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Li I AND K I SCATTER IN COOL PLEIADES DWARFS*

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ABSTRACT

We utilize high-resolution ($R \sim 60{,}000$), high signal-to-noise ratio ($\sim$100) spectroscopy of 17 cool Pleiades dwarfs to examine the confounding star-to-star scatter in the $\lambda6707$ Li I line strengths in this young cluster. Our Pleiades, selected for their small projected rotational velocity and modest chromospheric emission, evince substantial scatter in the line strengths of $\lambda6707$ Li I feature that is absent in the $\lambda7699$ K I resonance line. The Li I scatter is not correlated with that in the high-excitation $\lambda7774$ O I feature, and the magnitude of the former is greater than the latter despite the larger temperature sensitivity of the O I feature. These results suggest that systematic errors in line strength measurements due to blending, color (or color-based $T_{\rm eff}$) errors, or line formation effects related to an overlying chromosphere are not the principal source of Li I scatter in our stars. There do exist analytic spot models that can produce, via line formation effects, the observed Li scatter without introducing scatter in the K I line strengths or the color–magnitude diagram. However, these models predict factor of $\geqslant3$ differences in abundances derived from the subordinate $\lambda6104$ and resonance $\lambda6707$ Li I features; we find no difference in the abundances determined from these two features. These analytic spot models also predict CN line strengths significantly larger than we observe in our spectra. The simplest explanation of the Li, K, CN, and photometric data is that there must be a real abundance component to the Pleiades Li dispersion. We suggest that this real abundance component is the manifestation of relic differences in erstwhile pre-main-sequence Li burning caused by effects of surface activity on stellar structure. We discuss observational predictions of these effects, which may be related to other anomalous stellar phenomena.

Key words: open clusters and associations: individual (Pleiades) – stars: abundances – stars: activity – stars: atmospheres – stars: late-type – starspots

1. INTRODUCTION

Dramatic differences in the Li abundances of main-sequence stars in open clusters stand in stark contrast to the greater uniformity that is the general rule for many other elements. The complexity of the observed pattern of stellar Li depletion was recognized early (Herbig 1965; Wallerstein et al. 1965) and can be traced to the fragility of the species. Lithium is destroyed by proton capture at relatively low stellar interior temperatures (of order 2.6 million K for typical densities); these conditions are achieved for most low mass stars during the pre-main-sequence (pre-MS) phase, which yields a predicted mass-dependent depletion pattern (e.g., Iben 1965). Physical processes neglected in standard stellar models can also induce lithium depletion (Weymann & Sears 1965). Open cluster studies have revealed two other generic features of Li abundance patterns: the existence of a dispersion in abundance at fixed mass, composition, and age; and the existence of main-sequence depletion even in stars with convection zones too shallow to be able to burn lithium (for reviews see Pinsonneault 1997 and Jeffries 2006).

The specific case of star-to-star Li dispersion in the Pleiades, and other young clusters such as IC 2602 (Randich et al. 2001)

and α Per (Balachandran et al. 1996), has been extremely challenging to understand from both theoretical and observational perspectives. A substantial dispersion in the equivalent width of the 6707 Å Li I resonance line for cool Pleiades was reported by Duncan & Jones (1983) and confirmed by the much larger data set of Soderblom et al. (1993). Subsequent observations of the weak 6104 Å subordinate Li I feature by Ford et al. (2002) yielded a consistent result. The star-to-star Li equivalent width variations, which are superposed on a strong $T_{\rm eff}$-dependent depletion pattern that is presumably governed by pre-MS Li destruction in the deep surface convection zones whose extent is determined uniquely by stellar mass for a given composition and age in standard stellar models, have been difficult to explain in the context of differing surface Li abundances. Star-to-star Li abundance variations can develop in the context of rotational mixing (Pinsonneault et al. 1990; Ryan & Deliyannis 1995), and are certainly seen in older open clusters such as M67 (Pasquini et al. 1997; Jones et al. 1999). However, little such mixing is expected to have occurred at the Pleiades age ($\sim$100 Myr). Furthermore, the highest rate of mixing is expected in rapid rotators, while the rapid rotators tend to populate the upper envelope of the Li equivalent width distribution in the Pleiades.

It thus remains important to establish whether the star-to-star range in Pleiades' Li equivalent widths reflect a real star-to-star range in Li surface abundances before strong conclusions can be drawn about the underlying physical cause of the Li line strength dispersion. While Soderblom et al. (1993) suggest the Pleiades Li dispersion reflects real abundance differences, they note the difficulty for this explanation that comes from the scatter they find in the Pleiades' $\lambda7699$ K I resonance feature. Jeffries (1999) confirm this K I scatter, and note the concomitant danger in concluding that the Pleiades Li dispersion stems from

Table 1
HET Pleiades Sample

Star H II	S/N 6707	V_o	$(B-V)_o$	$(V-I)_o$	Mem. Probs.[a] BFJ, SRSG, DH	RV[b] (km s^{-1})	$v \sin i$[c] (km s^{-1})	EW(K I) (mÅ)	EW(Li I) (mÅ)
0152	96	10.60	0.645	0.685	$\cdots$, 0.98, $\cdots$	5.2 ± 0.2	11.5	194.0	191.2
0193	100	11.18	0.75	0.80	0.97, 0.95, $\cdots$	7.6 ± 0.2	6.6	216.4	161.5
0250	97	10.59	0.645	0.68	$\cdots$, 0.98, 0.57	4.7 ± 0.3	6.4	190.6	166.7
0263	133	11.51	0.84	0.90	0.98, 0.98.0.17	3.1 ± 0.9	7.8	244.7	252.1
0298 [d]	80	11.79	0.89	*	$\cdots$, $\cdots$, $\cdots$	4.8 ± 0.2	6.5	355.9	266.8
0571	126	11.14	0.74	0.85	0.97, 0.97, 0.3	5.7 ± 0.1	7.2	223.8	164.0
0746	140	11.18	0.73	0.82	0.99, 0.98, $\cdots$	6.5 ± 0.4	4.9	208.4	107.6
0916	109	11.59	0.83	0.89	0.99, 0.98, 0.90	4.2 ± 0.7	6.2	241.3	191.3
1593	128	11.03	0.73	0.77	0.99, 0.04, 0.01	6.9 ± 0.1	2.4	193.5	183.5
2126	119	11.59	0.81	0.85	0.98, 0.00, 0.05	5.5 ± 0.2	$\leqslant 6$	244.0	184.9
2284	105	11.23	0.74	*	0.99, 0.97, $\cdots$	6.3 ± 1.1	3.6	216.0	190.3
2311	114	11.23	0.78	0.79	0.96, 0.99, 0.38	5.4 ± 0.2	6.4	232.3	170.4
2366	81	11.37	0.78	0.80	$\cdots$, 0.98, $\cdots$	6.2 ± 0.2	$\leqslant 5$	248.4	226.7
2406	150	10.98	0.72	*	0.98, 0.98, $\cdots$	6.0 ± 0.1	8.9	217.1	139.7
2462	110	11.37	0.80	0.80	0.99, 0.96, $\cdots$	6.4 ± 0.2	5.2	220.8	110.3
2880	84	11.63	0.82	*	0.98, 0.97, $\cdots$	5.4 ± 0.2	6.2	245.9	142.3
3179	158	9.93	0.53	0.62	$\cdots$, 0.98, $\cdots$	6.1 ± 0.2	$\leqslant 6$	160.5	140.2

