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# LITHIUM ABUNDANCE AND AGE SPREAD IN THE PLEIADES[1]

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## ABSTRACT

Surface lithium abundance, a parameter which usually decreases with age in late-type stars, has been determined for Pleiades stars as cool as $T_e \sim 4700$ K and Hyades stars as cool as $T_e \sim 5000$ K. A large abundance spread is seen among the coolest Pleiades stars, consistent with their having been formed over an interval as long as $0.4 \times 10^9$ yr, several times longer than the nuclear age of the cluster. Observations of the strength of the Ca II H and K line emission in three of the Pleiades stars also indicate a significant spread in age.

Some Pleiades stars as cool as $T_e \sim 5200$ K have primordial Li abundances, in conflict with the predictions of pre–main-sequence stellar evolution calculations, indicating that such calculations probably overestimate the importance of convection.

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

## I. INTRODUCTION

The Pleiades (nuclear age[2] $7.5 \times 10^7$ yr; Harris 1976; Patenaude 1978; Mermilliod 1981) has known members spanning a wider mass range than any other open cluster. The mass spread is large enough so that while high-mass stars are leaving the main sequence at the end of hydrogen burning, low-mass stars should still be contracting to the main sequence. Until recently, there has been no unambiguous detection of low-mass contracting stars, even though the observations extend well beyond the point where the current models predict such stars should lie above the main sequence. Landolt (1979) and Stauffer (1980) have made extensive new broadband photometric observations of faint stars given high proper motion membership probabilities by Jones (1973). Both found what appeared to be contracting stars at a mass of approximately 0.4 $M_\odot$ ($B-V \sim 1.4$). This would imply a minimum contraction age that is several times the nuclear age.

More recently, Jones (1981) suggested that this contraction sequence was probably a selection effect, brought about by the magnitude limits of the existing proper motion surveys. The new observations of Stauffer (1982) show this to be the case. Stauffer's new observations of faint Pleiades members, drawn from Jones's (1981) list of faint flare stars, indicate that the color-magnitude diagrams for the Pleiades and Hyades are nearly identical as far as the observations extend, making the problem of the ages of these faint stars even more severe. There are several problems in interpreting these results, however. Probably all Pleiades members fainter than $V=13$ are flare stars (Haro 1976; Jones 1981). They show Ca II H and K and hydrogen emission (Kraft and Greenstein 1969; Stauffer 1980), and color-color plots indicate they have peculiar colors, although Stauffer's comparison of $R-I$ from photometry and from spectra shows no obvious anomaly. It is not certain that the $B-V$ or even the $R-I$ colors accurately reflect the effective temperatures of these faint stars, or if the $V$-magnitudes are accurate indicators of their luminosities.

We have decided to take a different approach to date the Pleiades—that of using the lithium abundance as an age indicator. The correlation of Li abundance with age in solar-type stars was suggested by Herbig (1965). Early Pleiades observations were made by Danziger and Conti (1966). Duncan (1981) discusses Li abundance and the strength of emission in the core of the Ca II H and K lines as age indicators in solar-type dwarfs. In main-sequence stars later than spectral type F, the time scale for Li destruction is a very sensitive function of mass and, hence, of main-sequence temperature. It decreases from an $e$-folding time of about $1.0 \times 10^9$ yr at $\log T_e =$

[1] *Lick Observatory Bulletin*, No. **952**.
[2] Nuclear age is the age determined from the upper–main-sequence turnoff.

3.76 (G2 V) to less than $0.5 \times 10^9$ yr at log $T_e = 3.73$ (G5 V) and becomes shorter still for late G and K dwarfs. This is presumably due to the deepening convective zone in late stars, which mixes the Li to hotter interior regions where it is destroyed. A more extensive discussion of the mechanisms involved may be found in Duncan (1981) and Spite and Spite (1982). The sharp dependence of Li depletion rate for stars of solar abundance leads one to expect the following dependence of Li abundance on temperature for stars in a galactic cluster: Stars hotter than a certain temperature will have suffered essentially no main-sequence depletion and therefore will display the same dispersion in Li abundance they had when they reached the main sequence. Stars cooler than a certain temperature will have Li destruction time scales short enough to display any spread in the ages of the cluster stars. If such an age spread exists, it will increase the dispersion in Li abundance in these stars over what it was when they arrived on the main sequence.

