.85	4.73	-1.32	38.2	7.48	34.5	7.57	40.4	7.59	47.8	7.69	31.9	7.69
	6335.34	2.20	-2.20	...	...	123.2	7.42	125.1	7.33	...	...	99.2	7.26
	6336.83	3.69	-0.68	...	...	137.4	7.45	138.2	7.33	...	...	122.3	7.44
	6338.88	4.79	-1.06	58.9	7.59	51.0	7.65	...	...	47.1	7.48	...	...
	6344.15	2.43	-2.93	...	...	77.5	7.65	83.4	7.71	89.8	7.49	76.9	7.87
	6364.37	4.79	-1.35	...	...	35.2	7.67	...	...	...	...	...	...
	6376.20	4.32	-2.98	...	...	...	...	...	...	...	...	5.1	8.06
	6380.75	4.19	-1.44	66.5	7.44	57.6	7.56	57.6	7.51	64.9	7.52	58.7	7.75
	6385.73	4.73	-1.96	...	...	...	...	...	...	...	...	...	...
	6392.54	2.28	-4.04	...	...	...	...	...	...	...	...	...	...
	6419.96	4.73	-0.27	...	...	113.6	7.65	98.8	7.42	...	...	90.9	7.50
	6421.36	2.28	-2.01	...	...	130.1	7.39	137.8	7.34	...	...	120.4	7.45
	6430.86	2.18	-1.98	...	...	136.6	7.35	145.2	7.28	...	...	117.3	7.28
	6436.41	4.19	-2.51	...	...	...	...	21.9	7.81	...	...	...	...
	6475.63	2.56	-2.97	...	...	66.7	7.64	69.9	7.62	90.1	7.67	57.8	7.75
	6481.87	2.28	-3.01	...	...	72.7	7.49	75.5	7.47	...	...	62.1	7.59
	6494.50	4.73	-1.44	...	...	52.6	7.99	...	...	...	...	...	...
	6494.99	2.40	-1.24	...	...	179.7	7.25	184.5	7.03	...	...	191.4	7.62
	6495.74	4.83	-1.11	...	...	...	...	...	...	...	...	44.9	7.78

Table 3—Continued

Ion	λ	χ (eV)	JP298		JP366		JP415		JP489		JP515	
			EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>
	6496.47	4.79	...	...	71.1	7.53	65.9	7.41	72.4	7.43	80.4	7.79
	6498.94	0.96	...	...	57.9	7.61	47.6	7.13	...	...	40.0	7.70
	6551.70	0.99	...	...	...	...	16.2	7.52	...	...	...	...
	6556.81	4.79	...	...	15.4	7.55	...	...	...	...	...	...
	6574.25	0.99	...	...	27.9	7.42	42.5	7.34	...	...	...	...
	6581.22	1.48	58.1	7.55	26.9	7.72	41.2	7.68	46.6	7.49	...	...
	6591.33	4.59	...	...	12.0	7.61	...	...	...	...	...	...
	6593.88	2.43	...	...	109.9	7.56	110.0	7.50	...	...	84.6	7.38
	6608.04	2.28	...	...	27.2	7.72	...	...	46.3	7.63	9.0	7.48
	6609.12	2.56	...	...	75.4	7.47	78.3	7.46	...	...	66.1	7.56
	6625.04	1.01	...	...	27.6	7.81	29.3	7.45	...	...	...	...
	6627.56	4.55	...	...	26.9	7.51	...	...	...	...	...	...
	6663.45	2.42	...	...	93.9	7.40	...	...	...	...	113.1	7.89
	6667.45	2.45	...	...	...	...	...	...	...	...	...	...
	6667.74	4.58	...	...	...	...	...	...	...	...	...	...
	6678.00	2.69	...	...	145.5	7.15	169.7	7.18	...	...	130.1	7.15
	6696.32	4.83	...	...	...	...	...	...	...	...	...	...
	6699.14	4.59	...	...	...	...	...	...	...	...	5.7	7.58
	6703.58	2.76	71.1	7.57	38.7	7.53	51.6	7.59	63.0	7.61	...	...
	6710.32	1.48	48.4	7.47	20.6	7.64	...	...	50.6	7.64	...	...
	6713.74	4.79	...	...	34.2	7.81	...	...	...	...	...	...
	6716.25	4.58	...	...	17.8	7.62	...	...	...	...	...	...

Table 3—Continued

Ion	λ (Å)	χ (eV)	JP298		JP366		JP415		JP489		JP515	
			EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>
	6725.36	4.10	36.2	7.73	25.9	7.76	...	...	...	...	...	...
	6726.67	4.61	65.7	7.55	59.3	7.65	54.2	7.52	52.8	7.45	41.3	7.53
	6732.07	4.58	...	...	...	...	...	...	...	...	...	...
	6733.15	4.64	...	...	28.4	7.55	29.9	7.47	33.4	7.54	27.4	7.71
	6737.98	4.56	...	...	22.8	7.61	...	...	...	...	28.6	7.92
	6739.52	1.56	...	...	...	...	...	...	34.5	7.49	...	...
	6745.11	4.58	...	...	...	...	...	...	...	...	...	...
	6750.16	2.42	...	...	82.2	7.23	86.5	7.26	...	...	67.2	7.25
	6752.72	4.64	...	...	37.6	7.51	...	...	...	...	...	...
	6786.86	4.19	39.3	7.60	...	...	...	...	33.7	7.55	13.7	7.42
	6793.27	4.07	19.2	7.51	...	...	...	...	...	...	...	...
	6796.13	4.14	...	...	...	...	...	...	...	...	10.1	7.76
	6804.01	4.65	38.0	7.75	24.8	7.64	...	...	33.6	7.72	...	...
	6806.86	2.73	66.8	7.57	44.0	7.69	43.0	7.48	...	...	35.1	7.81
	6810.27	4.61	71.9	7.63	63.2	7.71	53.6	7.50	60.2	7.56	55.9	7.75
	6820.37	4.64	53.6	7.57	65.4	7.91	45.5	7.53	44.9	7.50	43.1	7.74
	6824.86	4.99	...	...	...	...	...	...	...	...	...	...
	6828.60	4.64	77.9	7.55	78.4	7.77	58.0	7.43	71.1	7.56	51.5	7.53
	6833.25	4.64	...	...	...	...	...	...	...	...	14.0	7.90
	6837.01	4.59	...	...	16.9	7.51	...	...	...	...	...	...
	6839.84	2.56	64.0	7.56	39.6	7.68	...	...	49.0	7.45	35.5	7.89
	6841.34	4.61	...	...	83.0	7.66	83.9	7.65	...	...	72.9	7.65

