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# LITHIUM IN THE HYADES CLUSTER

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## ABSTRACT

Twenty F dwarfs in the Hyades Cluster have been observed for Li content with the Canada-France-Hawaii telescope and the UH 2.2 m telescope at high spectral resolution and high signal-to-noise ratios. Abundances have been determined for Li/H and Fe/H from a standard model atmosphere abundance routine. There is a remarkable variation of Li/H with stellar surface temperature: stars with $T_{\rm eff}$ near 6600 K show Li depletions by factors $> 100$ relative to stars 300 K hotter and cooler. The hottest stars ($T > 7000$ K) show Li/H values of $10^{-9}$, the maximum observed in F field stars, meteorites, T Tauri stars, etc. The Li content shows a regular decrease toward 6600 K to values $< 10^{-11}$ and then a regular rise toward 6300 K where it again peaks at a maximum near $10^{-9}$. The dip in Li content is remarkable in the regularity of its temperature dependence, in its narrowness, and in its magnitude. Possible explanations include differential rotation and/or meridional circulation, or convective overshoot, all of which could carry Li to deeper layers where it could be destroyed, gravitational settling of Li atoms, mass loss of the surface layers containing the Li, etc.

*Subject headings:* clusters: open — stars: abundances

## I. INTRODUCTION

Main-sequence stars in the Hyades cluster were first studied for Li abundance by Herbig (1965) and Wallerstein, Herbig, and Conti (1965). Zappala (1972), Duncan (1981), and Duncan and Jones (1983) reexamined the falloff in Li abundance with temperature in the cooler (G-type) Hyades dwarfs. More recently, Cayrel *et al.* (1984) present a striking relation between Li depletion and stellar surface temperature for the Hyades G dwarfs which shows very little scatter. At higher temperatures Wallerstein, Herbig, and Conti (1965) could not detect Li in some of the Hyades F dwarfs. They reported upper limits that are factors of 2–3 less than the detected Li abundances in other Hyades F dwarfs. Zappala (1972) extrapolated the Li-temperature curve on the high temperature side to find the "initial" Li, Li/H = $8 \times 10^{-10}$, that presumably all stars in this cluster inherited at birth.

Here we report the discovery of large Li depletions in the Hyades mid-F dwarfs, depletions which are factors of 100 relative to stars only 300 K hotter and cooler.

## II. OBSERVATIONS AND DATA REDUCTION

The primary source of the observational data is the 3.6 m CFHT and $f/7.4$ coudé spectrograph camera with its 830 lines mm$^{-1}$ mosaic grating and liquid nitrogen–cooled Reticon detector. Spectra were obtained of 15 Hyades F dwarfs at 4.83 Å mm$^{-1}$ (0.11 Å resolution) covering 135 Å centered at 6700 Å on 1984 December 10 and 11. Typical exposure times of 15 minutes produced spectra with signal-to-noise ratios (S/N) of 400–500. The spectra were flat-fielded, and the usual four-channel normalization routine was applied (see Boesgaard and Tripicco 1986 for details). Samples of the CFHT Reticon spectra are shown in Figure 1 in order of decreasing temperature.

Spectra of eight Hyades F dwarfs were obtained on 1984 November 1 and 2 with the University of Hawaii 2.2 m telescope and coudé spectrograph with the *Galileo*/IFA CCD system. The CCD is a thinned, backside-illuminated, three-phase Texas Instruments device with 500 15 $\mu$m pixels on each side (Hlivak, Henry, and Pilcher 1984). When used with the 1.22 m focal length camera and 600 lines mm$^{-1}$ grating in the second order, the CCD gives $\sim 50$ Å of spectral coverage at a resolution of $\sim 0.16$ Å. Typical exposure times were 30 minutes for spectra with S/N 180–250. The CCD spectra were reduced in the standard manner (bias subtracted, flat-fielded, rows containing spectra extracted and co-added).