Notes.
[a] Proper-motion-based membership probabilities from Jones (1973), Schilbach et al. (1995), and Deacon & Hambly (2004).
[b] Mean radial velocities from WEBDA database: http://obswww.unige.ch/webda.
[c] Rotational velocities (or conservative upper limits) from Queloz et al. (1998).
[d] V and $(B-V)$ from the photometric decomposition of Mermilliod et al. (1992).

real abundance variations—a caveat echoed by Stuik et al. (1997) and Carlsson et al. (1994), who note the similarity in the details of the Li and K resonance line formation. King & Schuler (2004) catalog a rich variety of Li–K and alkali-activity correlations in young clusters, seen in the Pleiades by King et al. (2000), associating some 90% of the variance in Li and K in M34 (200–250 Myr) and IC 2391 (50 Myr) with the spread in chromospheric emission (though this emission is likely a proxy for surface inhomogeneities in the case of M34). Because rapid rotators in the Pleiades evince apparent Li overabundances (Soderblom et al. 1993; Garcia Lopez et al. 1994), chromospheric emission may simply serve as a proxy for rotation in this case. In their study of the 100 Myr old NGC 2451 A and B, Margheim et al. (2002) find that significant Li scatter, reminiscent of that in the Pleiades, is spuriously produced as an artifact of deriving Li abundances from equivalent widths; they suggest that accounting (via spectral synthesis) for blending features in rotationally broadened spectra might eliminate the Pleiades Li scatter.

Here, we seek to address the important question of a real Li dispersion component in cool Pleiades by utilizing new spectroscopy of higher resolution and/or signal-to-noise ratio (S/N) than in most previous studies to examine Li and K spreads in slow projected rotators that demonstrate modest chromospheric emission relative to other cluster members. We conclude that there is evidence for a real dispersion in abundance at fixed effective temperature, and (in the final section) advance the idea that variations in pre-MS depletion stemming from differences in stellar physical parameters arising from surface inhomogeneities, rather than variations in the rate of mixing, may be implicated.

2. OBSERVATIONAL DATA AND ANALYSIS

We selected 17 Pleiades having a range of T_{eff} believed to evince significant Li dispersion (Soderblom et al. 1993; King et al. 2000, hereafter KKP) and having $v \sin i \leqslant 12$ km s^{-1}.

All objects are radial velocity members and have at least one proper-motion study indicating cluster membership. Fourteen of the objects show no radial velocity or photometric evidence of binarity (Mermilliod et al. 1992). H II 571 and 2406 are single-lined binaries, but were included because their mass function determination and photometric decomposition suggest companion V-band contamination at only the $\leqslant 1\%$ level. H II 298 is the lower mass 6–7 arcsec distant visual binary companion to H II 299. Our sample is listed in Table 1, which gives information on S/N, luminosity, color, membership, and rotational velocity. Figure 1 shows our objects in the Ca II near-IR triplet- and Hα-based chromospheric emission versus V_o planes defined by the Pleiades sample from KKP. Our projected slow rotators exhibit well-below maximal chromospheric emission values at a given luminosity.

We used the Hobby–Eberly Telescope (HET) 9.2-m telescope and its High Resolution Spectrograph to obtain spectroscopy of our targets on numerous nights from 2002 August to 2003 October. Wavelength coverage from 5095 to 8860 Å was achieved over the High Resolution Spectrograph (HRS) 2-CCD mosaic. The S/N in the Li I λ6707 region is 80–160 per pixel. The 0.5 arcsec slit width yielded a nominal resolving power of $R \sim 60{,}000$. Standard reductions were carried out with the IRAF package to accomplish bias removal, scattered light subtraction, flat-fielding, order extraction, and wavelength calibration. We do not conduct spectrum synthesis of the λ6707 Li I and λ7699 K I lines since quantitative deblending is not required for these features in our spectra and absolute abundances are not the principal topic of interest. Instead, we focus on equivalent width differences of these lines for any subset of the program stars having a narrow range of color.

Equivalent widths of the λ6707 Li I and λ7699 K I resonance lines were measured with Gaussian and Voigt profile fitting routines using the SPECTRE package (Fitzpatrick & Sneden 1987). The principal potential danger in this approach is the mild blending some 0.4 Å to the blue of the Li I feature. However, its presence is of little importance here: the small projected
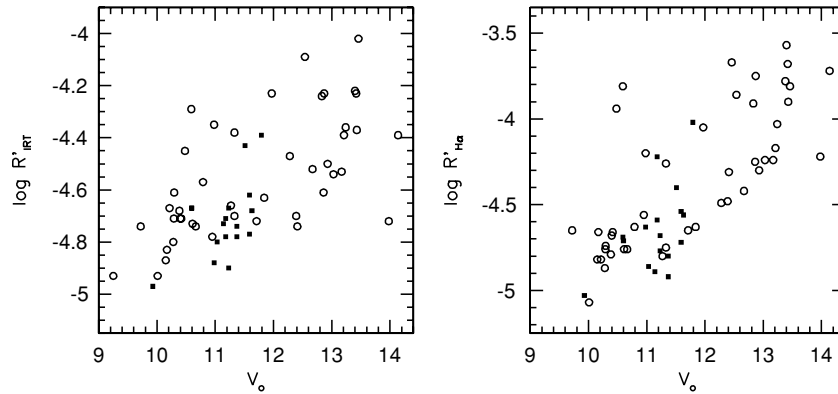
Figure 1. Our Pleiades sample (filled squares; Table 1) is plotted with other Pleiades from the study of KKP in the chromospheric emission (left panel: Ca II infrared triplet; right panel: Hα) vs. V_o planes. The chromospheric fluxes are taken from Soderblom et al. (1993).

rotational velocities mean that any residual contamination in the empirically *deblended* Li equivalent widths given in Table 1 is limited to a few mÅ (the size of random uncertainties in the line measurement), and the strength of the blending Fe I (augmented by CN in cooler dwarfs) feature proves to be nearly invariant among Pleiades of given intrinsic color. More importantly, even the full blend contribution is fractionally small, achieving strengths of 15–20 mÅ only in our coolest stars whose Li equivalent widths are an order of magnitude larger. A conservative upper limit on equivalent width uncertainties including continuum placement is $\leqslant 10$ mÅ.