Table 3—Continued

λ		χ	JP298		JP366		JP415		JP489		JP515	
Ion	($\text{\AA}$)	(eV)	$\log gf$	EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$	$\log N$
	6842.69	4.64	-1.28	...	...	46.1	7.63	54.6	7.71	...	...	43.9 7.75
	6843.65	4.55	-0.98	79.2	7.51	67.8	7.58	70.9	7.60	67.4	7.46	64.4 7.67
	6851.65	1.61	-5.33	...	...	...	...	12.2	7.54	...	...	... ..
	6855.17	4.56	-0.63	...	...	96.4	7.63	84.4	7.45	...	...	82.7 7.59
	6855.72	4.61	-1.83	...	...	28.2	7.83	...	...	...	...	... ..
	6857.25	4.07	-2.21	...	...	37.7	7.87	29.4	7.56	...	...	25.2 7.83
	6858.15	4.61	-1.09	62.0	7.48	63.0	7.67	...	...	66.6	7.62	52.9 7.68
	6860.33	2.61	-4.17	...	...	...	...	...	...	...	...	... ..
	6861.94	2.42	-3.90	...	...	36.1	7.90	...	...	...	...	... ..
	6862.50	4.56	-1.56	...	...	43.7	7.79	38.3	7.60	...	...	... ..
	6971.92	3.02	-3.49	...	...	...	...	...	...	...	...	... ..
	6976.91	4.58	-1.85	...	...	...	...	...	...	...	...	... ..
	6978.86	2.48	-2.41	...	...	89.1	7.32	90.0	7.29	...	...	101.6 7.71
	6988.53	2.40	-3.56	...	...	37.7	7.57	45.4	7.49	...	...	... ..
	6999.89	4.10	-1.55	...	...	66.4	7.69	55.7	7.46	...	...	... ..
	7000.62	4.14	-2.24	...	...	18.2	7.53	...	...	26.0	7.55	... ..
	7007.98	4.18	-1.97	...	...	26.4	7.51	...	...	...	...	45.6 8.04
	7010.37	4.58	-2.00	...	...	...	...	...	...	...	...	... ..
	7015.00	2.45	-4.25	...	...	...	...	...	...	...	...	... ..
	7068.42	4.07	-1.41	...	...	66.4	7.52	76.2	7.65	...	...	... ..
	7071.87	4.61	-1.69	...	...	...	...	...	...	...	...	... ..
	7083.39	4.91	-1.39	...	...	...	...	...	...	...	...	... ..

Table 3—Continued

Ion	λ (Å)	χ (eV)	JP298		JP366		JP415		JP489		JP515	
			EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>
	7090.39	4.23	...	...	76.2	7.58	76.4	7.57	...	...	70.5	7.66
	7093.09	4.56	...	...	...	...	...	...	...	...	18.9	7.95
	7112.17	2.99	...	...	37.9	7.71	42.4	7.61	...	...	...	...
	7114.57	2.69	...	...	...	...	...	...	...	...	...	...
	7125.02	3.69	...	...	...	...	...	...	...	...	...	...
	7127.57	4.99	...	...	37.9	7.76	33.8	7.60	...	...	...	...
	7130.93	4.22	...	...	99.7	7.45	115.9	7.59	...	...	98.9	7.58
	7132.98	4.07	...	...	51.5	7.65	46.2	7.46	...	...	37.9	7.62
	7142.52	4.95	...	...	41.3	7.63	41.8	7.57	...	...	38.5	7.73
	7151.46	2.48	...	...	26.5	7.57	...	...	...	...	...	...
	7155.63	5.01	...	...	...	...	31.6	7.42	...	...	21.2	7.44
	7212.44	4.95	40.0	7.63	...	...	...	...	...	...	25.3	7.60
	7213.85	4.26	...	...	...	...	...	...	...	...	...	...
	7219.68	4.07	67.7	7.56	56.5	7.64	43.9	7.34	...	...	35.9	7.50
	7221.20	4.56	...	...	49.9	7.69	37.4	7.38	...	...	32.2	7.56
	7228.70	2.76	...	...	24.9	7.48	27.6	7.29	...	...	16.3	7.54
	7256.14	4.95	...	...	17.4	7.64	...	...	...	...	...	...
	7284.84	4.14	...	...	42.8	7.54	...	...	...	...	55.3	7.92
	7285.30	4.61	...	...	20.9	7.52	...	...	...	...	...	...
	7288.74	4.22	...	...	82.8	7.81	83.5	7.81	...	...	77.0	7.88
	7351.52	4.95	45.0	7.40	53.9	7.64	...	...	...	...	...	...
	7353.51	4.73	...	...	...	...	...	...	...	...	...	...

Table 3—Continued

Ion	λ	χ	JP298		JP366		JP415		JP489		JP515	
			EW	log N	EW	log N	EW	log N	EW	log N	EW	log N
		(eV)	log gf									
		(Å)										
	7359.98	4.99	-1.89	...	...	...	...	...	...	...	...	...
	7366.37	4.64	-1.90	...	...	...	...	...	...	...	8.6	7.47
	7401.69	4.19	-1.69	60.8	7.59	7.63	...	...	57.5	7.64	39.0	7.65
	7411.16	4.28	-0.33	...	...	7.48	121.6	7.30	...	...	109.5	7.36
	7418.67	4.14	-1.59	...	...	7.64	49.6	7.41	...	...	...	...
	7421.56	4.64	-1.80	...	...	7.64	...	...	...	...	15.7	7.66
	7430.55	2.59	-3.87	...	...	...	...	...	...	...	...	...
	7440.92	4.91	-0.77	...	...	7.48	64.3	7.59	...	...	62.8	7.74
	7443.03	4.19	-1.83	49.0	7.56	7.70	39.2	7.49	44.0	7.55	34.3	7.71
	7445.76	4.26	-0.02	...	...	7.30	160.5	7.28	...	...	130.2	7.28
	7447.40	4.95	-1.14	...	...	7.74	...	...	...	...	32.0	7.67
	7447.91	5.52	-0.95	...	...	7.70	...	...	...	...	...	...
	7454.00	4.19	-2.42	...	...	...	...	...	...	...	8.6	7.58
	7511.03	4.18	0.32	...	...	7.34	...	...	...	...	155.9	7.14
	7531.15	4.37	-0.59	...	...	7.60	123.9	7.65	...	...	115.3	7.76
	7540.44	2.73	-3.90	...	...	7.58	20.6	7.58	...	...	...	...
	7547.90	5.10	-1.26	...	...	7.53	...	...	...	...	...	...
	7551.11	5.08	-1.64	...	...	...	...	...	...	...	...	...
	7568.91	4.28	-0.99	...	...	7.80	104.7	7.78	...	...	92.4	7.78
	7582.12	4.95	-1.77	...	...	7.91	...	...	...	...	...	...
	7583.80	3.02	-1.96	...	...	7.43	105.6	7.56	...	...	79.6	7.41
	7586.03	4.31	-0.18	...	...	7.54	...	...	...	...	136.9	7.54

