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A SEARCH FOR LITHIUM IN PLEIADES BROWN DWARF CANDIDATES USING THE KECK HIRES ECHELLE[1]

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ABSTRACT

We report Keck Observatory high-resolution echelle spectra of lithium at 670.8 nm in two of the lowest luminosity brown dwarf candidates in the Pleiades. These objects have estimated masses of 0.055–0.059 $M_\odot$ from their location on a color-magnitude diagram relative to theoretical isochrones. Stellar interior models predict that Li has not burned in them. However, we find no evidence of the Li line, at limits 100–1000 times below the initial abundance. This indicates that Li has in fact been depleted, presumably by nuclear processing as occurs in Pleiades stars. Interior models suggest that such large Li depletion occurs only for objects with $M > 0.09\ M_\odot$ at the age of the Pleiades. *Thus, it is unlikely that the candidates are brown dwarfs.* The brown dwarf candidates present a conflict: either they have masses greater than suggested from their placement on the H-R diagram, or they do have the very low suggested masses but are nonetheless capable of destroying Li, in only 70 Myr. Until this dilemma is resolved, the photometric identification of brown dwarfs will remain difficult. Resolution may reside in higher $T_{\rm eff}$ derived from optical and IR colors or in lower $T_{\rm eff}$ in the interior models.

Subject headings: open clusters and associations: individual (Pleiades) — stars: abundances — stars: interiors — stars: low mass, brown dwarfs

1. INTRODUCTION

No definitive detections of brown dwarfs have been made, despite their important implications in several disciplines of astrophysics (for reviews see Burrows & Liebert 1993; Bessell & Stringfellow 1993). Several candidates have been identified both in the general field and as companions to nearby stars (Kirkpatrick 1994; Henry & McCarthy 1993; Tinney 1993; Zuckerman & Becklin 1992), but they lack precise ages and masses. Recently, brown dwarf candidates have been found in open clusters from their location on IR color-magnitude diagrams as compared to theoretical models: Hyades (Bryja et al. 1992), ρ Oph cluster (Comeron et al. 1993), Pleiades (Stauffer et al. 1989; Simons & Becklin 1992; Steele, Jameson, & Hambly 1993, hereafter SJH).

The Pleiades brown dwarf candidates are compelling because of the secure cluster membership afforded by proper motions (Hambly, Hawkins, & Jameson 1993, hereafter HHJ). *JHK* photometry of the objects by SJH has permitted placement of the objects on a color-magnitude diagram along with corresponding theoretical tracks. Figure 5 of SJH presents I versus $I-K$ for 22 cluster members which appear to have masses less than 0.08 $M_\odot$ and therefore lie at or below the hydrogen-burning limit. The implied ages range from 70 Myr (nominal age of the Pleiades; Stauffer et al. 1989) to 10 Myr.

To assess the brown dwarf status of the HHJ objects, we have carried out the lithium test, proposed by Rebolo, Martin, & Magazzu (1992) and Magazzu, Martin, & Rebolo (1993). The premise is that lithium is not depleted by nuclear reactions in low-mass brown dwarfs, and thus its presence spectroscopically establishes their brown dwarf status. Lithium burns at $T > 2.5 \times 10^6$ K, and interior models predict that by Pleiades age, objects having 0.10 $M_\odot$ have depleted essentially all their Li, while objects having 0.08 $M_\odot$ have retained about 70% of their initial Li (Nelson, Rappaport, & Chiang 1993; Bessell & Stringfellow 1993). Bona fide brown dwarfs having 0.07 $M_\odot$ are predicted to retain 95% of their Li at that age. Li abundances greater than 20% of the Galactic disk value yield an easily detectable absorption line (670.8 nm), thus rendering identifiable those Pleiades objects having $M < 0.09\ M_\odot$. At higher masses, H-burning Pleiades M dwarfs exhibit little Li, consistent with models (Garcia Lopez et al. 1991; Soderblom et al. 1993; Jones & Soderblom 1994). Thus, the presence of lithium in a Pleiades brown dwarf candidate would signal both an upper limit to the core temperature and strong evidence of brown dwarf status via the de facto absence of nuclear burning, albeit at a slightly lower temperature than the *p-p* reaction.