For the purpose of full disclosure, we note that two spectra of H II 152 taken 2003 October 14 UT are clearly at least double-lined. Two other spectra (2002 December 8 UT) are single-lined. The flux levels and gross spectral appearance do not clearly establish a (queue) target misidentification for the 2003 spectra. However, this seems the simplest explanation inasmuch as several previous independent high-resolution spectroscopic studies (e.g., Soderblom et al. 1993; Wilden et al. 2002; Boesgaard et al. 2003) have not noted an SB2 classification. While the BY Dra classification by Kholopov et al. (1989) is not inconsistent with binarity, it appears to be based on the modest photometric variation attributed to 4.1 day variations from spot pattern migration by Magniitsky (1987). We proceed here with the 2002 spectra and the assumption that the spectrum is single-lined.

3. RESULTS AND DISCUSSION

Our results are presented in Figure 2, containing purely observational planes showing equivalent widths versus (dereddened) $(B - V)$ color. Several conclusions can be reached: first, our new data nearly remove the star-to-star scatter in the λ7699 K I equivalent widths seen in Soderblom et al. (1993) for our stars. While measurement uncertainty is therefore important in the Soderblom et al. (1993) results, this cannot be the source of most of the star-to-star Li dispersion in their data since this scatter (up to a factor of 2 in equivalent width for $0.72 \leqslant (B - V)_0 \leqslant 0.84$) persists in our own higher quality data. Second, the significant Li scatter in our projected slow rotators indicates that abundance errors due to blending features (Margheim et al. 2002) do not provide the primary explanation of the Pleiades Li scatter.

Finally, the vast extent of scatter in Li I compared to K I suggests that simple color or $T_{\rm eff}$ errors or the influence of an overlying chromosphere are not a significant source of star-to-star Li scatter in our Pleiades. Color or temperature errors would

lead to a similarly large dispersion in the similarly temperature-dependent K I lines that is absent in our data. Since the details of λ6707 Li I and λ7699 line formation in cool dwarfs are similar (Houdebine & Doyle 1995; Stuik et al. 1997), the dramatic difference between the Li and K in our Pleiades rules out differences in the global properties of overlying chromospheres as a sole or dominant source of the Li scatter. Indeed, our sample selection was made to mitigate such effects: as seen in Figure 1, our stars evince modest scatter in chromospheric emission compared to a more representative cluster sample. This is not to say that such differences are unimportant contributors to Li scatter in other samples (King & Schuler 2004). Indeed, even here the K I equivalent width of our reddest Pleiad (H II 298), which also possesses the largest chromospheric emission index in our sample, is anomalously large compared to a modest linear extrapolation of the K I–$(B - V)$ relation that can be seen to be linear as red as $(B - V)_0 \sim 1.4$ in Figure 1 of Randich (2001) for the 35 Myr IC 2602 cluster.

3.1. Photospheric Inhomogeneities

It is expected that surface magnetic activity (spots and plages) could alter Li I line strengths. Spatially resolved solar observations show variations by factors of ∼2 and 10 in the Li I equivalent width in spot and plage regions, respectively (Giampapa 1984). Patterer et al. (1993) have found Li I line strength variations in weak-lined T Tau stars that are not correlated with chromospheric emission variations, but are consistent in size with those expected from the simple spot/plage model of Giampapa (1984). Jeffries et al. (1994) find rotational modulation of the λ6707 (and/or nearby blended features) in the young Local Association K6 dwarf BD+22 4409.

One might think that the stark difference between the factor of ∼2 scatter in λ6707 Li I line strengths for $0.7 \leqslant (B - V)_0 \leqslant 0.8$ versus the absence of scatter in λ7699 K I over this same range is a powerful argument against spots as a source of Li scatter in our stars. Surprisingly, this is not necessarily the case. The influence of various analytic spot models on the location of Pleiades in the K, Li line strength versus color plane can be seen in Figures 3 and 6 of Barrado y Navascues et al. (2001). The models with the two lowest photosphere-spot temperature contrasts (their models 2a and 2b) and 80% spot coverage are able to displace stars redward and to higher Li I equivalent width into the $0.7 \leqslant (B - V)_0 \leqslant 0.8$ color range in such a way as to introduce a near factor of 2 scatter in Li line strength, but move stars nearly parallel to the intrinsic K I line strength versus color locus; i.e., the analytic spot models *can*, in fact, produce the Li I
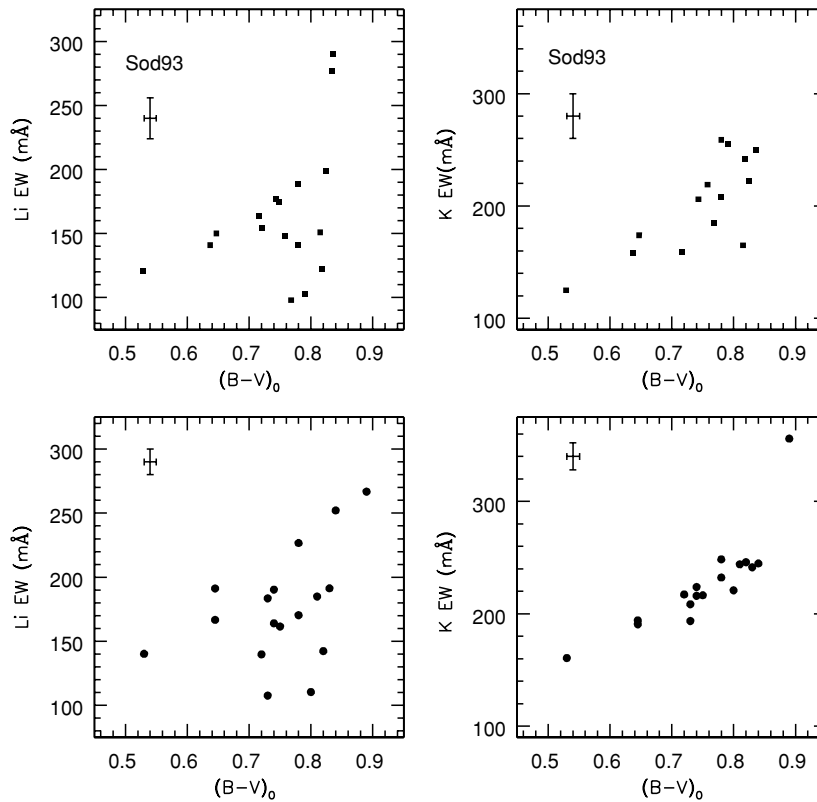
Figure 2. Top panels show λ6707 Li I (left panel) and λ7699 K I (right panel) equivalent widths from Soderblom et al. (1993) vs. dereddened $(B − V)$ color. The bottom panels show the (empirically deblended in the case of Li) equivalent widths measured from our HET/HRS spectra. Representative error bars are shown in the upper left of each panel.

scatter we observe while *not* introducing substantial scatter in the K line strengths.