Table 3—Continued

Ion	λ	χ	JP298			JP366			JP415			JP489			JP515		
			EW	log gf	log N	EW	log N	EW	log N	EW	log N	EW	log N	EW	log N	EW	log N
	7588.31	5.03	...	-1.26	...	34.4	7.75	...	...	...	...	...	...	...	...	...	...
	7710.37	4.22	...	-1.22	...	83.7	7.69	...	...	...	...	86.5	7.59	...	...	...	...
	7719.05	5.03	...	-1.18	...	34.9	7.67	...	...	...	...	...	...	...	...	...	...
	7723.21	2.28	83.3	-3.59	7.57	61.3	7.81	54.6	7.53	67.1	7.52	...	...	22.3	7.43	...	...
	7742.72	4.99	...	-0.47	...	101.0	7.85	95.4	7.76	...	...	...	...	103.6	8.01	...	...
	7745.52	5.08	...	-1.29	...	25.2	7.63	...	...	...	...	...	...	15.5	7.53	...	...
	7746.60	5.06	...	-1.39	...	...	...	...	...	...	...	...	...	...	...	...	...
	7748.28	2.95	...	-1.74	...	121.6	7.51	125.7	7.48	...	...	...	...	98.7	7.37	...	...
	7751.12	4.99	...	-0.90	...	57.5	7.71	...	...	...	...	...	...	...	...	...	...
	7780.57	4.47	...	-0.09	...	158.2	7.61	...	...	...	...	...	...	...	...	...	...
	7844.57	4.83	...	-1.82	...	...	...	...	...	...	...	...	...	...	...	...	...
	7855.40	5.06	...	-1.22	...	...	...	23.8	7.41	...	...	...	...	...	...	...	...
	7869.64	4.37	...	-1.89	...	25.4	7.55	...	...	...	...	...	...	20.3	7.62	...	...
	7912.87	0.86	...	-4.90	...	63.2	7.68	66.1	7.48	84.7	7.41	...	...	41.0	7.74	...	...
	7941.10	3.27	...	-2.57	...	59.2	7.73	...	...	...	...	...	...	40.9	7.68	...	...
	7945.86	4.39	...	0.26	...	199.7	7.48	181.9	7.21	...	...	...	...	146.6	7.25	...	...
NiI	6327.60	1.68	58.8	-3.23	6.23	35.8	6.26	44.9	6.28	57.2	6.36	...	...	24.9	6.33	...	...
	6339.12	4.15	50.3	-0.70	6.37	48.0	6.36	...	...	46.3	6.38	...	...	...	...	...	...
	6370.36	3.54	14.5	-2.02	6.27	...	...	...	...	...	...	...	...	...	...	...	...
	6378.26	4.15	35.9	-1.00	6.44	34.7	6.43	38.2	6.47	30.9	6.39	...	...	...	...	...	...
	6424.86	4.17	...	-1.55	...	...	...	...	...	...	...	...	...	17.3	6.75	...	...
	6482.81	1.93	67.3	-2.97	6.38	40.4	6.32	40.0	6.17	49.1	6.23	...	...	...	...	...	...

Table 3—Continued

Ion	λ (Å)	χ (eV)	JP298		JP366		JP415		JP489		JP515	
			EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>
	6586.32	1.95	60.5	6.28	46.6	6.42	44.0	6.26	64.5	6.52	36.1	6.51
	6598.61	4.23	30.6	6.44	...	...	...	...	...	...	...	...
	6842.04	3.66	31.3	6.33	39.9	6.55	34.4	6.40	26.8	6.28	22.1	6.37
	7001.55	1.93	...	...	...	...	...	...	18.4	6.16	...	...
	7062.98	1.95	22.2	6.18	...	...	...	...	23.1	6.25	...	...
	7122.21	3.54	...	...	124.6	6.19	121.6	6.17	...	...	97.4	5.95
	7220.79	5.36	...	...	...	...	...	...	...	...	...	...
	7385.24	2.74	62.9	6.33	47.3	6.29	51.5	6.33	50.0	6.25	39.5	6.38
	7393.61	3.61	...	...	105.7	5.98	108.0	6.06	...	...	87.3	5.85
	7401.13	5.36	...	...	12.6	6.20	...	...	...	...	7.2	6.04
	7409.35	3.80	...	...	112.8	6.36	...	...	93.7	6.12	...	...
	7414.51	1.99	...	...	...	...	...	...	...	...	...	...
	7422.29	3.63	...	...	110.6	6.04	93.9	5.88	...	...	100.7	6.02
	7522.78	3.66	...	...	94.6	6.39	92.9	6.44	95.1	6.40	70.2	6.17
	7525.12	3.63	84.8	6.24	78.8	6.26	83.4	6.41	85.4	6.38	69.8	6.26
	7552.50	5.61	...	...	...	...	...	...	...	...	...	...
	7555.61	3.85	...	...	102.3	6.05	104.6	6.13	...	...	94.4	6.05
	7574.10	3.83	80.6	6.35	79.1	6.39	...	...	69.8	6.33	72.7	6.42
	7714.31	1.93	...	...	113.9	6.20	122.6	6.34	...	...	90.3	6.04
	7715.59	3.70	...	...	73.2	6.68	...	...	55.8	6.48	45.6	6.42
	7727.62	3.68	...	...	96.1	6.00	99.9	6.12	...	...	89.4	6.02
	7748.89	3.70	...	...	101.1	6.12	94.7	6.10	...	...	86.3	6.0

Table 3—Continued

Ion	λ	χ	JP298		JP366		JP415		JP489		JP515	
			EW	log N	EW	log N	EW	log N	EW	log N	EW	log N
TiI	7917.43	3.74	...	6.41	...	...	...	...	...	...	...	...
	6336.11	1.44	44.0	4.85	8.3	5.06	...	...	33.0	4.72	...	...
	6508.15	1.43	...	...	...	...	...	...	...	...	...	...
	6554.24	1.44	...	...	...	...	...	...	...	...	...	...
	6556.08	1.46	82.9	4.83	...	...	34.6	4.83	59.4	4.64	...	...
	6599.11	0.90	61.1	4.80	...	...	21.7	4.87	42.9	4.62	...	...
	6745.55	2.24	...	...	...	...	...	...	...	...	...	...
	7069.06	3.18	...	...	...	...	...	...	...	...	...	...
	7138.93	1.44	50.1	4.93	...	...	...	...	36.5	4.78	...	...
	7216.19	1.44	85.3	4.99	26.6	5.23	...	...	...	...	...	...
CrI	7251.72	1.43	...	...	43.8	5.09	47.1	4.76	83.2	4.72	17.6	4.89
	7352.14	2.49	...	...	...	...	...	...	...	...	...	...
	7357.74	1.44	92.3	4.87	24.7	4.98	43.5	4.94	74.6	4.82	...	...
	7364.11	1.43	...	...	...	...	...	...	...	...	...	...
	7440.58	2.25	...	...	...	...	...	...	...	...	...	...
	7580.28	2.23	...	...	...	...	...	...	...	...	...	...
	7949.15	1.50	65.6	4.88	21.0	5.25	...	...	...	...	21.0	5.58
	6330.10	0.94	...	...	30.5	5.78	46.6	5.66	...	...	...	...
	6501.20	0.98	24.9	5.20	...	...	...	...	...	...	...	...
	6605.57	4.14	...	...	...	...	...	...	...	...	...	...
	6661.08	4.19	29.4	5.67	...	...	...	...	24.7	5.59	...	...
	6680.15	4.16	...	...	...	...	...	...	...	...	...	...

