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OXYGEN IN OPEN CLUSTER DWARFS: PLEIADES¹ AND M34²

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ABSTRACT

We analyze the high-excitation O I $\lambda 7774$ triplet in high-resolution, moderate signal-to-noise ratio spectra of 15 Pleiades and eight M34 open cluster dwarfs over the effective temperature range of 5048–6172 K. Relative O abundances have been derived using model atmospheres interpolated from four different sets of ATLAS9 grids. In contrast to existing non-LTE (NLTE) predictions, a dramatic increase in the O I triplet abundance with *decreasing* temperature is seen for both clusters, regardless of the atmospheric model. S I abundances of three Pleiades stars derived from the high-excitation $\lambda 6053$ feature mimic the O I abundance behavior. O abundances have also been derived from the [O I] $\lambda 6300$ feature in three Pleiades stars; the abundances exhibit a much lower mean value than do the cool dwarf triplet results. Inasmuch as the [O I] abundances are presumed to be free from NLTE effects, their mean values ($[O/H]_{6300} = +0.14$) provide the current best estimate of the Pleiades O abundance. Spreads in $[O/H]_{\text{trip}}$ at a given temperature are also seen in both clusters; no correlation is found between the spreads and the chromospheric emission measures.

Subject headings: open clusters and associations: individual (M34, Pleiades) — stars: abundances — stars: atmospheres — stars: late-type — stars: Population II

On-line material: machine-readable table

1. INTRODUCTION

The current state of mapping stellar O abundances may be best described as convoluted. This is quite unfortunate given the possibly critical role the [O/Fe] ratio plays in understanding the chemical evolution of the Galaxy (Wheeler, Sneden, & Truran 1989). Excellent reviews of stellar O abundances and their importance are given by King (1993), Israelian, García López, & Rebolo (1998), Nissen et al. (2002), Takeda (2003), and references therein. A matter of great spectroscopic interest is the often reported discrepancy between O abundances derived from the high-excitation O I $\lambda 7774$ triplet lines (hereafter the triplet) and those derived from the low-excitation [O I] forbidden lines at 6300 and 6363 Å. While observational evidence indicates that the triplet yields higher O abundances than does [O I] for solar metallicity dwarfs with $T_{\text{eff}} > 6300$ K (King & Boesgaard 1995) and highly evolved metal-poor subgiants (e.g., Cavallo, Pilachowski, & Rebolo 1997), the current picture for stars in other temperature and metallicity regimes is unclear or a matter of contention. Conventional wisdom holds that the triplet forms in non-LTE (NLTE) conditions, while the [O I] lines are well described by LTE calculations (Kiselman 1991; Takeda 2003). Thus, the permitted forbidden O abundance discrepancies are usually attributed to the triplet and to NLTE effects.

Aside from understanding the physical environment of stellar atmospheres, knowledge of the conditions (NLTE or otherwise) affecting the formation of the triplet is highly desirable for a genuinely practical reason. Namely, the triplet is much stronger and more easily measured in stellar spectra than the [O I] lines are. In fact, the [O I] lines become vanishingly weak in late G and K dwarfs. Corrections for the effects of NLTE conditions, if present, are needed for the triplet if accurate abundances are going to be derived from these features. However, the extent of NLTE effects on the derived triplet abundances is not clear. Studies have indicated that the magnitude of the effects may be dependent on metallicity (e.g., Nissen & Edvardsson 1992), temperature (e.g., Takeda 2003), and/or systematic errors (e.g., King & Boesgaard 1995). Furthermore, O data for metal-rich ($[Fe/H] \geq 0$) dwarfs are sparse.

In open clusters we find collections of presumably chemically homogeneous, coeval stars that offer a unique scrutiny of stellar processes. Cluster members are distinguished by mass, and thus the spectroscopic delineation of possible temperature-dependent effects and any model atmosphere inadequacies that are otherwise difficult to identify in assemblages of field stars is facilitated. Examples of this are the discovery of the Li gap in the Hyades open cluster (650 Myr; Boesgaard & Tripicco 1986) and the large Li abundance scatter observed among cool Pleiades dwarfs (Soderblom et al. 1993a). Here we describe our analysis of O abundances of late F, G, and early K dwarfs in the Pleiades (100 Myr) and M34 (250 Myr) open clusters. We address the adequacy of deriving triplet-based O abundances in warm/cool cluster dwarfs.