As seen in Figure 2 of Barrado y Navascues et al. (2001), these models also move the Pleiades roughly parallel to the main-sequence in the H–R diagram such that significant photometric scatter, $\Delta V \geqslant 0.1$ mag, is not introduced either; such scatter is not evinced by our stars (Figure 3). Barrado y Navascues et al.'s (2001) larger photosphere-spot temperature contrast models (models 2c and 2d) can reproduce the observed scatter in Li line strengths with spot coverage fractions of ∼60%; however, their Figure 2 shows that such stars would be subluminous by $\Delta V \geqslant 1$ mag in the color–magnitude diagram. The photometric data in Figure 3 clearly excludes these large temperature contrast spot models. The large photosphere-spot temperature contrast models only modestly alter the star's color (Figure 2 of Barrado y Navascues 2001). As a result, a similar degree of scatter is introduced into the Li and K line strengths (Figures 3 and 8 of Barrado y Navascues et al. 2001)—a prediction also excluded by our spectroscopic data.

In sum, the marked difference between K I and Li I scatter cannot exclude a spot origin for the Li scatter in our Pleiades. While the indistinguishable spread of Li in the $(V − I)$– and V–Li EW planes (Figure 4) compared to that in the $(B − V)$-based plane of Figure 2 does not betray the presence of spots, two spectroscopic signatures do robustly exclude the analytic spot models 2a and 2b of Barrado y Navascues et al. (2001) as a source of the Li scatter. The first is the difference in Li abundances derived from the λ6707 Li I resonance line and the weaker blended 1.85 eV λ6103.6 Li I subordinate feature(s) previously investigated in the Pleiades by Ford et al. (2002). We selected several interesting sets of Pleiades of similar color but with significantly different λ6707 Li I line strengths (Table 2).

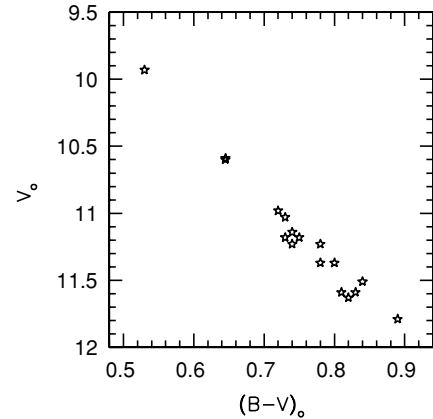**Figure 3.** Color–magnitude diagram of our Pleiades stars. The $\geqslant 1$ mag scatter in V implied by large photosphere-spot temperature contrast spot models of Barrado y Navascues et al. (2001) that might reproduce the Li line strength dispersion in Figure 2 is not present; any modest photometric scatter is not inconsistent with Barrado et al.'s smaller temperature contrast spot models, however.

Effective temperatures and microturbulent velocities are adapted from the spectroscopic parameters determined by Ford et al. (2002). Following these authors, we assumed $\log g = 4.5$ for all stars since the derived Li abundances are insensitive to the assumed gravity. We determined Li abundances from the λ6707 resonance line from our measured equivalent widths via Dr. A. Steinhauer's LIFIND program discussed in King & Schuler (2005); these are given in Column 6 of Table 2.

Abundances from the λ6104 Li I features were determined via spectral synthesis carried out with an updated version of the LTE analysis MOOG Sneden (1973) and Kurucz model
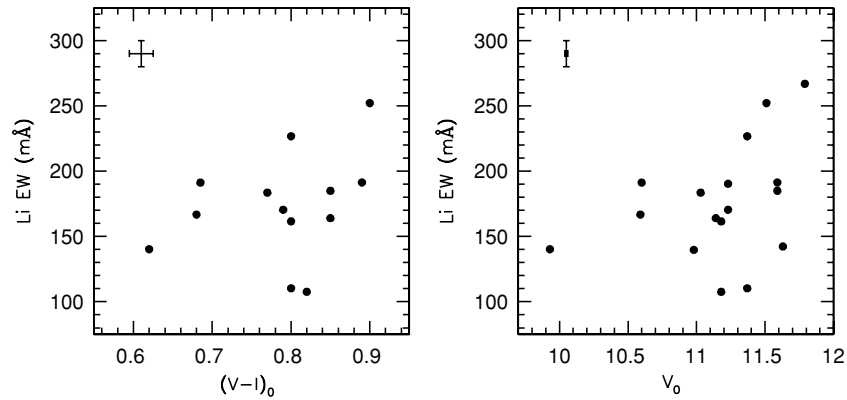
Figure 4. λ6707 Li I equivalent widths of our Pleiades sample vs. $(V - I)$ color (left panel) and V magnitude (right panel). Typical uncertainties are shown in the upper left of both panels.

Table 2
λ6707 Li I versus λ6104 Li I

Star H II	$(B - V)_o$	T_{eff} (K)	ξ (km s^{-1})	EW(6707) (mÅ)	A(Li) λ6707	A(Li) λ6104	ΔA(Li) λ6104–λ6707
250	0.645	5726	2.00	166.7	3.03	3.09	0.06
746	0.73	5383	2.10	107.6	2.31	2.33	0.02
1593	0.73	5383	2.10	183.5	2.75	2.73	−0.02
2284	0.74	5450	2.88	190.3	2.87	2.90	0.03
2311	0.78	5350	2.30	170.4	2.64	2.77	0.13
2366	0.78	5350	2.30	226.7	2.98	2.91	−0.07
2462	0.80	5283	2.15	110.3	2.21	2.37	0.16
2880	0.82	5250	2.15	142.3	2.36	2.30	−0.06
2126	0.81	5267	2.15	184.9	2.61	2.55	−0.06
916	0.83	5228	2.15	191.3	2.60	2.52	−0.08
263	0.84	5213	2.13	252.1	2.97	2.96	−0.01

atmospheres.[6] The λ6104 region line list was formed utilizing atomic data from the Vienna Atomic Line Database (Kupka et al. 2000) and Kurucz line data,[7] and CN data from Davis & Phillips (1963). The line list was calibrated by adjusting some oscillator strengths in order to produce solar syntheses matching the Kurucz solar flux atlas (Kurucz 2005) using input abundances from Anders & Grevesse (1989) except for CNO; solar values of $\log N(C) = 8.39$, $\log N(N) = 7.78$, and $\log N(O) = 8.68$ were adopted from Asplund et al. (2005) and Allende Prieto et al. (2001). The Pleiades syntheses assumed input scaled solar abundances with [m/H] = −0.06 based on the results of Ford et al. (2002)

Sample λ6104 Li I spectra and syntheses are shown in Figure 5. Abundances are given in the penultimate column of Table 2, whose final column lists the λ6104- and λ6707-based Li abundance differences. There are two notable features in the abundance comparisons. First, the significant Li scatter persists when measured from the λ6104 feature. Second, we find no significant difference between the resonance line- and subordinate line-based abundances. The mean difference (6104–6707) is +0.01 dex with small scatter (±0.08 dex, s.d.).