Table 3—Continued

Ion	λ	χ	(eV)	JP298		JP366		JP415		JP489		JP515	
				EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>	EW	log <i>N</i>
CaI	6729.74	4.39	-0.66	...	...	...	...	2.6	5.39	...	...	...	...
	6978.48	3.46	0.01	...	...	71.9	5.89	53.3	5.42	96.6	5.61	...	...
	6979.81	3.46	-0.46	75.4	5.71	46.2	5.98	55.5	5.93	65.2	5.68	...	...
	6980.91	3.46	-1.12	...	...	...	...	...	...	...	...	...	...
	7355.89	2.89	-0.28	...	...	88.0	5.85	98.4	5.84	...	...	50.2	5.52
	7400.19	2.90	-0.08	...	...	99.7	5.82	103.1	5.71	...	...	65.1	5.54
	6417.69	4.44	-0.75	...	...	12.9	6.54	16.5	6.52	...	...	...	...
	6455.60	2.52	-1.50	...	...	63.7	6.46	77.4	6.47	93.0	6.13	58.8	6.59
	6464.68	2.52	-2.53	43.8	6.40	...	...	...	...	29.4	6.19	...	...
	6499.65	2.52	-1.00	...	...	99.4	6.45	113.9	6.45	...	...	84.1	6.43
SiI	6572.80	0.50	-3.97	...	...	38.2	6.54	59.6	6.51	...	...	46.7	7.00
	6798.47	2.71	-2.72	...	...	...	...	...	...	...	...	...	...
	7148.15	2.71	-0.08	...	...	161.3	6.32	172.7	6.15	...	...	157.6	6.49
	7202.21	2.71	-0.34	...	...	133.7	6.32	122.8	6.01	...	...	...	...
	6555.47	5.98	-1.00	26.8	7.55	37.4	7.39	...	...	35.5	7.70	...	...
	6741.63	5.98	-1.62	...	...	15.7	7.56	...	...	...	...	...	...
	6848.57	5.86	-1.74	...	...	...	...	...	...	...	...	...	...
	7003.57	5.96	-0.86	35.5	7.58	58.3	7.52	38.8	7.35	43.0	7.70	13.2	7.54
	7005.90	5.98	-0.68	...	...	72.9	7.51	79.6	7.70	53.2	7.66	56.0	7.54
	7226.21	5.61	-1.50	...	...	38.3	7.59	44.5	7.78	...	...	76.1	7.59
	7235.34	5.61	-1.50	30.7	7.81	49.3	7.75	...	...	32.7	7.87	36.1	7.61
	7235.82	5.61	-1.72	22.2	7.85	...	...	...	...	...	...	94.1	8.34
												...	...

Table 3—Continued

λ		χ	JP298		JP366		JP415		JP489		JP515	
Ion	(Å)	(eV)	$\log gf$	EW	$\log N$	EW	$\log N$	EW	$\log N$	EW	$\log N$	
AlI	7289.19	5.62	-0.62	...	...	...	...	...	...	...	...	
	7405.79	5.61	-0.57	75.4	7.49	100.0	7.43	93.6	7.47	83.6	7.61	
	7409.10	5.61	-1.04	...	...	...	...	...	...	56.8	7.78	
	7415.96	5.61	-0.63	75.3	7.55	94.6	7.43	83.8	7.43	85.4	7.68	
	7849.98	6.19	-0.80	...	...	49.2	7.52	...	...	42.5	7.85	
	7912.38	6.10	-1.66	5.5	7.59	15.2	7.66	...	...	...	...	
	7918.38	5.95	-0.59	65.0	7.71	86.4	7.55	72.0	7.52	69.2	7.77	
	6696.03	3.14	-1.65	73.2	6.44	43.6	6.63	48.6	6.50	57.7	6.30	
MgI	6698.67	3.14	-1.95	50.5	6.47	...	...	...	...	39.1	6.34	
	7362.29	4.02	-1.00	60.4	6.54	51.2	6.82	...	...	47.5	6.41	
	6318.71	5.11	-1.68	50.3	7.12	43.4	7.25	35.0	6.98	54.7	7.19	
	7691.57	5.75	-0.78	121.6	7.34	100.6	7.41	108.0	7.06	108.3	7.09	

Table 4 Final Stellar Parameters and Uncertainties

Star	T_{eff} (K)	$\sigma_{T_{\text{eff}}}$ (K)	ξ (km s ⁻¹)	σ_{ξ} (km s ⁻¹)	$\log g$ (cgs)	$\sigma_{\log g}$ (cgs)
JP133...	5710	±58	1.88	±0.10	4.54	±0.10
JP199...	5385	±40	1.65	±0.11	4.63	±0.10
JP208...	5675	±35	1.80	±0.08	4.56	±0.10
JP296...	5460	±48	1.09	±0.11	4.58	±0.10
JP298...	4750	±25	1.55	±0.14	4.66	±0.10
JP366...	5760	±38	1.63	±0.07	4.55	±0.10
JP415...	5290	±45	0.67	±0.18	4.59	±0.10
JP489...	4750	±25	0.80	±0.12	4.66	±0.10
JP515...	6130	±65	2.07	±0.10	4.50	±0.10
Sun.....	5770		1.10		4.44	

We also plot the line-by-line $[\text{Fe}/\text{H}]$ values against wavelength, showing no statistically significant dependence of derived abundance on wavelength. Figure 3 shows the line-by-line Fe abundances for JP208 plotted against χ , $\log(\text{EW}/\lambda)$, and wavelength. Uncertainties in these parameters were calculated by considering the correlations in the above quantities as each parameter was varied individually. Final uncertainties are those that resulted in a 1- σ deviation in the correlation coefficients of $[\text{Fe}/\text{H}]$ and χ for T_{eff} , and $[\text{Fe}/\text{H}]$ and $\log(\text{EW}/\lambda)$ for ξ . Final temperatures and microturbulent velocities are listed in columns two and four of Table 4, with their uncertainties in columns three and five. $\log g$ values and the adopted uncertainty are listed in columns six and seven.

We note that while many other studies use the same approach in determining spectroscopic T_{eff} and ξ values, in many cases the solutions may be degenerate. This can happen when a particular sample of lines demonstrates an ab initio correlation between line strength and lower excitation potential. Happily, no such significant correlation exists in our particular selection of Fe I lines.

Figure 3 Line-by-line Fe relative abundance correlation relations for JP208. The top panel shows the abundances as a function of excitation potential. The middle panel shows the abundances as a function of reduced equivalent width. The bottom panel shows the abundances as a function of wavelength. The line drawn in all three panels represents the mean Fe abundance for JP208.

CHAPTER 4

RESULTS

Final relative abundances, $[X/H]$ and $[X/Fe]$, were obtained by subtracting line-by-line the solar abundances from the stellar abundances. Mean abundance ratios for the nine star sample are given in Table 5, along with the number of lines measured for each species and the internal (σ_{int}) and total (σ_{tot}) mean uncertainties. The internal errors are based solely on the line-to-line scatter about the star's mean abundance. The total errors were derived from these internal errors and errors in T_{eff} , ξ , and $\log g$. Sensitivities to these parameters were calculated by varying each parameter singly and creating additional models, one with $\Delta T = 150$ K, one with $\Delta \xi = 0.30$ km s⁻¹, and one with $\Delta \log g = 0.25$ dex, for each star. The abundances resulting from these individual models were compared to the originally derived abundances to obtain the sensitivities. The low temperatures of JP298 and JP489 make their abundances more susceptible to ionization state changes which occur for some of the elements near these lower effective temperatures. Accordingly, sensitivities for these two stars were calculated for both positive and negative changes in temperature (as well as microturbulent velocity and $\log g$). Typical sensitivities are given in Table 6.