The equivalent widths were determined by a straightforward integrating routine for five lines of Fe I, the Li I blend at λ6707, and the Ca I line at λ6717. Only three lines of Fe I were available on the CCD spectra. A list of the stars observed, the equipment used, the approximate S/N, and the equivalent widths are given in Table 1.

## III. ABUNDANCE ANALYSIS

A temperature scale for the Hyades has been determined by Cayrel, Cayrel de Strobel, and Campbell (1985, hereafter C$^3$) based on model atmosphere profile-fitting of the wings of H$\alpha$. They calibrate this to $(V - K)$ broad-band colors by adopting the slope of the $\theta_{\rm eff}$ $(= 5040/T_{\rm eff})$ versus $(V - K)$ of Carney (1983) but with a zero point change based on their H$\alpha$ data.[2] We have adopted their $(\theta_{\rm eff}, V - K)$ relation, valid for $V - K$

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[2]LaBonte (1986) presents evidence that Balmer line *wings* are affected by activity in solar-type stars so that the C$^3$ temperature scale may be affected. The magnitude of this effect is small ($\sim 100$ K) and should not affect the conclusions we draw here.

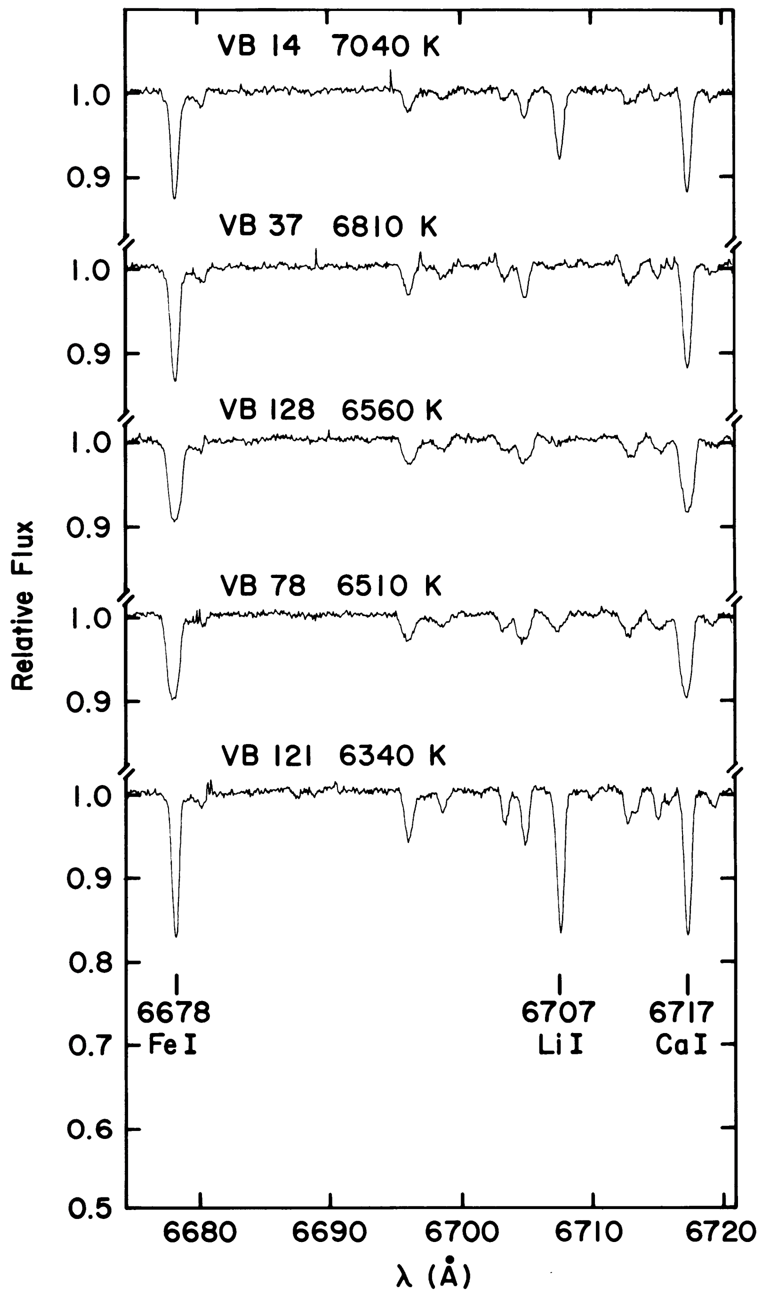


FIG. 1.—Sample spectra of the Hyades F stars in the Li region taken with the 3.6 m CFHT. They are arranged in order of decreasing temperature. For the hottest (VB 14) and coolest (VB 121) stars the Li line is clearly strong. It is present but weaker in the intermediate temperature stars.

≈ 0.9–2.2. In an attempt to keep the temperature scale as consistent as possible, we have used Carney's (1983) relationship between $V-K$ and $B-V$ for the Hyades to find calculated $(V-K)$ colors from measured $(B-V)$ values. We also found temperatures from $(V-I)$ and Carney's $(\theta_{\text{eff}}, V-I)$ relation for the Hyades using Mendoza's (1967) measurements of $(V-I)$ with the correction of $+0.006$ discussed by $C^3$. Table 2 gives the adopted temperatures and sources.

For the purpose of calculating abundances from the Li I line and the selected Fe I lines, the value of $\log g$ is unimportant since the calculated curves of growth for $\log g = 4.0$ and 4.5 are virtually identical (Boesgaard and Tripicco 1986). We have used Nissen's (1981) derived dependence of microturbulence on $T_{\text{eff}}$ and $\log g$ with the mean $T_{\text{eff}}$ of 6650 K and an assumed $\log g$ of 4.0 to find microturbulence of 1.8 km s$^{-1}$.

The model atmosphere abundance program makes use of a grid of model atmospheres of Kurucz (1979). The details of the abundance calculations are given in Boesgaard and Tripicco (1986), and sample curves of growth are shown there. For this analysis the final Li/H values are determined by