We find that the Barrado y Navascues et al. (2001) analytic spot models reproducing the observed Li dispersion of our sample in the range $0.7 \leqslant (B - V)_0 \leqslant 0.8$, lead to significantly larger predicted 6104–6707 Li differences. Syntheses of the λ6104 and λ6707 Li I regions—the latter using the line list from King et al. (1997) updated with VALD atomic data and
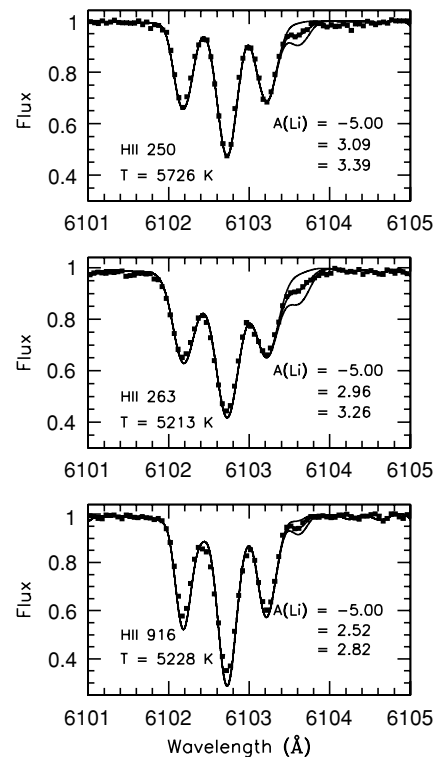

Figure 5. Observed (points) and synthetic (lines) spectra of the λ6103.6 Li I region in H II 250, 263, and 916 (top, middle, and bottom panels). The syntheses are shown for three input Li abundances for each star: no Li, the best-fit Li abundance, and a Li abundance 0.3 dex larger than the best-fit value.
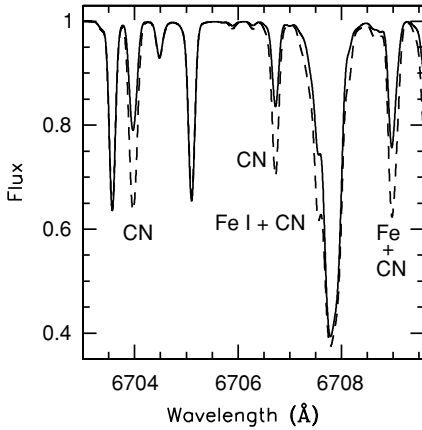

Figure 6. Dashed line: synthetic spectrum of the λ6707.8 Li I region for the Barrado y Navascues et al. (2001) analytic spot model 2a with T_{phot} = 5655 K (20% coverage) and T_{spot} = 4870 K (80% coverage), yielding a spotted model having $T_{eff} \sim 5225$ K. Solid line: synthetic spectrum for T_{eff} = 5225 K. All syntheses employ a 0.11 Å FWHM Gaussian smoothing and assume identical input abundances (solar) except for Li, for which log N(Li) = 2.8 was utilized. The CN features are significantly stronger in the spotted model.

recalibrated to the solar flux spectrum—were performed using the photosphere and spot parameters of models 2a and 2b with 80% spot coverage from Barrado y Navascues et al. (2001) assuming log g = 4.5, ξ = 2.0 km s^{-1}, [m/H] = −0.06, and an input abundance of log N(Li) = 2.80. The photospheric and spot spectra were weighted by their respective Planck functions and coverage fractions before adding and renormalizing.

The resulting λ6104 and λ6707 photosphere+spot spectra were analyzed as observed data via spectrum synthesis computed for T_{eff} = 5225 (the value of the spotted models consistent with flux conservation), log g = 4.5, ξ = 2.0, and [m/H] = −0.06. The λ6707 Li abundances deduced from the spotted synthetic spectrum are log N(Li) = 2.90 and 3.02 for spot models 2a and 2b, respectively. The corresponding λ6104 Li abundances are 3.32 and 3.62. The Li differences (6104–6707 Å) deduced from the two Li I lines—0.42 and 0.6 dex for spot models 2a and 2b—are significantly larger than the zero difference exhibited by our stars.

The second spectroscopic signature that is inconsistent with the analytic spot models reproducing the observed Li spread in our stars is the strength of CN lines in both the λ6104 and λ6707 region. The CN line depths in the T_{eff} = 5225 spotted synthetic spectra are some 3–5 times deeper than observed in our actual object spectra. Figure 6 illustrates a related important point: while the warmer photosphere (T_{phot} = 5655 K; 20% coverage) and cool spots (T_{spot} = 4870 K; 80% coverage) in model 2a of Barrado y Navascues et al. (2001) conspire to yield a spotted star of $T_{eff} \sim 5225$, the spectrum of such a model is not equivalent to that of an unspotted model with T_{eff} = 5225. Figure 6 indicates the CN features are significantly stronger in the spotted model.

3.2. Over-excitation and Over-ionization Effects

Schuler et al. (2004) find that our cool Pleiades' O abundances derived from the high-excitation O I λ7774 triplet in our spectra show a dramatic increase with declining T_{eff} and significant star-to-star scatter. Schuler et al. (2006b) show that photospheric hot spots provide a plausible explanation for this behavior. In order to examine whether the Li and O scatter are related, the λ6707-based Li and λ7774-based O abundances were fit as functions of T_{eff} using low-order polynomials. To ensure consistency for this
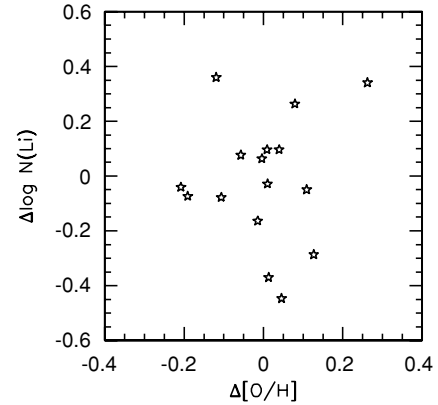

Figure 7. Residuals of Pleiades Li I abundances derived from our line strengths about a low-order T_{eff}-dependent polynomial vs. the residuals in λ7774-based O I abundances derived from the same spectra (Schuler et al. 2006b).

purpose, Li abundances were determined with LIFIND using the stellar parameters of Schuler et al. (2004); these were updated for H II 298 using our $(B - V)_0$ value, adjusting the Schuler et al. (2004) O abundance (to [O/H] = +0.80) in the process. The resulting abundance residuals (observed minus fitted), shown in Figure 7, are not correlated. Moreover, the rms dispersion of the observed Li abundances (∼0.22 dex) is twice that of the O abundances (∼0.12 dex) despite the fact that the temperature sensitivity of the (logarithmic) O abundances is 2–3 times larger than that for Li. We conclude that the dispersion in our Pleiades' Li is not associated with that in O I.