Table 5. Final Abundances and Uncertainties

Star	[Fe/H]	[Ni/H]	[Ni/Fe]	[Ti/H]	[Ti/Fe]	[Cr/H]	[Cr/Fe]	[Ca/H]	[Ca/Fe]	[Si/H]	[Si/Fe]	[Al/H]	[Al/Fe]	[Mg/H]	[Mg/Fe]
JP133	0.07	-0.06	-0.13	-0.10	-0.17	0.18	0.11	0.10	0.02	0.05	-0.02	...	...	0.01	-0.06
# Lines	71	16		3		3		5		7		...		2	
$\sigma_{\text{int}} \dots$	0.02	0.04	0.04	0.08	0.08	0.05	0.05	0.08	0.08	0.07	0.07	...	...	0.11	0.11
$\sigma_{\text{tot}} \dots$	0.05	0.06	0.05	0.10	0.08	0.07	0.05	0.09	0.08	0.07	0.08	...	...	0.11	0.12
JP199	0.08	-0.03	-0.12	0.08	0.00	0.06	-0.02	0.15	0.06	0.04	-0.04	0.03	-0.05	-0.01	-0.09
# Lines	111	21		6		6		5		7		3		2	
$\sigma_{\text{int}} \dots$	0.01	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.05	0.05	0.03	0.03	0.01	0.01
$\sigma_{\text{tot}} \dots$	0.03	0.03	0.02	0.05	0.03	0.06	0.04	0.07	0.05	0.05	0.06	0.04	0.03	0.02	0.03
JP208	0.05	-0.08	-0.13	0.02	-0.03	0.06	0.02	0.10	0.05	0.01	-0.04	-0.09	-0.14	-0.08	-0.12
# Lines	118	22		7		6		6		12		3		2	
$\sigma_{\text{int}} \dots$	0.01	0.03	0.03	0.07	0.07	0.08	0.08	0.03	0.03	0.03	0.03	0.11	0.11	0.08	0.08
$\sigma_{\text{tot}} \dots$	0.02	0.04	0.03	0.08	0.07	0.09	0.08	0.05	0.04	0.03	0.04	0.11	0.11	0.08	0.08
JP296	-0.02	0.05	0.06	-0.13	-0.11	-0.11	-0.10	-0.04	-0.03	0.14	0.15	-0.02	0.01	-0.19	-0.17
# Lines	113	25		7		7		6		10		3		2	
$\sigma_{\text{int}} \dots$	0.02	0.03	0.04	0.06	0.06	0.03	0.04	0.05	0.05	0.03	0.04	0.09	0.09	0.01	0.02
$\sigma_{\text{tot}} \dots$	0.04	0.04	0.04	0.08	0.07	0.04	0.04	0.07	0.06	0.03	0.05	0.09	0.10	0.03	0.04
JP298	-0.06	-0.07	-0.02	-0.19	-0.13	-0.16	-0.10	-0.14	-0.08	0.10	0.15	-0.14	-0.08	-0.16	-0.10
# Lines	26	13		7		2		1		8		3		2	
$\sigma_{\text{int}} \dots$	0.02	0.02	0.03	0.03	0.04	0.06	0.06	...	0.02	0.03	0.04	0.03	0.04	0.08	0.08
$\sigma_{\text{tot}} \dots$	0.03	0.03	0.03	0.05	0.05	0.09	0.09	0.02	0.04	0.04	0.05	0.03	0.05	0.08	0.10
JP366	0.06	-0.03	-0.09	0.03	-0.03	0.10	0.03	0.05	-0.01	0.00	-0.07	0.09	0.03	-0.06	-0.12
# Lines	106	20		5		5		6		11		2		2	
$\sigma_{\text{int}} \dots$	0.01	0.02	0.02	0.06	0.06	0.04	0.04	0.04	0.04	0.02	0.02	0.11	0.11	0.04	0.04
$\sigma_{\text{tot}} \dots$	0.03	0.04	0.02	0.07	0.06	0.05	0.04	0.05	0.04	0.02	0.03	0.11	0.11	0.05	0.04

Table 5—Continued

Star	[Fe/H]	[Ni/H]	[Ni/Fe]	[Ti/H]	[Ti/Fe]	[Cr/H]	[Cr/Fe]	[Ca/H]	[Ca/Fe]	[Si/H]	[Si/Fe]	[Al/H]	[Al/Fe]	[Mg/H]	[Mg/Fe]
JP415	-0.05	-0.05	0.00	-0.17	-0.12	0.04	0.08	-0.03	0.01	0.01	0.05	-0.12	-0.07	-0.37	-0.32
# Lines	69	15		4		6		6		6		1		2	
$\sigma_{\text{int}} \dots$	0.02	0.03	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.06	0.06	...	0.02	0.01	0.02
$\sigma_{\text{tot}} \dots$	0.04	0.05	0.04	0.07	0.06	0.07	0.05	0.07	0.05	0.06	0.07	0.02	0.02	0.03	0.05
JP489	-0.05	-0.06	-0.01	-0.33	-0.28	-0.22	-0.17	-0.34	-0.29	0.15	0.20	-0.27	-0.22	-0.25	-0.20
# Lines	29	14		6		3		2		10		3		2	
$\sigma_{\text{int}} \dots$	0.02	0.02	0.03	0.05	0.05	0.01	0.02	0.01	0.02	0.04	0.04	0.03	0.04	0.14	0.14
$\sigma_{\text{tot}} \dots$	0.03	0.03	0.03	0.06	0.06	0.03	0.04	0.04	0.05	0.05	0.05	0.03	0.04	0.14	0.15
JP515	0.08	-0.08	-0.16	...	...	-0.13	-0.21	0.09	0.01	-0.02	-0.10	0.03	-0.05	0.00	-0.08
# Lines	75	17		...		2		3		7		2		2	
$\sigma_{\text{int}} \dots$	0.02	0.04	0.04	...	...	0.06	0.06	0.06	0.06	0.03	0.04	0.03	0.04	0.08	0.08
$\sigma_{\text{tot}} \dots$	0.05	0.06	0.05	...	...	0.07	0.06	0.08	0.06	0.04	0.04	0.04	0.04	0.09	0.09
Mean	0.02	-0.04	-0.07	-0.10	-0.11	-0.02	-0.04	-0.01	-0.03	0.05	0.03	-0.06	-0.08	-0.12	-0.14
$\sigma_{\text{me}} \dots$	0.02	0.01	0.03	0.05	0.03	0.05	0.03	0.05	0.04	0.02	0.04	0.04	0.03	0.05	0.03

Table 6 Parameter Sensitivities

Star	Ratio	ΔT_{eff}	$\Delta \xi$	$\Delta \log g$
		(+150K)	(+0.30kms ⁻¹)	(+0.25dex)
JP296	[Fe I/H]	+0.09	-0.05	-0.01
	[Fe II/H]	-0.09	-0.07	+0.11
	[Ni/H]	+0.06	-0.05	+0.01
	[Ti/H]	+0.16	-0.02	-0.01
	[Cr/H]	+0.11	-0.04	-0.03
	[Ca/H]	+0.13	-0.05	-0.06
	[Si/H]	-0.01	-0.01	+0.01
	[Al/H]	+0.07	-0.01	-0.02
	[Mg/H]	+0.06	+0.01	-0.05
JP298	[Fe I/H]	-0.01	-0.03	+0.03
		+0.02	+0.04	-0.04
	[Fe II/H]	-0.20	-0.04	+0.12
		+0.23	+0.04	-0.16
	[Ni/H]	-0.02	-0.03	+0.05
		+0.03	+0.03	-0.06
	[Ti/H]	+0.18	-0.05	0.00
		-0.18	+0.06	0.00
	[Cr/H]	+0.07	-0.03	-0.16
		-0.06	+0.02	0.00
	[Ca/H]	+0.13	-0.02	-0.02
		-0.14	+0.02	+0.01
	[Si/H]	-0.01	-0.01	+0.04
		+0.12	+0.01	-0.05
JP515	[Al/H]	+0.07	-0.01	-0.01
		-0.07	+0.02	+0.02
	[Mg/H]	-0.01	+0.01	-0.01
		+0.04	-0.05	+0.02
	[Fe I/H]	+0.01	-0.04	-0.03
	[Fe II/H]	-0.03	-0.05	+0.11
	[Ni/H]	+0.10	-0.04	-0.01
	[Ti/H]	...	...	...
	[Cr/H]	+0.10	-0.03	-0.02
	[Ca/H]	+0.10	-0.05	-0.04
	[Si/H]	+0.05	-0.02	-0.01
	[Al/H]	+0.07	-0.01	-0.01
	[Mg/H]	+0.05	-0.02	-0.04