2. OBSERVATIONS AND ANALYSIS

Pleiades targets were chosen from cool members that were previously reported to display large dispersions in Li (Soderblom et al. 1993a; Jones et al. 1996). Echelle spectra of the Pleiades stars were obtained with the 9.2 m Hobby-Eberly Telescope (HET) and the High Resolution Spectrograph (HRS). The HET data presented herein were obtained on 22 separate nights starting on 2002 August 23 UT and ending on 2003 February 17 UT. The HET/

¹ Based on observations obtained with the High Resolution Spectrograph on the Hobby-Eberly Telescope, which is operated by McDonald Observatory on behalf of the University of Texas at Austin, Pennsylvania State University, Stanford University, the Ludwig-Maximilians-Universitaet, Munich, and the George-August-Universitaet, Goettingen. Public Access time is available on the Hobby-Eberly Telescope through an agreement with the National Science Foundation.

² Data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

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TABLE 1
PLEIADES AND M34 PARAMETERS AND ABUNDANCES

STAR	$(B-V)_0$ (mag)	T_{eff} (K)	ξ (km s ⁻¹)	log g (cgs)	TRIPLET EW ^a			[O/H] _{trip}			
					$\lambda 7771$	$\lambda 7774$	$\lambda 7775$	OVER	NOVER	MLT5	CGM72
H II 0193	0.750	5339	0.58	4.61	48.7	43.4	...	0.31	0.32	0.29	0.29
H II 0250	0.645	5715	0.96	4.55	78.2	61.1	59.8	0.26	0.25	0.26	0.26
H II 0263	0.840	5048	0.30	4.64	...	45.6	55.2	0.97	1.00	0.95	0.95
H II 0298	0.835	5048	0.30	4.64	43.2	...	34.7	0.58	0.60	0.56	0.56
H II 0571	0.748	5373	0.61	4.60	61.6	55.4	48.9	0.50	0.51	0.48	0.48

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

^a Equivalent widths are given in milliangstroms.

HRS detector is a 4096 × 4100 side-by-side CCD mosaic of two 2048 × 4100 CCDs with 15 μ m pixels. The instrumental configuration consisted of the 316g6948 cross-disperser, 3" fiber, and 2 × 2 binning. A wavelength coverage of 5095–8860 Å was achieved with typical per pixel signal-to-noise ratios of 100. A slit width of 0".5 (4.2 pixel–projected) was used, giving a resolving power of 60,000. The initial CCD mosaic image contains the spectra from both the blue and red CCDs; each chip was reduced individually using standard IRAF routines to remove the bias pattern, subtract scattered light, flat-field, and wavelength-calibrate the data. M34 data were obtained with the Keck I 10 m telescope and the HIRES echelle spectrograph (Vogt 1992). The spectra have a resolution of $R = 45,000$ and a typical per pixel signal-to-noise ratio of 70. These data are those described and utilized in Jones et al. (1997) and Schuler et al. (2003).

Dereddened $(B-V)_0$ and T_{eff} values of the Pleiades stars, excluding H II 298, H II 571, H II 916, H II 2284, H II 2406, and H II 2880, were taken from King, Krishnamurthi, & Pinsonneault (2000a); the six stars listed are not included in the King et al. (2000a) sample. Effective temperatures for these six stars were calculated using $(B-V)_0$ colors from Soderblom et al. (1993a) and equation (3) from Soderblom et al. (1993b). Microturbulent velocities and log g values were calculated using relations in Edvardsson et al. (1993, eq. [9]) and Gray (1992, eq. [16.2]), respectively. Spectroscopic parameters for the M34 dwarfs, excluding JP 320,⁶ were taken from Schuler et al. (2003). The adopted $(B-V)_0$ color and effective temperature of JP 320, which is not included in the Schuler et al. sample, is from Jones et al. (1997). The JP 320 microturbulent velocity and log g value were calculated as above. Stellar parameters of the stars from both clusters are listed in Table 1.

Four sets of atmospheric grids have been utilized in the derivation of the O abundances: (1) Kurucz grids with convective overshoot (OVER) based on the ATLAS9 code; (2) grids with no convective overshoot (NOVER) based on a modified version of ATLAS9 (Castelli, Gratton, & Kurucz 1997); (3) ATLAS9 grids computed with the mixing-length parameter set to $\alpha = 0.5$

(MLT5); and (4) grids computed with ATLAS9 modified based on the formulation of Canuto, Goldman, & Mazzitelli (1996, CGM72). The OVER and NOVER grids were obtained from the Web site of R. L. Kurucz,⁷ and the MLT5 and CGM72 grids, both described in Heiter et al. (2002), were obtained at the NeMo.2003 Web site.⁸ Atmospheric models characterized by our stellar parameters were interpolated from each of the grids.