4. CONCLUSIONS, A PROPOSED EXPLANATION, AND FUTURE WORK

4.1. Summary and Key Conclusions

We have utilized high-resolution and high-S/N spectroscopy to measure λ6707 Li I and λ7699 K I line strengths and λ6707- and λ6104-based Li abundances in 17 slowly (projected) rotating cool Pleiades dwarfs. A significant factor of ∼2 dispersion is seen in the λ6707 Li I line strengths over the $0.72 \leqslant (B - V)_0 \leqslant 0.82$ color range; this large Li scatter is also inferred from λ6104 subordinate line-based abundances. The scatter in our selected sample eliminates line blending due to rapid projected rotation as a source of Li dispersion in our Pleiades. In contrast to previous studies, our high-resolution and S/N data evince no substantial scatter in the λ7699 K I line strengths of our particular Pleiad sample. This stark distinction relative to the Li line strengths excludes simple color or T_{eff} errors or line formation effects due to an overlying chromosphere as the source of Li scatter in our stars.

The difference in the dispersions of the K I and Li I line strengths does not, however, exclude spots as a source of the Li scatter; in particular, the analytic spot models 2a and 2b of Barrado y Navascues et al. (2001) can produce the Li scatter we observe without leading to significant scatter in K I line strengths or in the color–magnitude diagram. The equivalence of the λ6707- and λ6104-based Li abundances in our stars does, however, exclude these spot models, which predict a factor of $\geqslant 3$ difference in the resonance and subordinate line-based Li abundances. These spot models also would lead to CN line strengths significantly larger than observed in our spectra.

The simplest explanation of the Li I dispersion in our Pleiades is scatter due to real abundance differences. There are numerous candidate mechanism(s) to explain these pre- or

near-zero-age main sequence abundance differences: chemical inhomogeneities, magnetic field differences, variable mass accretion, and individual rotational histories (Ventura et al. 1998; Garcia Lopez et al. 1994). While the effects of chromospheres on Li I line formation and the effects of rotation on measurements of the Li I line strength espoused by King & Schuler (2004) and Margheim et al. (2002) may contribute to an (illusory) Li dispersion, our results suggest that there must also be a real component to the Pleiades Li dispersion—at least over the range $0.7 \lesssim (B - V)_0 \lesssim 0.8$ seen in Figure 2.

The size of the real component is difficult to determine directly; however, future work can deduce the size and mass range of real scatter since sources of possible illusory dispersion are amenable to observation. Systematic effects of rotation on Li abundance *measurement* of rapid rotators or from low spectral resolution (neither characterize our data) can be mitigated by determining abundances from spectrum syntheses with suitable accounting of macroscopic broadening. The influence of chromospheric emission and surface magnetic activity (spots and plages) on Li I (and K I) lines can be measured by searching for correlated temporal variations in alkali line strength and chromospheric emission and photometric indices via a simultaneous spectroscopic and photometric monitoring program of the Pleiades (Jeffries 1999). Our Li equivalent widths and those of Soderblom et al. (1993) for five stars (H II 152, 263, 2126, 2311, and 2366) differ at the $\geqslant 2\sigma$ level, providing impetus for such a program. Additional constraints may be gleaned from observations of ^{9}Be in our cool Pleiades, as well as in similarly cool Hyades stars, whose degree of Li scatter is unknown due to vanishingly weak Li line strengths (Soderblom et al. 1995).

4.2. A Proposed Differential Pre-MS Li Burning Mechanism

We believe that the most likely theoretical explanation of a real star-to-star Li dispersion in the Pleiades is a range in pre-MS lithium depletion. Such a range would naturally emerge if the radii of protostars of the same mass, composition, and age during the epoch of pre-MS lithium depletion were somehow different. To explain the empirical trend, one would also require the more rapidly rotating and active stars to have been larger. There is now emerging evidence that activity impacts the radii of both main-sequence and pre-MS stars in precisely this sense. Torres & Ribas (2002) found that the radii of the near-twin stars in YY Gem were far too large to be consistent with the predictions of standard stellar theory. Subsequent data confirmed this result, and Morales et al. (2008) found a correlation between activity and the radius excess in low mass stars. Berger et al. (2006) also found this to be a relatively common phenomenon in their measurements of the radii of field M stars, although it is more challenging to perform a rigorous test in the absence of direct mass constraints in such systems. Andronov & Pinsonneault (2004), in a study of cataclysmic variable systems, found that excess activity could induce radius changes of the proper order of magnitude (see also Chabrier et al. 2007).

The physical mechanism linking activity-related radii differences with those in Li depletion is that spots inhibit convective energy transport, requiring the star to carry the flux through a smaller effective volume. The star therefore requires a larger radius, corresponding to an effective reduction in the mixing length or efficiency of energy transport. This in turn reduces pre-MS lithium burning because the central temperature and pressure of a star is decreased if the radius is increased. We performed a simple numerical test of this phenomenon. A 10%

difference in radius (of order seen in active eclipsing binaries) during standard pre-MS convective burning for a 0.9 $M_\odot$ solar abundance model led to a factor of 2.5 increase in the remaining surface lithium abundance at an age of 100 Myr relative to an inactive model with the same mass but a smaller radius. How the spot properties of single pre-MS stars (the precursors of our Pleiad sample) compare to those of active binaries remains an open question. Some meaningful context, however, might be provided by chromospheric emission fluxes. We note that the log R'(HK) indices for active solar-type binaries widely range from -4.4 to -3.3 at a given color or Rossby number (Figure 4 of Montes et al. 1996), while the corresponding Pleiades (pseudo-)indices (which must be transformed from Hα and Ca II infrared triplet data) widely range from -4.5 to -3.5 (Figure 3 of King et al. 2003); i.e., active binaries show wide chromospheric emission at the same levels and with similar wide dispersion as present-day Pleiades.

When/if spot filling factors are reduced subsequent to pre-MS Li depletion, stars would converge to similar radii, but would retain a fossil record of their differences in earlier stages. If more spotted stars on the main sequence retained their lower effective temperatures, one would also shift more massive (and less depleted) stars to the same effective temperature as less massive (and more depleted) bare stars, further amplifying the apparent Li dispersion. There is evidence that activity can differentially impact protostellar radii. Stassun et al. (2007) found a reversal in the predicted $T_{\rm eff}$–radius relationship between a more active primary and a less active secondary of a brown dwarf binary system in the young (1 Myr) Orion Nebula Cluster.