TABLE 1

OBSERVATIONS AND EQUIVALENT WIDTHS OF HYADES F DWARFS

| IDENTIFICATION | | | | Fe I 6677.993 Å | Fe I 6703.573 Å | Fe I 6705.117 Å | Li I + Fe I 6707.761 Å 6707.912 Å + 6707.441 Å | Fe I 6726.685 Å | Fe I 6750.152 Å |
|---|---|---|---|---|---|---|---|---|---|
| VB | HD | S/N | SOURCE[a] | $W_\lambda$ (mÅ) | $W_\lambda$ (mÅ) | $W_\lambda$ (mÅ) | $W_\lambda$ (mÅ) | $W_\lambda$ (mÅ) | $W_\lambda$ (Å) |
| 6 | 24357 | 250 | UH | 105. | ... | ... | 60. | ... | ... |
| 11 | 26015 | 240 | UH | 101. | 19. | 44. | 19. | ... | ... |
| 13 | 26345 | 240 | UH | 101. | 12. | 44. | < 5. | ... | ... |
| 14[b] | 26462 | 480 | CFHT | 100.2 | 11.9 | 28.6 | 65.0 | 22.5 | 31.6 |
| 14[b] | 26462 | 260 | UH | 97.3 | 8.5 | 34.9 | 69.1 | ... | ... |
| 34b[c] | 27483b | 490 | UH | 57.6 | 9.0 | 19.0 | < 2: | 18.0 | 26.1 |
| 34r | 27483r | ... | CFHT | 57.5 | 9.4 | 21.3 | 5.9 | 22.1 | ... |
| 36 | 27534 | 480 | CFHT | 121.6 | 17.2: | 41.6 | 5.9 | 36.7 | 96.5: |
| 37[b] | 27561 | 450 | CHFT | 106.6 | 16.3 | 33.2 | 10.3 | 28.8 | 46.0 |
| 37 | 27561 | 130 | UH | 109. | 14. | 41. | < 13. | ... | ... |
| 38 | 27628 | 430 | CFHT | ... | 10.5 | 30.5 | 19.6 | 24.7 | 31.6 |
| 44 | 27731 | 340 | CFHT | 116.5 | 18.7 | 37.4 | 20.4 | 41.4 | 54.4: |
| 48 | 27808 | 390 | CFHT | 122.5 | 25.2 | 41.9 | 92.6 | 38.8 | 61.5 |
| 51 | 27848 | 380 | CFHT | 114.0 | 24.1 | 42.0 | 6.5 | 40.4 | 55.2: |
| 57 | 27991 | 350 | CFHT | 113.4 | 19.9 | 36.6 | 61.9 | 34.2 | 55.6 |
| 78 | 28406 | 450 | CFHT | 111.9 | 20.4 | 39.0 | 29.8 | 36.0 | 54.2 |
| 81 | 28483 | 400 | CFHT | 114.1 | 20.6 | ... | 15.6 | 38.0 | 57.9 |
| 86 | 28608 | 350 | CFHT | 109.7 | 23.8 | 38.6 | 20.7 | 29.2 | 50.9 |
| 90 | 28736 | 230 | UH | 107. | 13. | 36. | < 6. | ... | ... |
| 94 | 28911 | 500 | CFHT | 114.9 | 7.1: | 38.5 | < 2.2 | 38.4 | 37.2: |
| 121 | 30738 | 400 | CFHT | 109.1 | 25.1 | 41.7 | 114.9 | 41.2 | 59.2 |
| 124 | 30869 | 180 | UH | 134. | 29. | 45. | 9. | ... | ... |
| 128 | 31845 | 500 | CFHT | 112.1 | 20.3 | 35.3 | 14. | 37.1 | 51.4 |
| Sun | ... | ... | ... | 137. | 38. | 47. | ... | 48. | 75. |

[a] UH refers to the University of Hawaii 2.2 m telescope and CCD, and CFHT refers to the Canada-France-Hawaii Telescope and Reticon.

[b] The upper set of numbers for VB 14 and VB 37 are from the CFHT data, the lower set from the UH 2.2 m data. The values used for the abundance determinations were a mean which weighed the CFHT numbers 4 times the 2.2 m numbers.

[c] VB 34 is a double-lined spectroscopic binary. The upper set of numbers corresponds to the component with the blueward displaced lines. The lower set is for the redward component. These are the measured values, uncorrected for the effect of two continua; the appropriate multiplication factors are 2.050 (blue) and 1.950 (red).

interpolation between the Li-Fe blend curves for [Fe/H] = 0.0 and [Fe/H] = 0.3. Note that the strength of the blending Fe I line at 6707.441 Å is only about 2 mÅ at $T_{\rm eff} = 6500$ K so its influence is small, but not negligible for stars with severe Li depletions.

The Fe abundances were reduced to [Fe/H] through line-by-line comparisons with the solar line strengths from Branch, Lambert, and Tomkin (1980) and Beckers, Bridges, and Gilliam (1976) and abundance calculations with the Kurucz (1979) solar model and microturbulence of 1.2 km $s^{-1}$ (Blackwell *et al.* 1976).

The abundance results are given in Table 2.

## IV. RESULTS AND DISCUSSION

The Li abundance results are presented as a function of temperature in Figure 2, which includes the Li abundances for the G dwarfs from Cayrel *et al.* (1984). The most remarkable aspect of this figure is the severity of the Li depletions that occur over the narrow temperature interval between 6500 and 6850 K. The delineation of this Li chasm is very striking in its regularity. The abundances from the measured line strengths define the dip down to depths where abundances are typically 50 or more times less than the maximum.