2. TARGET SELECTION AND HIRES SPECTRA

We selected two of the faintest Pleiades brown dwarf candidates from SJH, namely, HHJ 3 and HHJ 14, which have inferred masses of 0.055 and 0.059 $M_\odot$, respectively. HHJ 3 is their faintest brown dwarf candidate with complete photometry and is nearly as faint as the candidates of Stauffer et al. (1989), but it is ~2 mag brighter than the candidates of Simons & Becklin (1992), which await confirmation of membership. HHJ 3 and HHJ 14 represent two of the lowest mass objects known in the Pleiades or in any open cluster.

Object coordinates and finding charts were taken from HHJ. Comparison field stars of similar $I-K$ color were drawn from Leggett (1992), namely, LHS 1070, LHS 36, LHS 248, and LHS 292 (Luyten & Albers 1979). From photometric considerations, these four M dwarfs have ages greater than 1 Gyr and masses of 0.085–0.13 $M_\odot$, and thus are expected to have depleted their lithium. We also observed the extremely young low-

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mass T Tauri star UX Tau C (age ≈ 2×10^6 yr, $M = 0.08$–$0.2\ M_\odot$), which has not yet depleted its lithium (Jones & Herbig 1979; Magazzu, Martin, & Rebolo 1991).

Observations were made on 1993 November 11 UT with the W. M. Keck 10 m telescope on Mauna Kea using the HIRES echelle spectrometer (Vogt 1992). The instrument yielded 15 spectral orders from 640 to 860 nm (with small missing gaps between orders), detected with a Tektronix 2048^2 CCD having pixels of size 24 μm, and binned 2×2, the bins hereafter referred to as individual "pixels." Each pixel covered 99 mÅ, and use of slit decker "D1" gave a slit width of 1".15 projected on the sky, corresponding to 2 pixels on the CCD and a resolution $R = 31{,}000$. The CCD exhibited a dark count of $\sim 2e^-$ hr^{-1} and readout noise of $5e^-$ per pixel.

Spectra were flat-fielded by dividing by exposures of an incandescent lamp using the same slit height as for the stellar spectra, 36 pixels. A slit function was found by mashing the order in the dispersion direction to assess where the spectrum faded to 10% of the sky value, yielding a width of 6 pixels. Sky was removed in each column by averaging the median value on either side of the stellar spectrum, thus eliminating effects from cosmic rays. To smooth the pixelization effects due to tilted orders, we extracted the image along arcs with careful accounting of the fractional pixel contributions. Then the stellar spectrum was optimally extracted using a version of the method given in Horne (1986). A wavelength scale was established using the Th-Ar spectrum, achieving an accuracy of ~0.003 nm. Radial velocity shifts were removed from the spectra using cross-correlations. For the reduction of UX Tau C, contamination from UX Tau A was removed by fitting a double Gaussian to the slit function, enabling subtraction of UX Tau A.

3. THE LITHIUM SPECTRA AND RESULTS

All program stars are listed in Table 1, which gives names from HHJ, R magnitude, $I-K$ color (from SJH and Leggett 1992), exposure times, estimated signal-to-noise ratio per pixel, and measured Li equivalent widths (or upper limits) derived from these spectra. Figure 1 shows the spectra of HHJ 3, HHJ 14, UX Tau C, and the average of four field M dwarfs of similar $I-K$ color. For UX Tau C, the Li line at 670.8 nm is clearly visible in absorption. For HHJ 3 and HHJ 14, the Li line is apparently absent. The general appearance of the HHJ spectra (i.e., TiO bandhead at 668.0 nm) is similar to the M6 field stars (top of Fig. 1), indicating similarity of spectral type. Both HHJ spectra showed Hα in emission, with $W_{\rm eq} = 5 \pm 1$ Å, which supports their membership in the Pleiades. None of the field M dwarfs show the Li line. A detailed view of the region near the Li line is exhibited in Figure 2, showing the two HHJ objects overplotted on the spectrum of UX Tau C. This illustrates the severe reduction of the Li line in the brown dwarf candidates, relative to an undepleted T Tauri star of similar spectral type.

We measured the equivalent width of the Li line in UX Tau C by first assessing the "continuum" within 1 nm of the Li line at 670.8 nm. The continuum determination is complicated by

TABLE 1

PROGRAM STARS

Name	R (mag)	$I-K$ (mag)	Exposure Time (s)	S/N	$W_{\rm eq}$(Li) (mÅ)
HHJ 3	19.6	3.30	10800	15	<190
HHJ 14	18.9	3.30	5866	20	<180
UX Tau C	15:	2.9:[a]	1800	30	620 ± 40
LHS 1070	13.7	3.40	600	50	<80
LHS 36	11.6	3.31	120	50	<80
LHS 248	12.8	3.27	600	50	<80
LHS 292	13.5	3.24	600	30	<80

[a] $I-K$ estimated from $T_{\rm eff} = 2800$ K (Magazzu et al. 1991; Leggett 1992).