Our suggested explanation of the Pleiades Li dispersion has several attractive features. It explains why the dispersion is large among cooler stars, which experience significant pre-MS depletion, compared to hotter stars, and the propensity for more rapidly rotating (and perhaps more spotted) cool dwarfs to exhibit larger Li line strengths. It can also qualitatively explain the apparent narrowing of dispersion in cool main-sequence stars in older open clusters as follows. Beyond the Pleiades age, more heavily spotted and rapidly rotating stars deplete more Li than barer and more slowly rotating stars due to rotationally induced main-sequence mixing; as spottedness declines with increasing age and stellar radii concomitantly relax, the former stars also become hotter relative to the latter stars. The combined effect would be a reduction in the star-to-star dispersion in cool cluster Li abundances that is controlled by the timescales of stellar angular momentum loss and spot coverage diminution. Because the former timescale could, in principle, be longer than the latter, the passage of additional time would then witness the resurgence of substantial Li dispersion due to rotationally induced main-sequence mixing acting in stars whose radii and temperatures are no longer scattered due to surface inhomogeneities. This is not inconsistent with the observation that the ratio of rapid and slow rotators in the $\sim$100 Myr Pleiades is the inverse of that of Li-rich and -poor solar mass stars in the 4.6 Gyr cluster M67 (Jones et al. 1999). Our suggested explanation, which recognizes the importance of surface inhomogeneities on stellar radii and possible differences in time evolution of rotationally induced mixing and spot coverage, dovetails with the important observational picture painted by Jones et al. (1999): a significant Li dispersion in cool dwarfs in very young clusters such as the Pleiades that markedly declines in intermediate age clusters such as M34 and the Hyades, and then reappears in older clusters such as M67. We caution, though, that the dwarf Li abundances in M67 are

available only for stars of $T_{eff} \geqslant 5500$–5600 K; abundances in lower mass M67 dwarfs akin to our cooler Pleiades have not yet been determined. It should also be noted that a variety of observational studies (e.g., Piau et al. 2003; Randich et al. 2007; Jeffries et al. 2002) have suggested other mechanisms besides or in addition to rotationally induced mixing as the source of main-sequence Li depletion and explaining the resulting main-sequence Li–T_{eff} morphologies manifested by open cluster data.

4.3. Related Stellar Phenomena and Future Work

It is also tempting to speculate that the starspot-radius mechanism might be connected with other puzzling stellar phenomena. The alleged existence of a gap (or gaps) in the number distribution of Pop I main-sequence stars Mendoza (1956); Bohm-Vitense (1970); Rachford & Canterna (2000) around $(B - V) \sim 0.3$ could be accommodated if this color corresponds to the onset of surface spot formation driving stars to lower T_{eff} values compared to bluer barer stars. The accompanying increase in stellar radii might give rise to the surprising number of luminosity class II–IV stars that reside in the main-sequence region of the Hipparcos-based H–R diagram (Newberg & Yanny 1998). The precipitous rise in apparent [Fe II/H] abundances and more gradual but nevertheless surprising rise in apparent [Fe I/H] abundance in the Hyades with declining T_{eff} (Yong et al. 2004), the rise in high-excitation permitted [O I/H] abundances with declining T_{eff} in the Hyades and the even steeper rise in the younger Pleiades (Schuler et al. 2006b), the rise in forbidden line-based [O I/H] abundances with declining T_{eff} in the Hyades (Schuler et al. 2006a), the rise in [Si I/H] abundances with declining T_{eff} in M34 (Schuler et al. 2003) are at least qualitatively consistent with a T_{eff}-dependent disparity between spot-adjusted radii and assumed standard stellar radii. Such a disparity would lower log g with declining T_{eff}; the sensitivity of the features noted above is such that lowering log g increases their line strengths in cool dwarfs.

Future observational work is needed to confirm these speculative connections; quantifying or parameterizing spot coverage and properties rather than chromospheric emission indices per se that are used as measures of "activity" will be of particular importance. Such work includes: continued exploration of the reality of main-sequence gaps in open clusters, their evolution with age, and the spot properties of stars adjacent to these gaps; understanding the nature of luminosity class II–IV stars, in particular spot properties and physical radii, near the main-sequence region of the H–R diagram; the spot properties of stars as a function of T_{eff} in the Pleiades, M34, and Hyades open clusters, and their association with the abundance anomalies (especially star-to-star variations in permitted line [O I/H] values in cool Pleiades and Hyads) listed above.

A possible signature of the mechanism we propose here is the Li/Be ratio in stars sufficiently cool and old to suffer main-sequence mixing of ^{9}Be, but not so cool as to have suffered pre-MS convective burning of ^{9}Be. Such rotationally induced main-sequence mixing would deplete more Be (and Li) in stars with larger initial rotational velocities; however, if such stars were more heavily spotted, they suffered reduced pre-MS convective burning of Li; depending on the balance of spot-induced retarded pre-MS Li depletion and rotation-induced enhanced MS Li depletion, this effect could create a population of higher Li/lower Be stars whose number depends upon the initial distribution of rotation, its time evolution, and age. Identifying such stars using extant disk field abundance data is difficult given differences in stellar structure due to metallicity

differences, unknown relative initial Li and Be abundances, and a dispersion in age. Such a search is best carried out in cool dwarfs of open clusters of at least intermediate (e.g., Hyades) age. For the purpose of constraining the origin of Li scatter in the Pleiades, a monitoring program to identify short- (days) and long- (years) term variations in Li I line strengths and spot properties is critical. If our proposed origin of the Pleiades Li dispersion is correct, we expect to see variations in Li line strength that are consistent only with changes in photospheric structure/parameters and the details of spot-included radiative transfer alone; once these variations are accounted for, a significant dispersion in Li line strength should remain as a relic of spot-induced differences in pre-MS Li burning. While observationally challenging, these future observational programs (accompanied by detailed modeling of pre-MS Li depletion in stars of various spotted conditions) will be required to fully understand the magnitude, mass distribution, and thus the ultimate origin of real star-to-star Li dispersion in the Pleiades.

REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Andronov, N., & Pinsonneault, M. H. 2004, ApJ, 614, 326
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes III & F. N. Bash (San Francisco, CA: ASP), 25
Balachandran, S., Lambert, D. L., & Stauffer, J. R. 1996, ApJ, 470, 1243
Barrado y Navascues, D., Garcia Lopez, R. J., Severino, G., & Gomez, M. T. 2001, A&A, 371, 652
Berger, D. H., et al. 2006, ApJ, 644, 475
Boesgaard, A. M., Armengaud, E., & King, J. R. 2003, ApJ, 582, 410
Bohm-Vitense, E. 1970, A&A, 8, 283
Carlsson, M., Rutten, R., Bruls, J. H. M. J., & Shchukina, N. G. 1994, A&A, 288, 860
Chabrier, G., Gallardo, J., & Baraffe, I. 2007, A&A, 472, L17
Davis, S. P., & Phillips, J. G. 1963, The Red System of the CN Molecule (Berkeley, CA: Univ. California Press)
Deacon, N. R., & Hambly, N. C. 2004, A&A, 416, 125
Duncan, D. K., & Jones, B. F. 1983, ApJ, 271, 663
Fitzpatrick, M. J., & Sneden, C. 1987, BAAS, 19, 1129
Ford, A., Jeffries, R. D., & Smalley, B. 2002, A&A, 391, 253
Garcia Lopez, R., Rebolo, R., & Martin, E. L. 1994, A&A, 282, 518
Giampapa, M. S. 1984, ApJ, 277, 235
Herbig, G. H. 1965, ApJ, 141, 588
Houdebine, E. R., & Doyle, J. G. 1995, A&A, 302, 861
Iben, I., Jr. 1965, ApJ, 141, 993
Jeffries, R. D. 1999, MNRAS, 309, 189
Jeffries, R. D. 2006, in ESO Astrophysics Symp., Chemical Abundances and Mixing in Stars in the Milky Way and its Satellites, ed. S. Randich & L. Pasquini (Berlin: Springer), 163
Jeffries, R. D., Byrne, P. B., Doyle, J. G., Anders, G. J., James, D. J., & Lanzafame, A. C. 1994, MNRAS, 270, 153
Jeffries, R. D., Totten, E. J., Harmer, S., & Deliyannis, C. P. 2002, MNRAS, 336, 1109
Jones, B. F. 1973, A&AS, 9, 313
Jones, B. F., Fischer, D., & Soderblom, D. R. 1999, AJ, 117, 330
Kholopov, P. N., Samus, N. N., Kazarovets, E. V., Frolov, M. S., & Kireeva, N. N. 1989, IBVS, 3323, 1
King, J. R., Deliyannis, C. P., Hiltgen, D. D., Stephens, A., Cunha, K., & Boesgaard, A. M. 1997, AJ, 113, 1871
King, J. R., Krishnamurthi, A., & Pinsonneault, M. H. 2000, AJ, 119, 859 (KKP)
King, J. R., & Schuler, S. C. 2004, AJ, 128, 2898
King, J. R., & Schuler, S. C. 2005, PASP, 117, 911

King, J. R., Villarreal, A. R., Soderblom, D. R., Gulliver, A. F., & Adelman, S. J. 2003, AJ, 125, 1980

Kupka, F. G., Ryabchikova, T. A., Piskunov, N. E., Stempels, H. C., & Weiss, W. W. 2000, Balt. Astron., 9, 590

Kurucz, R. L. 2005, Mem. Soc. Astron. Ital. Suppl., 8, 189

Magniitsky, A. K. 1987, Pis'ma Astron. Zh., 13, 1071

Margheim, S. J., Deliyannis, C. P., King, J. R., & Steinhauer, A. 2002, BAAS, 34, 1307

Mendoza, E. E. 1956, ApJ, 123, 54

Mermilliod, J.-C., Rosvick, J. M., Duquennoy, A., & Mayor, M. 1992, A&A, 265, 513

Montes, D., Fernandez-Figueroa, M. J., Cornide, M., & de Castro, E. 1996, A&A, 312, 221

Morales, J. C., Ribas, I., & Jordi, C. 2008, A&A, 478, 507

Newberg, H. J., & Yanny, B. 1998, ApJ, 499, L57

Pasquini, L., Randich, S., & Pallavicini, R. 1997, A&A, 325, 535

Patterer, R. J., Ramsey, L., Huenemoerder, D. P., & Welty, A. D. 1993, AJ, 105, 1519

Piau, L., Randich, S., & Palla, F. 2003, A&A, 408, 1037

Pinsonneault, M. 1997, ARA&A, 35, 557

Pinsonneault, M. H., Kawaler, S. D., & Demarque, P. 1990, ApJS, 74, 501

Queloz, D., Allain, S., Mermilliod, J.-C., Bouvier, J., & Mayor, M. 1998, A&A, 335, 183

Rachford, B. L., & Canterna, R. 2000, AJ, 119, 1296

Randich, S. 2001, A&A, 377, 512

Randich, S., Pallavicini, R., Meola, G., Stauffer, J. R., & Balachandran, S. C. 2001, A&A, 372, 862

Randich, S., Primas, F., Pasquini, L., Sestito, P., & Pallavicini, R. 2007, A&A, 469, 163

Ryan, S. G., & Deliyannis, C. P. 1995, ApJ, 453, 819

Schilbach, E., Robichon, N., Souchay, J., & Guibert, J. 1995, A&A, 299, 696

Schuler, S. C., Hatzes, A. P., King, J. R., Kurster, M., & The, L.-S. 2006a, AJ, 131, 1057

Schuler, S. C., King, J. R., Fischer, D. A., Soderblom, D. R., & Jones, B. F. 2003, AJ, 125, 2085

Schuler, S. C., King, J. R., Hobbs, L. M., & Pinsonneault, M. H. 2004, ApJ, 602, L117

Schuler, S. C., King, J. R., Terndrup, D. M., Pinsonneault, M. H., Murray, N., & Hobbs, L. M. 2006b, ApJ, 636, 432

Sneden, C. 1973, ApJ, 184, 839

Soderblom, D. R., Jones, B. F., Balachandran, S., Stauffer, J. R., Duncan, D. K., Fedele, S. B., & Hudon, J. D. 1993, AJ, 106, 1059

Soderblom, D. R., Jones, B. F., Stauffer, J. R., & Chaboyer, B. 1995, AJ, 110, 729

Stassun, K. G., Mathieu, R. D., & Valenti, J. A. 2007, ApJ, 664, 1154

Stuik, R., Bruls, J. H. M. J., & Rutten, R. J. 1997, A&A, 322, 911

Torres, G., & Ribas, I. 2002, ApJ, 567, 1140

Ventura, P., Zeppieri, A., Mazzitelli, I., & D'Antona, F. 1998, A&A, 331, 1011

Wallerstein, G., Herbig, G. H., & Conti, P. S. 1965, ApJ, 141, 610

Weymann, R., & Sears, R. L. 1965, ApJ, 142, 174

Wilden, B. S., Jones, B. F., Lin, D. N. C., & Soderblom, D. R. 2002, AJ, 124, 2799

Yong, D., Lambert, D. L., Allende Prieto, C., & Paulson, D. B. 2004, ApJ, 603, 697