A number of mechanisms have been suggested for the Li depletion in solar-type stars which involve circulation of matter containing Li to depths where the temperature is high enough that Li atoms will be destroyed, such as meridional circulation, convective overshoot, and microscopic and turbulent diffusion. The effect of any of these mechanisms may be enhanced by a reduction in the surface layers containing Li via mass loss. The depletion found in the Hyades mid-F dwarfs could have occurred during pre–main-sequence and/or main-sequence evolution.

One of the more promising mechanisms for the Hyades seems to us to be the circulation of matter in the star by currents set up through differential rotation. Stellar rotation is known to decrease with stellar mass or surface temperature (Kraft 1965, 1970) in main-sequence stars in clusters and in the field. Convective zones are known to increase in depth (and thus in the temperature at the bottom) with decreasing mass or effective temperature in main-sequence stars. These

TABLE 2

TEMPERATURES AND ABUNDANCES FOR THE HYADES STARS

| VB | $T_{eff}$ | Source and Comment[a] | log $N$(Li) log $N$(H) = 12.00 | [Fe/H] |
|---|---|---|---|---|
| 6........ | 7107 | 1 | 3.27 | 0.3: |
| 11........ | 6847 | 2 | 2.48 | 0.30 |
| 13........ | 6725 | 2 | < 1.54 | 0.17 |
| 14........ | 7042 | 2 | 3.28 | 0.15 |
| 34........ | 6700 | 3 | < 1.3 | 0.21 |
| | 6800 | 3 | 2.19 | 0.29 |
| 36........ | 6613 | 2 | 1.56 | 0.15 |
| 37........ | 6814 | 4 | 2.18 | 0.18 |
| 38........ | 7376 | 4 | 2.89 | 0.29 |
| 44........ | 6563 | 1 | 2.30 | 0.14 |
| 48........ | 6246 | 2 | 2.95 | 0.04 |
| 51........ | 6596 | 4 | 1.30 | 0.23 |
| 57........ | 6371 | 4 | 2.76 | 0.01 |
| 78........ | 6512 | 4 | 2.50 | 0.11 |
| 81........ | 6471 | 1 | 2.08 | 0.08 |
| 86........ | 6484 | 2 | 2.23 | 0.07 |
| 90........ | 6738 | 1 | < 1.71 | 0.13 |
| 94........ | 6651 | 1 | ≤ 0.88 | 0.08 |
| 121........ | 6337 | 2 | 3.13 | 0.06 |
| 124........ | 6630 | 5 | 1.66 | 0.3 |
| 128........ | 6562 | 1 | 2.13 | 0.14 |
| 31........ | 6044 | 2 | 3.73[b] | ... |
| 59........ | 6154 | 2 | 2.80[b] | ... |
| 65........ | 6190 | 2 | 2.81[b] | ... |

[a] SOURCE AND COMMENT.—(1) From $(V-K)_{calc}$. (2) Mean from $(V-K)_{calc}$ and $(V-I)$ used when the two temperatures agreed to $\pm 50$ K. (3) VB 34 is a double-lined spectroscopic binary, so photometric indices were not used to derive the temperatures. Following Boesgaard and Tripicco 1986, we used Fe I line ratios to estimate the temperatures, corrected to the Hyades scale. The results for the component with the blueward displaced lines appears on the upper line and for the redward and displaced component on the lower line. (4) From observed $(V-K)$. (5) VB 124 is a triple system with the primary classified as F5 V by Griffin *et al.* 1985. The mean $(B-V)$ for Hyades F5 V stars is 0.435 which was used to find $T_{eff}$.