CHAPTER 5

DISCUSSION

Iron in M34

The mean iron abundance for the nine stars is $[\text{Fe}/\text{H}] = +0.02 \pm 0.02$ (uncertainty in the mean). The standard deviation about this mean is ± 0.06 dex. Given that the average individual total uncertainty in $[\text{Fe}/\text{H}]$ is ± 0.04 dex, this limits any real star-to-star scatter to ≤ 0.05 dex. While the full range in $[\text{Fe}/\text{H}]$ is a modest 0.14 dex, the two coolest stars demonstrate relative underabundances (Figure 4). Although their deviations are not significant when considered individually, collectively they result in a linear correlation in the $[\text{Fe}/\text{H}]-T_{\text{eff}}$ plane significant at greater than the 99% confidence level. Similar behavior is seen for Ti, Ca, Si, Al, and (perhaps marginally so) Mg, with statistically significant correlation coefficients found for these elements. Excluding JP298 and JP489 - the two coolest stars in the sample and in general the most anomalous with regards to abundances - eliminates any significant correlation in the $[\text{X}/\text{H}]-T_{\text{eff}}$ planes for all the elements except Mg, where a marginal correlation remains. *If real*, there are a number of effects that could be causing the observed relations, most notably non-LTE (NLTE) effects resulting in over-ionization/excitation. Systematic errors associated with the atmospheric models and derivation of the stellar parameters could also produce such trends. Each of these possibilities will be discussed in the following sections, starting with the atmospheric models and stellar parameters.

Figure 4 $[X/H]$ as a function of T_{eff} . The solid line represents the cluster mean based on all nine stars.

Models, Stellar Parameters, & Measurements

The present study is the first to spectroscopically measure the chemical abundances (other than Li) of M34 cluster stars. We are thus using the model atmospheres in a manner rarely done - applying them to presumed chemically homogeneous stars having a range of temperatures. This opens the possibility of exposing shortcomings in the model atmosphere grids. Could there be T_{eff} -dependent deficiencies in the grids that would produce modest abundance anomalies in our cooler stars? If the models are to be suspected in creating any trends, it would be expected that the trends would be consistent. Consistent is to be taken as similar parameters should produce similar results. This is not the case in the $[\text{Fe}/\text{H}]-T_{\text{eff}}$ relation in Figure 4. The $[\text{Fe}/\text{H}]$ ratios for the cool stars ($T_{\text{eff}} < 5500$ K) are all below solar except for JP199, which is cooler than Fe-deficient JP296. Thus there may not be a consistent bias in the model atmospheres that necessarily results in low Fe abundances for the coolest stars (similar conclusions apply to ξ and $\log g$). We cannot, however, make strong assertions based on one star. Expanding the cool M34 dwarf sample size is needed to explore this issue further.

It should also be mentioned that Kurucz models have been used extensively in additional studies deriving Fe abundances of various open clusters. Examples of these are Boesgaard (1989), Boesgaard & Friel (1990), and Barrado y Navascus, Deliyannis, & Stauffer (2001). To our knowledge, there is no report in any cluster study, including those listed, of a correlation of $[\text{Fe}/\text{H}]$ with T_{eff} . However, none of these studies included stars as cool (< 5300 K) as those in our sample. Wilden *et al.* (2002) derived abundances of eleven elements for 16 Pleiades dwarfs, including stars with $T_{\text{eff}} \leq 5300$ K, using the Spectroscopy Made Easy software package and Kurucz model atmospheres. No T_{eff} -dependent abundance effects were noted; however, it appears in Table 4 therein that their Cr, Ti, and Sc abundances are relatively lower

in the cool stars. Additionally, Si is relatively higher in their cool stars, similar to the behaviors seen here. Plotting these abundances against temperature results in statistically significant linear correlation coefficients, verifying the relations.

Generally, abundances derived from neutral species are not sensitive to surface gravity, and it plays a minor role in the stellar models. The use of the polynomial fitted to the ZAMS isochrones is appropriate for M34, which has an estimated age of 250 Myr (JP). Another method of calculating $\log g$ was considered, namely ionization balance. However, ionization balance - requiring that equivalent abundances be derived from, *e.g.*, the Fe I and Fe II lines - is subject to overionization effects that might be present (especially in cool stars), resulting in surface gravities that are unbelievably low. Gratton, Carretta, & Castelli (1996) found such results in their analysis of metal-poor field stars using the Kurucz 1992 models. They reported that their data suggested the Kurucz models were not suitable for stars with $T_{\text{eff}} < 4400$ K but further commented that deviations from LTE needed to be investigated.

With respect to the initial metallicity of M34, forehand knowledge was limited. The metallicity has been determined by only one previous study, that of Canterna, Perry, & Crawford (1979). They found the mean metallicity-sensitive Strömgren index to be $\delta m_1 = 0.01$, the same as the Pleiades, which was taken to be similar to the solar value. Thus, all the model atmospheres for the present M34 stars were created with the metallicity set to zero. The deviations from this assumption are less than ± 0.1 dex for all the stars, and thus the effects associated with deviations from zero metallicity are negligible.

In order to investigate their affect on the $[X/H]$ - T_{eff} relations, the initial photometric T_{eff} and ξ (along with the $(B - V)_0$ determined $\log g$) were used to generate additional model atmospheres. The resulting abundances followed the same behavior as those derived from the final parameters. It should also be noted that the differences

between our final temperatures and those of JFSS show no trend with temperature. Adopting $\xi = 0$ for each star did not eliminate the relations either. The parameter sensitivities (Table 6) can be used to determine if any modification of the parameters can eliminate the $[X/H]-T_{\text{eff}}$ relations. In general, the sensitivities to T_{eff} are such that changing the individual temperatures could not result in the simultaneous flattening of the $[X/H]-T_{\text{eff}}$ correlations for each element. Particularly for Fe and Si, the sensitivities are dissimilar in magnitude and often in the same sense, *i.e.*, reducing the temperature for JP515 lowers the $[\text{Fe}/H]$ ratio, which could contribute to the levelling of the $[\text{Fe}/H]-T_{\text{eff}}$ relation, while at the same time lowers the $[\text{Si}/H]$ ratio, increasing the dispersion in the Si abundance between JP515 and the cooler stars. The effects of altering ξ and $\log g$ are similar in that the $[X/H]-T_{\text{eff}}$ relations cannot be removed. We are confident then that the parameters adopted are not the cause of any anomalous behavior seen in the abundance ratios.

We also exclude several other sources of the modest but consistent abundance deviations for our two coolest M34 dwarfs. Relative line strength measurement errors induced by scattered light or continuum location do not provide a self-consistent explanation for both the Si overabundances in the cool stars and the underabundances of the other elements. Moreover, they cannot explain the difference in the Fe I- and Fe II-based abundances (see below). We also note that while we used a more restricted selection of Fe I lines for the two coolest dwarfs to avoid possible blending effects, the odd cool star abundance patterns persist when using the same set of lines as for the warmer stars.

NLTE Effects: Overionization & Increased Excitation

The possible NLTE effects seen in the $[X/H]-T_{\text{eff}}$ relations motivated the analysis of the Fe II lines to investigate ionization balance; the abundance results are given in Table 7. Column one lists the wavelengths of the Fe II lines that were measured

Figure 5 Difference in Fe abundance from Fe II and Fe I against T_{eff} . Notice JP298 and JP489 (4750 K) both have the same Fe II - Fe I difference of 0.62 dex. The errorbar represents the typical uncertainty in the differences.