Equivalent widths of the O I infrared triplet for 15 Pleiades and eight M34 dwarfs were measured using the one-dimensional spectrum analysis software package SPECTRE (Fitzpatrick & Sneden 1987). Solar equivalent widths were measured in the same manner from sky spectra obtained at HET and lunar spectra obtained at Keck I. All of the O I features were fitted with Gaussian profiles. O abundances have been derived using an updated version of the LTE stellar line analysis software package MOOG (2002 ver.; Sneden 1973). Final O abundances derived from the triplet are reported relative to the Sun and are thus essentially independent of adopted g_f -values; the equivalent widths and final abundances are listed in Table 1. Relative errors in the $[\text{O}/\text{H}]_{\text{trip}}$ abundances were calculated by considering the abundance sensitivities to uncertainties in line strength, T_{eff} , and log g . Line-strength errors are due to photon noise and are generally 2.7 and 3.7 mÅ for the Pleiades and M34, respectively. The Pleiades T_{eff} errors were determined from the uncertainty in the photometry and are typically ± 50 K. The M34 T_{eff} errors were taken from Schuler et al. (2003). Random errors in log g due to photometry are negligible, and the uncertainty due to equation (16.2) of Gray (1992) is estimated to be 0.10 dex, which we have adopted as the error in log g . The individual $[\text{O}/\text{H}]_{\text{trip}}$ sensitivities to line strength, T_{eff} , and log g were added in quadrature to obtain the final relative uncertainty for each star. The typical relative uncertainty in $[\text{O}/\text{H}]_{\text{trip}}$ is ± 0.08 dex for stars in both clusters.

Moderate signal-to-noise ratio spectra require care to be taken when identifying and measuring the notoriously weak 6300 Å forbidden line ($[\text{O I}]_{6300}$); selection effects related to possible line enhancement due to background noise can result in overestimated

⁶ Identification numbers for the M34 dwarfs are from Jones & Prosser (1996).

⁷ See <http://kurucz.harvard.edu/grids.html>.

⁸ See <http://ams.astro.univie.ac.at/nemo>.

TABLE 2
PLEIADES [O I] ABUNDANCES

STAR	$\lambda 6300$ EW ^a	[O/H] ₆₃₀₀							
		OVER	σ	NOVER	σ	MLT5	σ	CGM72	σ
H II 0571	6.6	0.14	± 0.10	0.13	± 0.11	0.14	± 0.11	0.16	± 0.12
H II 2284	6.9	0.16	± 0.15	0.16	± 0.16	0.18	± 0.14	0.21	± 0.13
H II 2406	6.6	0.12	± 0.16	0.13	± 0.16	0.15	± 0.16	0.17	± 0.15
Sun	5.5	8.76 ^b	...	8.73	...	8.71	...	8.69	...

^a Equivalent widths are given in milliangstroms and include the $\lambda 6300.32$ Ni I feature.

^b log $N(\text{O})$.

FIG. 1.—Pleiades and M34 relative O abundances as derived from the $\lambda 7774$ triplet vs. effective temperature. Pleiades and M34 abundances are plotted as triangles and squares, respectively. The relative triplet abundances derived from each of the four grids of model atmospheres are plotted, without individual error bars; the typical error in the relative triplet abundances (0.08 dex), which is the same for both clusters, is given as the vertical error bar. [S/H] abundances for H II 193, H II 571, and H II 3179 are also shown plotted as crosses. The horizontal bar represents the mean $[\text{O}/\text{H}]_{6300}$ abundance spanning the T_{eff} of the three Pleiades stars for which the forbidden line was measurable. The mean is the average of the abundances derived using the four different model atmospheres.

equivalent widths. Of the 15 Pleiades stars in our sample, data quality and telluric contamination eliminated all but three for which $[\text{O I}]_{6300}$ could be measured: H II 571, H II 2284, and H II 2406. After the $[\text{O I}]_{\lambda 6300}$ line was identified in each star, its relative strength was compared with that of the Sc II $\lambda 6300.7$ line and, in each case, was found to be slightly weaker than the Sc II feature, as expected for solar-type stars. The equivalent widths of the identified $[\text{O I}]_{6300}$ feature in each star and the Sun were measured using SPECTRE and are given in Table 2. The 6300 Å region was not present in the M34 spectra.