If one observes the Pleiades in a mass range for which the *e*-folding time is comparable to or less than the nuclear age, then one can, in principle, determine both the cluster age and the spread in formation time. If the cluster were coeval, one would expect a small dispersion in Li abundance at a given mass, provided other complications are absent. If the cluster were non-coeval, then one would expect a dispersion in Li abundance that increases with decreasing mass.

Two effects may complicate this pattern. Duncan (1981) shows that some stars apparently avoid the usual main-sequence depletion of Li. Only about 15% of his sample behaves in this fashion, however, and the anomalous Li depletion is apparently more likely in metal-poor stars. If the percentage of such anomalous stars is not higher in a given cluster, this should not be a major source of confusion. Pre–main-sequence Li depletion is expected in solar-type stars, due to the convective mixing of the Li to depths where the temperature is high enough to destroy it (Bodenheimer 1965). The amount of depletion increases with decreasing mass. Bodenheimer's predictions, however, have not been adequately tested on late-type stars (late G to early K) where the expected depletion is large. The zero-age main-sequence (ZAMS) Li abundances and, consequently, the *e*-folding time for Li depletion in such stars are therefore less certain than for early G stars. These uncertainties would affect estimates of the duration of any indicated age spread.

With these caveats in mind, we decided to make a comparative study of Li in the Pleiades and Hyades. We could not observe far enough down the Pleiades main sequence to reach many stars with *e*-folding times as short as $8 \times 10^7$ yr, but we did successfully observe a number of stars of $T_e = 5200$ K for which the destruction time scale is approximately $2 \times 10^8$ yr.

## II. OBSERVATIONS

### *a*) *Hyades*

Extensive observations of Li in the Hyades stars have been made by Zappala (1972) using photographic spectra obtained at 17 Å mm$^{-1}$ dispersion on Kodak 103a-D emulsion through a Varo image intensifier. Zappala's observations show relatively constant Li abundance with little dispersion among the mid-F to G0 Hyades stars but with a decline in abundance toward later types.

We have added observations of eight Hyades stars concentrated near a $B-V$ of approximately 0.8. These are listed in Table 1. The instruments used were a two-channel photoelectric spectrometer (Duncan 1981) and a bare Reticon detector (Vogt 1981), both fed by the Lick 120 inch (3.05 m) telescope. The Reticon spectra in particular are of much higher signal-to-noise ratio than Zappala's photographic image-tube spectrograms. Several of our Reticon spectra are shown in Figure 1. Our observations of VB 91 and VB 181, the two latest stars in which Zappala reported Li, do not confirm its presence. Reexamination of the Varo photographic plates which are in the Lick files show no convincing evidence of Li in these stars. These stars are faint and hard to reach with the equipment used by Zappala and, consequently, were taken at lower dispersion than his spectra of the brighter stars.

### *b*) *Pleiades*

New observations of the Pleiades were combined with the photoelectric spectrometer measurements of Duncan (1981) and the image-tube spectrogram measurements of Zappala (1972). These are listed in Table 2. The new observations were made using five different experimental setups: the two-channel photoelectric scanner and bare Reticon mentioned above, used with the Lick 120 inch telescope; the Cassegrain echelle spectrograph and photon-counting intensified Reticon array of the Multiple Mirror Telescope (Davis and Latham 1979; Chaffee and Schroeder 1976); the Mount Wilson 2.5 m coudé used with an intensified Reticon detector (Shectman 1976, 1981); and the Mount Palomar 5 m coudé used with the same intensified Reticon detector used at Mount Wilson. The Multiple Mirror Telescope and Mount Wilson spectra have a resolution of 0.3 Å, and those from Mount Palomar have 0.5 Å, with a typical signal-to-noise ratio of 25. Figure 2 shows MMT spectra of H II 296 and H II 1275, and a Mount Palomar spectrum of H II 2462. All are stars of similar temperature. Also shown is the H II 296 spectrum with resolution degraded to match that of the Mount Palomar spectrum. It will be discussed later.