[b] Li abundance from the Duncan and Jones 1983 equivalent widths and our temperatures and abundance program. No Fe line strengths were given, and therefore no [Fe/H] values could be determined.

two phenomena acting in concert could qualitatively reproduce the character of the Li depletion seen in Figure 2. For the hottest F stars, stellar rotation is high, but the outer convection zone is of negligible thickness, so there is little differential rotation, little circulation, and thus little depletion. (Note also that we could observe only stars with $v \sin i < 50$ km s$^{-1}$ to be able to detect a Li I line.) The Li dip arises in the mid-temperature range when the deepening convection zone and the lessening of rotation combine to produce a maximum effect on Li circulation and depletion. We note that Belvedere and Paternò (1983) predict that differential rotation reaches a maximum at F5 in rapidly rotating (i.e., ~ 40 km s$^{-1}$) dwarfs. As the rotation declines further, circulation of Li is inhibited and stars near $T = 6000$–6300 K show the original Li/H content. Still cooler stars (G stars) show the increasing effect of the deepening of the convection zone which circulates Li atoms to deeper layers in the stellar interior.

In the narrow temperature range of the Hyades mid-F depletion, Boesgaard and Tripicco (1986) found that at least half of the field stars have *no* Li depletion, i.e., have Li/H = $10^{-9}$. Thus the Hyades Li depletion might have occurred during pre–main-sequence evolution. While the star is on the pre–main-sequence track, the outer convection zone retreats. An interplay between stellar rotation and convective circulation might result in complete destruction of Li in stars in a narrow mass region, partial destruction in slightly more massive stars due to their greater rotation, and in slightly less massive stars due to deeper pre–main-sequence convective motions.

Calculations of Li diffusion in F stars have been made by Michaud (1985). These calculations fairly well reproduce the Li depletion pattern found in the mid-F stars by predicting underabundances in stars in the temperature range 6400–6800 K. His calculations also show that Li abundances are not modified by diffusion in stars cooler than 6400 K nor in those about 7000 K.

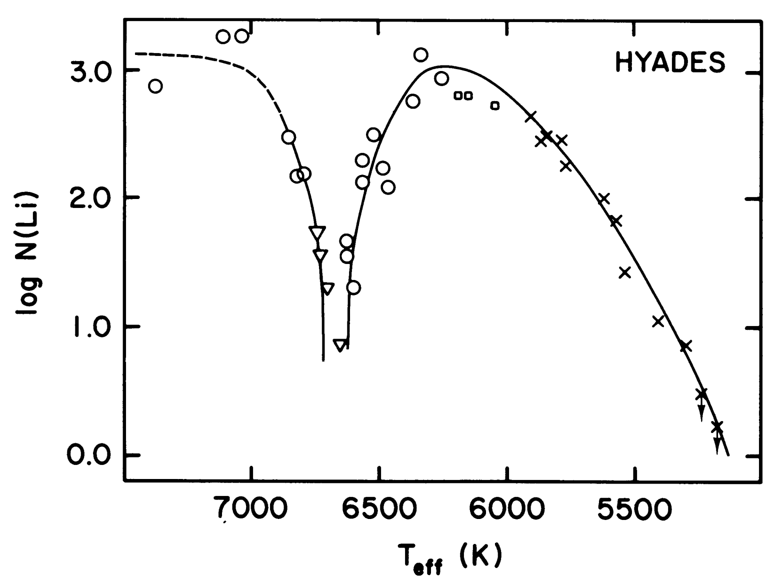


FIG. 2.—Lithium abundance [on the scale of log $N$(H) = 12.00] for the Hyades dwarfs as a function of effective temperature. The open circles and open triangles correspond to detections and upper limits, respectively. The crosses are the G dwarf data of Cayrel *et al.* (1984). The small open squares are abundances from equivalent widths of Duncan and Jones (1983) from spectra taken at Lick Observatory.

Observations of Li in F stars in other galactic clusters are currently underway to search for the presence of this Li depletion in groups of stars with different characteristic ages, metallicities, activity, etc. The field F stars which show similar Li depletions have Hyades-like metallicities, $[Fe/H] \approx +0.15$, and projected rotational velocities (Boesgaard and Tripicco 1986). About one-third of the field stars in the temperature range of the Hyades Li dip are Be-deficient also (Boesgaard 1976).

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