(not all lines were measurable in all stars), column two gives the solar abundance ($\log N_{\odot}$) for each line, and the remaining columns are the $[\text{Fe II}/\text{H}]$ for each star. Plotting the abundance difference derived from Fe II and Fe I against temperature shows a dramatic overionization of Fe for JP296, JP298, JP415, and JP489 (Figure 5). Unfortunately, no clean ionic lines of suitable strength were available for the other elements which could have been used to check for overionization in those cases.

Feltzing & Gustafsson (1998) studied metal-rich G and K *field* dwarfs and found overionization in the five K dwarfs ($4510 \leq T_{\text{eff}} \leq 4833$) of their sample. They used photometric temperatures in their derivation of elemental abundances; excitation equilibrium with Fe I resulted for all stars except the K dwarfs. Furthermore, they

experienced difficulty in obtaining definite ξ values for the K dwarfs using the methods that enforced zero correlation between Fe I equivalent widths and ξ for the other stars. As a result, the same $\xi = 1.0 \text{ km s}^{-1}$ was adopted for the K dwarfs. A result of their abundance analysis was the appearance of overionization of Fe and four other elements (Sc, V, Cr, and Y) in their five cool K dwarfs. Although they acknowledged that ill-adopted effective temperatures could partially explain the observed overionization, their final conclusion was NTLE effects were the cause and thus affected the derived abundances for all of the elements for these stars. Interestingly, their $[\text{Fe}/\text{H}]$ ratios derived from the Fe I lines showed no correlation with T_{eff} . Thorén & Feltzing (2000) reanalyzed three of the five K dwarfs of Feltzing & Gustafsson (1998), deriving effective temperatures by requiring excitation balance of the Fe I lines. As a result, the overionization seen in the initial study was all but extinguished, pointing to the erroneous effective temperatures adopted by Feltzing & Gustafsson (1998) as the cause. Additionally, the adoption of the new effective temperatures also brought their Fe and Cr abundances nearly into ionization balance. The present study is not subject to such temperature problems because effective temperatures for all stars were derived by demanding Fe I excitation balance. Furthermore, we do see a modest relative underabundance of Fe in the cool stars, except JP199, which is demonstrated in Figure 4.

Standard LTE analyses use the Boltzmann and Saha equations to calculate the populations of excited and ionized states, which are directly related to the absorption and emission coefficients. These populations are dependent on the temperature and density of the stellar atmosphere if LTE holds. Deviations from LTE which lead to inaccurately calculated populations could give rise to the effects seen in Figures 4 and 5, if the deviations result in under-populating lower bound levels of neutral atoms. In this sense, both overionization and overexcitation are significant factors.

Table 8 Final Mean Cluster Abundances

Ratio	Abund	σ_{me}
[Fe/H]	0.07	0.01
[Ni/Fe]	-0.12	0.02
[Ti/Fe]	-0.06	0.05
[Cr/Fe]	-0.01	0.06
[Ca/Fe]	0.03	0.02
[Si/Fe]	-0.05	0.02
[Al/Fe]	-0.05	0.04
[Mg/Fe]	-0.10	0.02

Of all the lines measured, the Si lines as a group have higher excitation potentials ($5.61\text{eV} \leq \chi \leq 6.19\text{eV}$) than all the lines of the rest of the elements. Both of the Mg lines have excitation potentials above 5 eV (5.11 eV and 5.75 eV), with only one in the same range as those for Si. Of the remaining elements, only Fe and Ni (which shows no trend) have lines with χ greater than 5 eV, but these lines are few in each case. Thus, an increase in excitation would depopulate the lower energy levels being measured for Fe, Ti, Cr, Ca, Al, and possibly Mg, and in a converse fashion, populate the higher levels seen in Si. We would then expect to see an enhancement in the abundance of Si for these stars and a deficiency of the other elements. Such modest effects may explain the cool star abundances in Figure 4. Though most theoretical and observational work on NLTE effects has been limited to metal-poor, evolved, or warmer stars (making comparison with our results difficult), recent discussions of the basic framework of the NLTE problem on stellar Fe abundances can be found in, *e.g.*, Thévenin & Idiart (1999) and Gehren, Korn, & Shi (2001) and references therein.

Whatever the cause, the anomalous behavior of JP296, JP298, JP415, and JP489 lowers the confidence in their derived abundances. We have thus excluded them from the final cluster mean abundances, which are given in Table 8. The iron abundances

of the remaining stars agree very well. Furthermore, an interesting consequence of excluding the four anomalous stars is that those remaining nearly obtain Fe ionization balance. The cluster mean iron abundance derived from both states match nicely, 0.07 ± 0.01 for Fe I and 0.05 ± 0.03 for Fe II. The final cluster mean Fe abundance adopted is that derived from Fe I (Table 8).

Metal Abundances

The final mean abundances are void of any statistically significant trends with respect to temperature. Additionally, no scatter is seen in any element except for possibly Cr. χ^2 tests demonstrate that Cr is the only element for which the observed scatter is approaching statistical significance, with $\sim 97\%$ confidence that the scatter is real. JP199, JP208, and JP366 have [Cr/H] ratios that agree marginally well, with values of 0.06, 0.06, and 0.10 dex respectively. JP133 and JP515 have the most deviant abundances with 0.18 and -0.13 dex, but only three Cr lines were measured for JP133 and only two for JP515. Having more measurable Cr lines in these stars would allow the validation of these “extreme” values.

All of the elements except Ni scale well with Fe within the final uncertainties, fitting nicely with the field star data of Edvardsson *et al.* (1993). The final mean ratios are $[\text{Ti}/\text{Fe}] = -0.06 \pm 0.05$, $[\text{Cr}/\text{Fe}] = -0.01 \pm 0.06$, $[\text{Ca}/\text{Fe}] = 0.03 \pm 0.02$, $[\text{Si}/\text{Fe}] = -0.05 \pm 0.02$, $[\text{Al}/\text{Fe}] = -0.05 \pm 0.04$, and $[\text{Mg}/\text{Fe}] = -0.10 \pm 0.02$. Mg shows a minor deviation from the Fe abundance but still fits within the Edvardsson *et al.* data. Ni is somewhat more anomalous, with $[\text{Ni}/\text{Fe}] = -0.12 \pm 0.02$. This would place M34 stars on the extreme boundary of the Edvardsson *et al.* Ni distribution. King *et al.* (2000) found a similar result for Ni ($[\text{Ni}/\text{Fe}] = -0.08 \pm 0.03$) in their two Pleiades K dwarfs, and they tentatively concluded that the underabundance was real based on the similarities of Ni and Fe line strengths, excitation distribution, ionization potential, and parameter sensitivities. In addition to these factors, the

low uncertainty in the final Ni abundance seen here leaves us to conclude that the underabundance in M34 is also real.

Li in M34

JFSS investigated the Li abundance of M34 stars. They found depletion and dispersion of Li abundances at a given temperature, especially for stars with $T_{\text{eff}} \leq 5400$ K, that is intermediate to the younger Pleiades (~ 80 Myr) and the older Hyades (~ 800 Myr). Star-to-star Fe abundance scatter (more generally, intracluster variations of opacities, which are influenced by chemical composition; Swenson *et al.* 1994) is a mechanism that could give rise to the observed Li spread in some open clusters, especially for cool stars. As stated previously, Chaboyer *et al.* (1995) demonstrated that $\Delta[\text{Fe}/\text{H}] = 0.05$ dex resulted in a change of ~ 0.4 dex in the predicted Li abundance for Pleiads at $T_{\text{eff}} = 5000$ K. The low confidence in the abundances of JP296, JP298, JP415, and JP489 does not allow a direct comparison of those abundances and the Li abundances from JFSS, yet some general observations can be made.