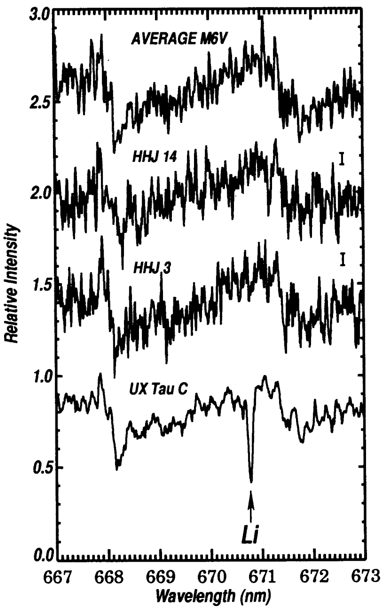

FIG. 1.—Spectra of program stars near the Li line at 670.8 nm. The continuum is unity, and spectra are boxcar-smoothed with a width of 3 pixels. *Top spectrum*: average of four field M6 dwarfs, showing no Li. All visible spectral features are intrinsic (mostly TiO) to the star; the noise is ≈1% of the continuum. *Middle two spectra*: two Pleiades brown dwarf candidates, neither showing the Li line. The error bar indicates noise from photon statistics. *Bottom spectrum:* T Tauri star, UX Tau C, showing Li due to its extreme youth, and rotational broadening. The noise is ≈3%.

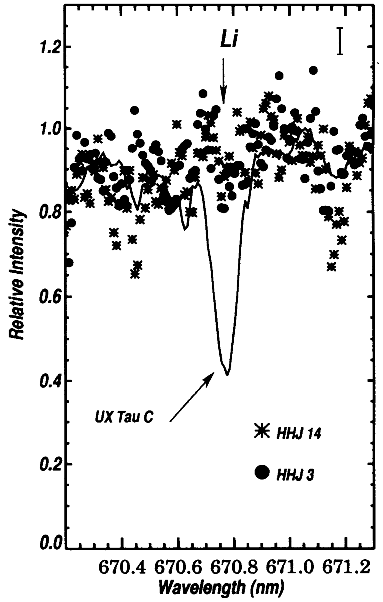

FIG. 2.—Detailed plot of the Li line for both Pleiades brown dwarf candidates, HHJ 3 and HHJ 14, and for the T Tauri star UX Tau C. The brown dwarf candidates show no Li, demonstrating severe depletion.

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the presence of TiO features with depths ~20% of peak flux. The continuum was set by fitting a straight line to the highest flux points at 670.5 and 671.0 nm. The result is $W_{\rm eq} = 620 \pm 40$ mÅ for UX Tau C. The uncertainty represents the scatter in $W_{\rm eq}$ obtained with different continuum placements. We redetermined $W_{\rm eq}$ by synthesizing the Li line in UX Tau C, using a Gaussian superposed on the field dwarf spectrum and applying artificial rotational broadening. This yielded $W_{\rm eq} =$ 630 mÅ. For comparison, Magazzu et al. (1991) found $W_{\rm eq} =$ 800 ± 100 mÅ. Intrinsic Li variations due to changing starspots could account for the difference (Patterer et al. 1993).

We measured $W_{\rm eq}$(Li) upper limits for the two Pleiades brown dwarf candidates by several methods. We first synthesized the spectra of HHJ 3 and HHJ 14 by adopting the Li spectrum of UX Tau C as a "template" and adding Gaussian noise of 15%, equal to that in the actual spectra. We successively diluted the Li line in this template by adding artificial continuum, until the Li line became just barely visible against the forest of nearby TiO lines. The TiO lines are smeared by rotational Doppler broadening of 28 ± 7 km s^{-1} in UX Tau C, which thereby masks the amount of TiO contamination. We demanded that the synthetic Li line exceed the depths of the strongest TiO features, to ensure detection. Thus, we judged the $W_{\rm eq}$ upper limit for both HHJ 3 and HHJ 14 to be 25% of that in UX Tau C, i.e., $W_{\rm eq} < 160$ mÅ for both. We carried out a similar measurement, using BP Tau (K7), which suffers little rotational broadening (Basri & Batalha 1991), as a template. This approach yielded $W_{\rm eq} < 200$ mÅ for HHJ 3 and HHJ 14. Finally, we estimated upper limits to the Li $W_{\rm eq}$ in HHJ 3 and HHJ 14 by simply integrating their spectra directly, within 0.2 nm centered on the expected location of the Li line. This $W_{\rm e}$ is influenced by both intrinsic noise and TiO, representing the noise pattern against which any Li line must compete. We obtained $W_{\rm eq}$(HHJ 3) $< 190 \pm 40$ mÅ and $W_{\rm eq}$(HHJ 14) $< 180 \pm 40$ mÅ. The final upper limits listed in Table 1 represent the averages of the three methods.