One must be cognizant of the blended Ni I line at 6300.34 Å (Lambert 1978; Allende Prieto, Lambert, & Asplund 2001) when deriving the abundance of O from the $[\text{O I}]_{6300}$ feature. For the present analysis, we constructed curves of growth using synthetic spectra of the 6300 Å region with input O abundances ranging from 8.63 to 9.13 dex and utilizing each of the four model atmospheres described above. For each instance, the equivalent width of the synthesized $[\text{O I}]_{6300}$ line, which included the Ni I feature synthesized with $\log N(\text{Ni}) = 6.25$ (Anders & Grevesse 1989) and $\log gf = -2.31$ (Allende Prieto et al. 2001), was measured using SPECTRE in the same manner as the observed spectra. The O abundances for the three Pleiades stars and the Sun were derived using these curves of growth. The solar and $[\text{O}/\text{H}]$ abundances as derived from the $[\text{O I}]_{6300}$ line and each model atmosphere are listed in Table 2. Uncertainties in the $[\text{O}/\text{H}]_{6300}$ abundances are dominated by line-strength errors and are listed in Table 2.

3. DISCUSSION

The results of our analysis of both the Pleiades and M34 data are presented in Figure 1; all abundances are given relative to the Sun. The most striking aspect of the figure is the dramatic

FIG. 2.—Pleiades relative triplet abundances vs. effective temperature. Open circles are the original abundances derived using the OVER grids. Red triangles are the rederived abundances using luminosity-based effective temperatures and OVER grids as described in the text. The horizontal bar is as in Fig. 1.

increase in $[\text{O}/\text{H}]_{\text{Trip}}$ with *decreasing* T_{eff} seen for both clusters, independent of model atmosphere; model-to-model spreads are ≤ 0.05 dex for each star, well within the typical errors. Our results confirm the preliminary finding of $[\text{O}/\text{H}]_{\text{Trip}}$ overabundances in two cool Pleiades stars reported by King et al. (2000b). We also identified and measured the high-excitation ($\chi = 7.87$ eV) S I $\lambda 6052.67$ line in the spectra of three Pleiades stars—H II 0193, H II 0571, and H II 3179—and the Sun. The relative [S/H] abundances appear to mimic the behavior of the $[\text{O}/\text{H}]_{\text{Trip}}$ abundances (Fig. 1), suggesting that the $[\text{O}/\text{H}]_{\text{Trip}}-T_{\text{eff}}$ trend is not unique in these stars. Although we cannot rule out inadequacies shared by the atmospheres used here, it appears that the observed trends are independent of the convective treatment and value of the mixing-length parameter.

Schuler et al. (2003) observed an increase in Si abundances with decreasing T_{eff} and, concurrently, a decrease in Fe, Ti, Cr, Ca, Al, and Mg abundances with decreasing T_{eff} for nine M34 dwarfs, seven of which are in the current M34 sample. The Si abundances were derived from moderately high excitation lines ($\chi \approx 6.0$ eV), and the abundances of Fe, Ti, Cr, Ca, Al, and Mg were derived from low-excitation lines ($\chi \approx 2-4$ eV). Schuler et al. suggested a scenario of overexcitation/ionization in the cool members as a possible source for the observed abundance trends. The behavior of $[\text{O}/\text{H}]_{\text{Trip}}$ and [S/H] observed in the Pleiades and M34 is consistent with this scenario. Additionally, Ford, Jeffries, & Smalley (2002) found that the Li I $\lambda 6104$ line ($\chi = 1.848$ eV) yielded a higher abundance than the Li $\lambda 6707$ resonance line did ($\chi = 0$) for Pleiades stars ($5172 \text{ K} \leq T_{\text{eff}} \leq 5449 \text{ K}$) for which they had definite $\lambda 6104$ equivalent width measurements; their findings are also in agreement with the hypothesis of overexcitation/ionization conditions in the cool Pleiades stars.