K abundances are useful when analyzing Li because of the similarities in the $\lambda 7699$ K I and $\lambda 6707$ Li I transitions and atomic data, and because K is not depleted throughout the MS lifetime of the star, which remains a possibility for Li. As such, relative K abundances were derived for all nine stars and are plotted against T_{eff} in the left panel of Figure 6; an analogous plot for $\log N(\text{Li})$ is given in the right panel, the Li abundances for which were taken from JFSS. The similar behavior seen in these plots suggests that a portion of the observed Li depletion in cool dwarfs may be due to the same mechanism causing the trend in the K- T_{eff} plane. Indeed, the derived M34 Li abundances generally lie below standard model Li depletion predictions (Figure 7). Linear approximations to the K, Li- T_{eff} relations were made using the least squares method, and the calculated slopes were compared. The K slope is $\sim 60\%$ of the Li

Figure 6 $[K/H]$ and $\log N(\text{Li})$ plotted against T_{eff} . The Li abundances are taken from JFSS.

slope, pointing to the possibility that the cooler M34 Li abundances are systematically low. Investigating this effect to first order, we have assumed that the warmest star in our sample has the characteristic cluster K abundance ($[K/H] \sim 0.34$). Fitted K abundances were then calculated using the effective temperatures from JFSS and the linear approximation to the K- T_{eff} relation. Star-to-star differences of the adopted cluster K abundance and the fitted K abundance were used to systematically raise the Li abundances. These modified Li abundances, along with the original JFSS Li abundances, are plotted as a function of T_{eff} in Figure 7. The solid lines are replicated standard PMS model Li depletions from Figure 3 of JFSS. The modified Li abundances are generally higher than the model predictions, but this first-order approximation raises questions concerning the true slope of the Li depletion seen in cool cluster dwarfs. In the case of M34, this possibly eliminates the need for MS Li depletion to describe the general trends of the observed data.

χ^2 tests provide a greater than 99 percent confidence level that the heavy element

Figure 7 Li abundance as a function of T_{eff} . The solid lines are Li depletion predictions as seen in Figure 3 of JFSS. The T_{eff} in both plots and the Li abundances in the left panel are those from JFSS. The Li abundances in the right panel are the modified JFSS abundances as described in the text.

spreads seen in Figure 4 are greater than statistically expected for all the elements except for Ni and Si. Again, the spreads are mostly a result of the four anomalous stars, pointing to a possible relation between the scatter of the elements (whatever the cause) considered herein and the scatter seen in the Li abundances. To test this, polynomial fits were made to the $\log N(\text{Li}) - (B - V)_0$ and $[M/H] - (B - V)_0$ data, where M here is Fe, Cr, Si, Al, Mg, and K. The differences in the observed and fitted abundances of Li are plotted against the same differences for M in Figure 8. No correlation is seen between the scatter of the heavy elements studied here and that of Li. Also, that there is no scatter in the elements for the five warm stars from which the mean cluster abundances have been derived suggests the intracluster Li dispersions seen in M34 are not correlated with star-to-star scatter of the heavy elements. Wilden *et al.* (2002) found similar results in their recent study of the Pleiades.

Figure 8 Observed and fitted Li abundance differences vs observed and fitted metal abundance differences. The fitted abundances are those calculated using a polynomial fit to the $N(\text{Li})-(B-V)_0$ and $[M/H]-(B-V)_0$ relations.

CHAPTER 6

SUMMARY

We have derived abundances for Fe, Ni, Ti, Cr, Ca, Si, Al, and Mg for nine G and K dwarfs in the open cluster M34 from high resolution spectra obtained with the HIRES spectrograph on the Keck I telescope. Accurate abundances of open cluster stars are important to modern astrophysics on many fronts, including determining the adequacy of stellar models, investigating the Li patterns seen in clusters of various ages, securing confidence in distances derived from MS fitting, and constraining Galactic chemical evolution. We have chosen stars with temperatures ranging from $4750 \text{ K} \leq T_{\text{eff}} \leq 6130 \text{ K}$ and with rotational velocities $\leq 11 \text{ km s}^{-1}$. Only those stars falling on or near the expected cluster MS and with high proper motion membership probabilities were analyzed, with the exception of JP296. This star is believed to be a member based on its position near the cluster MS, but its disparate radial velocity lies outside of that for the cluster, suggesting it is a single-line spectroscopic binary. Membership was assumed for JP296.

Plotting the derived abundances as a function of T_{eff} revealed a small but statistically significant correlation for all the elements except Ni. The relations were as such that the cool stars were found to have lower abundances than the warmer stars, the exception being Si, where the cooler stars were overabundant compared to the warmer stars. The opposite correlation seen in the $[\text{Si}/\text{H}]-T_{\text{eff}}$ plane is intriguing because of its differing excitation behavior compared to the other elements; its excitation potentials are higher. Comparing the abundances derived from Fe I and

Fe II revealed a significant overionization in JP296, JP298, JP415, and JP489, four of the coolest stars of the study. These observed relations implicate the action of NLTE mechanisms, though we cannot rule out systematic effects from the model atmospheres used. Gratton *et al.* (1996) also the validity of Kurucz models being applied to cool stars, though they found inadequacies for stars with $T_{\text{eff}} \leq 4400$ K. cooler than the stars considered here. Whatever the cause, the derived abundances of the four stars are of low confidence and not included in the cluster means.

The final mean cluster iron abundance derived from Fe I lines is 0.07 ± 0.04 dex. The Ni underabundance with respect to Fe of -0.12 ± 0.04 dex lies on the outer boundary of the Edvardsson *et al.* (1993) field star data, similar to what was found for the two Pleiades K dwarfs of King *et al.* (2000). The rest of the elemental abundances are unremarkable compared to the field star data of Edvardsson *et al.* and are generally solar. Cr is the only element for which a spread in the derived abundances is greater than statistically expected. We place an upper limit on the Cr scatter of 0.09 dex.

The study of M34 would be greatly benefited in several ways by more high quality data. First, and possibly most important, is the possible overionization real or is it a product of the inability of model atmospheres to correctly predict the abundances of cool stars? A broader wavelength coverage would provide ionized lines of other elements which can be used to corroborate the observed Fe overionization. Second, if NLTE effects are present in only selected cool stars, is there a correlation to the Li depletion seen among this group? A comparison of the Li and K trends with T_{eff} suggest that the apparent Li depletion in cool M34 stars may partially be due to mechanisms other than MS depletion. However, the Li scatter at a given T_{eff} seems not to be related to that in heavier elements, suggesting that the Li scatter is not due to intracluster abundance variations. A greater understanding and treatment

of NLTE in cool solar-type dwarfs is needed in regards to the depletion and scatter patterns; more data from cool dwarfs (< 5400 K) will help in this analysis. Third, is the $[\text{Ni}/\text{Fe}]$ underabundance real? A larger sample of stars would help pinpoint the Ni abundance. Fourth, more data are needed to solidify the abundances of all the elements. The cluster mean abundance of any element needs a statistically significant number of stars before it can be stated with true confidence.

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