The four (LHS) M dwarfs also showed no detectable Li (Fig. 1), as expected from nuclear depletion at the typical ages and masses of these field stars. To establish $W_{\rm eq}$ upper limits, we divided each spectrum by the (co-aligned) mean of all four field spectra. This division suppressed the TiO features in each individual spectrum. The presence of the Li line in just one of these stars would reveal itself as residual absorption at 670.8 nm. We integrated these TiO-suppressed spectra within a bandpass of 0.2 nm, centered on 670.8 nm, to obtain the $W_{\rm eq}$. These $W_{\rm eq}$ measures include Li absorption (if any) as well as contributions from noise and residual TiO lines. They were adopted as Li $W_{\rm eq}$ upper limits, given in Table 1.

4. DISCUSSION

4.1. *Lithium Abundances*

The absence of the Li line in both brown dwarf candidates marks real depletion of Li in their photospheres, rather than an effect of inadequate spectroscopy or unanticipated photospheric physics (i.e., continuous opacity or conversion to LiH). The comparison stars, UX Tau C and the field M dwarfs, display similar IR colors and TiO bandhead strengths (Fig. 1) to those of the brown dwarf candidates, attesting to similarity in $T_{\rm eff}$ and gravity. The presence of the 670.8 nm Li line in UX Tau C demonstrates that in such photospheres Li remains atomic (rather than in the form of LiH) and, when not depleted, produces an easily detectable absorption feature. The absence of the Li line in the Pleiades M dwarfs demonstrates that Li suffers depletion by at least a factor of 1000 in H-burning stars on a timescale less than the Pleiades age (Jones & Soderblom 1994; Garcia Lopez et al. 1994). Clearly, HHJ 3 and HHJ 14 have also suffered significant depletion of Li. Martin, Rebolo, & Magazzu (1994a) report a similar Li depletion for a third brown dwarf candidate, namely, HHJ 10 = STAUFF 10 (Stauffer et al. 1989).

The $W_{\rm eq}$ upper limits for the brown dwarf candidate lie ~4 times below the $W_{\rm eq}$ found in the T Tauri star, UX Tau C, which because of its youth has retained its initial Li abundance, log N(Li) ≈ 3 (Basri, Martin, & Bertout 1991; Martin et al. 1994b), where log N(H) = 12. The Pleiades F dwarfs also exhibit an undepleted abundance of Li, log N(Li) = 3.2 (Soderblom et al. 1993). Assuming a uniform initial Li abundance among Pleiades members, we conclude that the absence of the Li line in HHJ 3 and HHJ 14, compared with the T Tauri star, directly demonstrates significant Li depletion in them. If the Li line were on the linear portion of the curve of growth, one would infer that the HHJ objects have a Li abundance one-fourth that of UX Tau C. Since the Li line is significantly saturated, the actual Li abundance is much less and its determination requires knowledge of the line transfer through precise M dwarf atmospheres.

Duncan (1991) and Soderblom et al. (1993) provide theoretical LTE curve-of-growth tables that associate N(Li) with $W_{\rm eq}$ for $T_{\rm eff} = 4000$ K, higher than that of HHJ 3 and HHJ 14 (~2800 K), thus casting doubt on the applicability of the tables. We tested them via the known $W_{\rm eq}$ and Li abundance of UX Tau C, finding agreement within 20% of log N(Li). Using the Soderblom tables, we find that the upper limits of $W_{\rm eq}$ yielded log N(Li) < 1.1 for HHJ 3 and HHJ 14. NLTE line transfer calculations for Li have recently been done which use superior atmospheres, opacities, and line transfer treatment (Martin 1993; Martin et al. 1994b). These calculations show that the upper limits of Li $W_{\rm eq}$ for HHJ 3 and HHJ 14 imply log N(Li) < 0.0. *Thus, the HHJ brown dwarf candidates have retained at most* 1% *to* 0.1% *of their initial* Li, *based on current line transfer calculations.*