Temperatures were determined from $B-V$ and $R-I$ colors. Colors of Pleiades stars were dereddened as follows. A plot of $U-B$ versus $B-V$ was made, and

TABLE 1
HYADES DATA

| VB | $B-V$ | $R-I$ | $T$ | EW (mÅ) | $\sigma$ | log $n$(Li) | $\sigma$ | Remarks[a] |
|---|---|---|---|---|---|---|---|---|
| 3 ... | 0.75 | 0.39 | 5500 | < 25 | ... | < 1.60 | ... | D |
| 15 ... | 0.66 | 0.33 | 5780 | 90 | 25 | 2.71 | 0.25 | Z |
| 21 ... | 0.82 | 0.40 | 5340 | < 40 | ... | < 1.65 | ... | D |
| 22 ... | 0.77 | 0.42 | 5350 | 51 | 15 | 1.83 | 0.22 | R |
| 31 ... | 0.57 | 0.30 | 6020 | 86 | 17 | 2.90 | 0.21 | Z |
| 42 ... | 0.76 | 0.39 | 5450 | 20 | ... | < 1.50 | ... | D |
| 48 ... | 0.52 | 0.28 | 6170 | 95 | 17 | 3.11 | 0.22 | Z |
| 50 ... | 0.60 | 0.36 | 5850 | 69 | 15 | 2.56 | 0.19 | Z |
| 52 ... | 0.60 | 0.33 | 5870 | 97 | 15 | 2.88 | 0.20 | Z |
| 57 ... | 0.49 | 0.25 | 6330 | 82 | 15 | 3.15 | 0.19 | Z |
| 58 ... | 0.68 | 0.36 | 5650 | 52 | 15 | 2.22 | 0.22 | Z |
| 59 ... | 0.54 | 0.29 | 6100 | 84 | 17 | 2.95 | 0.22 | Z |
| 63 ... | 0.63 | 0.35 | 5760 | 90 | 15 | 2.68 | 0.18 | Z |
| 64 ... | 0.66 | 0.33 | 5780 | 81 | 17 | 2.62 | 0.19 | Z |
| 65 ... | 0.54 | 0.28 | 6140 | 85 | 15 | 2.98 | 0.18 | D, R |
| 73 ... | 0.61 | 0.29 | 5920 | 72 | 12 | 2.65 | 0.17 | Z |
| 78 ... | 0.45 | 0.25 | 6400 | < 47 | ... | < 2.77 | ... | Z |
| 88 ... | 0.54 | 0.29 | 6100 | 133 | 20 | 3.43 | 0.24 | W |
| 91 ... | 0.88 | 0.48 | 5030 | 15: | 12 | 0.73 | ... | D, R |
| 92 ... | 0.74 | 0.37 | 5540 | < 15 | ... | < 1.45 | ... | D, R |
| 96 ... | 0.84 | 0.44 | 5200 | < 15 | ... | < 1.00 | ... | D, R |
| 97 ... | 0.63 | 0.31 | 5890 | 128 | 20 | 3.17 | 0.23 | Z |
| 102 ... | 0.60 | 0.33 | 5870 | 84 | 20 | 2.73 | 0.23 | Z |
| 181 ... | 1.17 | 0.64 | 4230: | < 30 | ... | < 0.25: | ... | D |

[a] The Remarks column indicates the source of Li measurements as described in the text: D—Duncan 1981, two-channel scanner on Lick 120 inch; R—Reticon on Lick 120 inch; W—Mount Wilson; Z—Zappala 1972.