The O abundances derived using the $[\text{O I}]_{6300}$ line are also found to be independent of model atmosphere but are considerably lower than the triplet O abundances in the cool Pleiades stars (Fig. 1). The triplet is known to be susceptible to NLTE effects, but the $[\text{O}/\text{H}]_{\text{Trip}}-T_{\text{eff}}$ trend presented here is not accounted for by current NLTE calculations that predict $\log N(\text{O}_{\text{Trip}})$ increases with *in-*

creasing temperature (e.g., Takeda 2003). Indeed, the reanalysis of published triplet equivalent width data by Takeda utilizing his NLTE corrections generally resulted in agreement between $[\text{O}/\text{H}]_{\text{trip}}$ and $[\text{O}/\text{H}]_{6300}$ for disk stars ($-1 \leq [\text{Fe}/\text{H}] \leq 0$), suggesting that the results presented here may not be due to canonical NLTE effects. Alternatively, perturbations in local photospheric conditions due to spots, faculae, and/or plages in the cool Pleiades and M34 dwarfs might give rise to the abundance behavior seen in Figure 1. Studies have shown that reasonable areal coverages ($\sim 50\%$) can account at least partially for the observed Li abundance spreads in cool Pleiades dwarfs (Barrado y Navascués et al. 2001; Ford et al. 2002). Stauffer et al. (2003) suggest that such inhomogeneities are the cause of the long known, marked color anomalies in cool Pleiades stars, for which King et al. (2000a) note that color deviations are correlated with chromospheric emission deviations. *If surface inhomogeneities are at work in the cool dwarfs, the lack of similar color anomalies in the older Hyades and Praesepe clusters portends less anomalous $[\text{O}/\text{H}]_{\text{trip}}$ values for them than seen here.* We note the reduced Fe II-Fe I abundance differences at a given T_{eff} recently reported for the Hyades (Yong et al. 2004) compared with those seen for the younger M34 (Schuler et al. 2003) as limited support for the role of age in the abundance anomalies.

Another notable aspect of Figure 1 is the appearance of O abundance spreads below 5300 K for the Pleiades stars and below 5800 K for the M34 members. The M34 abundance spreads are generally smaller than those in the Pleiades, but the spreads in both clusters exceed the typical uncertainty. Similar $[\text{O}/\text{H}]$ spreads have been reported in Hyades and UMa group stars with $5800 \text{ K} < T_{\text{eff}} < 7150 \text{ K}$ (García López et al. 1993). Takeda (1995) suggested that the presence of a chromosphere (a global property distinct from spots) influences triplet line formation; we investigated this effect by plotting $[\text{O}/\text{H}]_{\text{trip}}$ against $\text{H}\alpha$ and Ca II chromospheric emission data from Soderblom et al. (1993a) and Soderblom, Jones, & Fischer (2001). No correlation between the triplet abundances and chromospheric emission was found for either cluster. A correlation between $[\text{O}/\text{H}]_{\text{trip}}$ residuals and chromospheric emission residuals—differences between observed and T_{eff} -dependent mean values—is also not present. While this might suggest that triplet abundances are affected by

local forms of “activity” (spots, faculae, and/or plages) as opposed to a global chromosphere, we point out that the chromospheric emission data and our data are not cotemporal.

Pinsonneault et al. (2004) have questioned the adequacy of stellar temperatures derived from colors, arguing that luminosity-temperature relations are in better agreement with spectroscopically derived temperatures. We thus rederived the triplet abundances (using the OVER grids) with new temperatures calculated using absolute magnitudes of each Pleiades star in our sample, assuming a distance modulus of 5.63 (Pinsonneault et al. 1998), and a 100 Myr isochrone provided by M. Pinsonneault. The rederived abundances are plotted against the luminosity-based effective temperatures in Figure 2. While the rederived abundances of stars with $T_{\text{eff}} > 5500 \text{ K}$ are brought into close agreement at $[\text{O}/\text{H}] \sim +0.15$, the range and scatter of the abundances remain significant among stars with $T_{\text{eff}} < 5500 \text{ K}$. It seems that the trends, at least among the coolest Pleiades stars, cannot be attributed to inaccurate temperature scales.

In conclusion, we point out that the O abundance derived from the $[\text{O I}]$ lines, $[\text{O}/\text{H}]_{6300} = +0.14$ (OVER/NOVER models), is approximately the O abundance derived from the triplet lines in the warmest star of the Pleiades sample and the four warmest Pleiades stars on the Pinsonneault T_{eff} scale and provides the best estimate of the cluster O abundance. Choosing the warmest star abundance for the M34 cluster O abundance in a similar manner gives $[\text{O}/\text{H}] \sim +0.04$. More observations providing a measurable $[\text{O I}]$ line or a resolution to the $[\text{O}/\text{H}]_{\text{trip}}$ behavior in Figure 1 are needed to provide confidence in the adopted Pleiades and M34 cluster O abundances.

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