4.2. *Masses of the Brown Dwarf Candidates*

Lower mass objects burn Li more slowly due to lower central temperatures (Nelson et al. 1993; Burrows & Liebert 1993), and the models of Nelson et al. show that, at the nominal age (70 Myr) of the Pleiades, only those stars having mass $M > 0.09\ M_\odot$ will have depleted at least 80% of their Li (see their Fig. 1), as observed for HHJ 3 and HHJ 14. Objects of lower mass will have retained most of their Li. The models of Bessell & Stringfellow (1993) lead to the same conclusion. Lower masses are admissible if one adopts an extreme Pleiades age of 200 Myr, for which objects having mass $M > 0.065\ M_\odot$ will have depleted 80% of their initial Li, marginally consistent with the nondetections here. However, this age of 200 Myr disagrees with the placement of the HHJ objects on the color-magnitude diagram; SJH show that they are, if anything, even younger than 70 Myr. Thus, masses lower than $0.065\ M_\odot$ are ruled out. Adoption of the nominal Pleiades age for HHJ 3 and HHJ 14 implies the most likely mass constraint: $M >$ $0.09\ M_\odot$, from the Nelson et al. models.

The Li-based mass limits for HHJ 3 and HHJ 14 exceed the masses (~$0.06\ M_\odot$) deduced from their placement on the H-R diagram (SJH). Mutual consistency of the mass estimates can be achieved by adopting higher values of $T_{\rm eff}$, by ~200 K, for

HHJ 3 and HHJ 14 (and for the ~10 similarly placed brown dwarf candidates in SJH Fig. 5). Such a shift to higher $T_{\rm eff}$ raises simultaneously their inferred masses and the ages on the H-R diagram. The new masses would agree with the Li-based mass limits, and the new ages would lie near the nominal Pleiades age, instead of the low ages (30–50 Myr) from their previous H-R diagram placement. Indeed, recent spectra of HHJ 3 from 1–2.5 μm imply a higher mass, 0.07–0.12 $M_\odot$ (R. Steele & R. Jameson 1994, private communication).

Indeed, the calibration of $T_{\rm eff}$ from *IJHK* photometry remains an outstanding challenge for the reddest objects (Stringfellow 1991; Berriman, Reid, & Leggett 1992; Leggett 1992; Tinney 1993; Bessell & Stringfellow 1993; Burrows & Liebert 1993) requiring treatment of metallicity and molecules (notably H_2O) with atmospheric modeling (Kui 1991; Graham et al. 1992; Leggett 1992; Allard 1994). Attempts to forge agreement between theory and observation for field M dwarfs have similarly pointed toward higher values of $T_{\rm eff}$ from IR colors (cf. Kirkpatrick et al. 1993; Bessell & Stringfellow 1993). Use of model atmospheres is indeed expected to increase derived temperatures (Bessell & Stringfellow 1993). We caution that calibration of $T_{\rm eff}$ should be accomplished with minimal dependence on interior models, to retain a check on them. In particular, an alternative explanation for the mass discrepancy is that stellar interior models currently predict values of $T_{\rm eff}$ that are too high by ~200 K (but see Dorman, Nelson, & Chau 1989).

With the mass limits derived from the observed Li *depletion, HHJ 3 and HHJ 14 are certainly capable of significant* H-*burning and therefore are not brown dwarfs.* These Li-based mass limits are higher than suggested (0.06 $M_\odot$) from their placement on the H-R diagram (SJH). The two mass estimates may be brought into agreement either by adopting higher values of $T_{\rm eff}$ or by requiring major adjustments to interior models. The Li-based mass limit is independent of the conversion from color to $T_{\rm eff}$ and is therefore preferred over analysis of color-magnitude diagrams. The objects may be Li-depleted brown dwarfs only if they are much older (~200 Myr), in disagreement with their location on isochrones.

The above uncertainties in the photometric identification of brown dwarfs suggest the need for an alternative criterion. The Li test of Magazzu et al. (1993) establishes an *empirically based* class of cool objects, "lithium brown dwarfs," identifiable by two criteria: (1) location at the cool end of the main sequence (not T Tauri stars) and (2) primordial Li abundance, $\log N({\rm Li}) \approx 3$, signaling the de facto absence of nuclear burning. No such objects have ever been found.

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