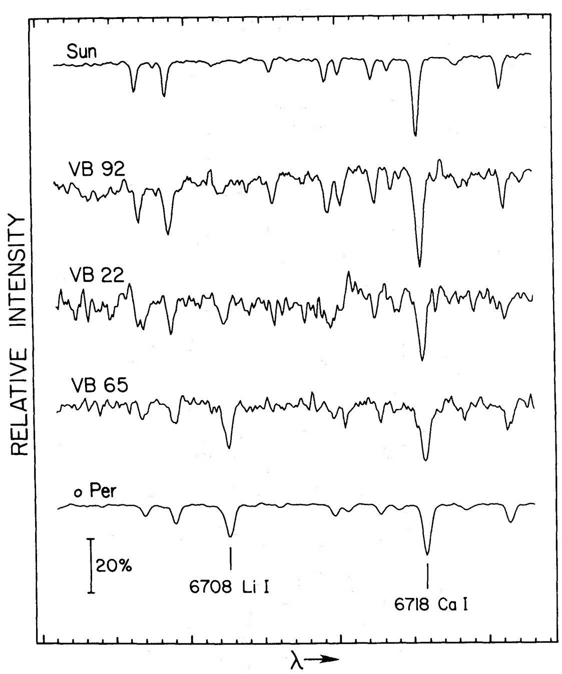


FIG. 1.—Lick Reticon spectra of several Hyades stars, the Sun, and a field standard in the region of Li I λ6707.9.

vectors of slope 0.75 were extended to the unreddened Pleiades main sequence to yield $(B-V)_0$. Note that the unreddened locus of the Pleiades main sequence is offset by +0.03 mag in $U-B$ from the Hyades locus in such a color-color diagram, because of the difference in metallicity between the two clusters. A similar plot of $U-B$ versus $R-I$ was constructed for stars with known $R-I$ colors, and stars were dereddened under the assumption that the reddening in $R-I$ is approximately equal to that in $U-B$. Near $B-V=0.6$, dereddened vectors are parallel to the unreddened locus and indeterminate. For the several stars of this color, reddening was determined from the colors of early F stars near them in the sky.

The temperature scales were similar to those used by Duncan (1981). The $R-I$ scale fits both the temperature derived by Peterson and Carney (1979) from continuum scans and those from fine analyses tabulated by Perrin *et al.* (1977). It is well represented by the formula $\log T_e = 3.961 - 0.676(R-I) + 0.265(R-I)^2$ for $3.64 < \log T_e < 3.82$. The $B-V$ scale is fitted to the fine-analysis temperature of Perrin *et al.* and the temperature of Johnson (1966). It is given by $\log T_e = 3.899 - 0.2199(B-V)$ for $3.72 < \log T_e < 3.82$, and by $\log T_e = 3.979 - 0.316(B-V)$ for $3.68 < \log T_e < 3.72$.

TABLE 2

Pleiades Data

| H II | $B-V$ | $(B-V)$ | $U-B$ | $R-I$[a] | $T$ | EW (mÅ) | $\sigma$ | log $n$(Li) | $\sigma$ | Remarks[b] |
|---|---|---|---|---|---|---|---|---|---|---|
| 173 ....... | 0.85 | 0.81 | 0.44 | 0.44 | 5220 | 185 | 30 | 2.94 | 0.23 | Z |
| 250 ....... | 0.68 | 0.62 | 0.14 | 0.40 | 5740 | 119 | 20 | 2.92 | 0.23 | W |
| 296 ....... | 0.84 | 0.82 | 0.45 | 0.46s | 5200 | 240 | 15 | 3.29 | 0.15 | Z, D, M |
| 314 ....... | 0.64 | 0.60 | 0.10 | 0.39 | 5750 | 130 | 40 | 3.05 | 0.40 | D, W |
| 405 ....... | 0.54 | 0.53 | 0.05 | ... | 6100 | 56 | 18 | 2.63 | 0.22 | D |
| 430 ....... | 0.83 | 0.73 | 0.34 | 0.44s | 5540 | 156 | 30 | 3.10 | 0.32 | D, W |
| 476 ....... | 0.80 | 0.75 | 0.27 | 0.48 | 5270 | 88 | 16 | 2.1 | 0.2 | D, M, AMS 0.5 |
| 522 ....... | 0.85 | 0.93 | 0.62 | ... | 4970 | 105 | 20 | 2.08 | 0.27 | W |
| 571 ....... | 0.78 | 0.72 | 0.30 | ... | 5540 | 202 | 30 | 3.49 | 0.26 | Z |
| 627 ....... | 0.50 | 0.48 | 0.03 | 0.31 | 6150 | 50 | 22 | 2.60 | 0.26 | D |
| 739 ....... | 0.62 | 0.60 | 0.06 | 0.36 | 5800 | 215 | 25 | 3.8 | 0.2 | D, Z, AMS 0.8 |
| 885 ....... | 1.01 | 0.99 | 0.84 | ... | 4650 | 165 | 16 | 2.0 | 0.2 | M, AMS 0.55 |
| 923 ....... | 0.62 | 0.59 | 0.09 | 0.33 | 5880 | 131 | 33 | 3.17 | 0.23 | D |
| 1032 ....... | 0.86 | 0.75 | 0.38 | 0.44s | 5810 | 150 | 22 | 3.29 | 0.22 | D |
| 1100 ....... | 1.16 | 1.12 | 1.15 | ... | 4270 | 157 | 35 | 1.3: | ... | Z, AMS 1.0 |
| 1101 ....... | 0.61 | 0.57 | 0.08 | 0.36 | 5890 | 96 | 20 | 2.54 | 0.24 | D |
| 1139 ....... | 0.48 | 0.42 | 0.00 | 0.29 | 6440 | < 25 | ... | < 2.46 | ... | D |
| 1215 ....... | 0.65 | 0.63 | 0.16 | 0.37 | 5720 | 138 | 20 | 3.06 | 0.22 | D, Z |
| 1275 ....... | 0.84 | 0.81 | 0.43 | 0.44s | 5280 | 145 | 15 | 2.64 | 0.17 | Z, M |
| 1726 ....... | 0.55 | 0.48 | 0.12 | 0.32 | 6240 | 100 | 13 | 3.2 | 0.2 | D, AMS 0.75 |
| 1766 ....... | 0.47 | 0.36 | 0.07 | 0.31 | 6640 | 43 | 18 | 2.95 | 0.32 | D |
| 1776 ....... | 0.72 | 0.67 | 0.22 | 0.41 | 5610 | 160 | 22 | 3.20 | 0.24 | D, Z |
| 1856 ....... | 0.56 | 0.53 | 0.09 | 0.32 | 6100 | 49 | 18 | 2.55 | 0.24 | D |
| 1924 ....... | 0.62 | 0.60 | 0.13 | 0.35 | 5830 | 132 | 18 | 3.15 | 0.20 | D |
| 2027 ....... | 0.86 | 0.84 | 0.50 | 0.48 | 5120 | 138 | 20 | 2.3 | 0.2 | D, AMS 0.75 |
| 2126 ....... | 0.86 | 0.83 | 0.48 | ... | 5240 | 207 | 40 | 3.08 | 0.33 | Z |
| 2244 ....... | 1.04 | 1.00 | 0.62 | ... | 4630 | 190: | ... | 2.1 | ... | *, M |
| 2278 ....... | 0.86 | 0.82 | 0.46 | 0.50 | 5150 | 151 | 15 | 2.4 | 0.2 | R, AMS 0.8 |
| 2311 ....... | 0.83 | 0.78 | 0.39 | 0.44s | 5380 | 145 | 17 | 2.76 | 0.20 | D, P |
| 2462 ....... | 0.83 | 0.83 | 0.46 | 0.44 | 5190 | 101 | 15 | 2.07 | 0.18 | D, P |
| 2741 ....... | 1.00 | 0.96 | 0.80 | ... | 4770 | 99 | 16 | 1.62 | 0.18 | M |
| 2881 ....... | 0.95 | 0.91 | 0.56 | 0.55s | 4850 | 220 | 50 | 2.6 | 0.3 | Z, P, AMS 0.7 |

[a] The "s" indicates that the $R-I$ color is from a spectral measurement.

[b] The Remarks column indicates the source of Li measurement as in Table 1, with M—Multiple Mirror Telescope, P—Mount Palomar. AMS indicates the star is above the main sequence by the amount given. *—broad lines.

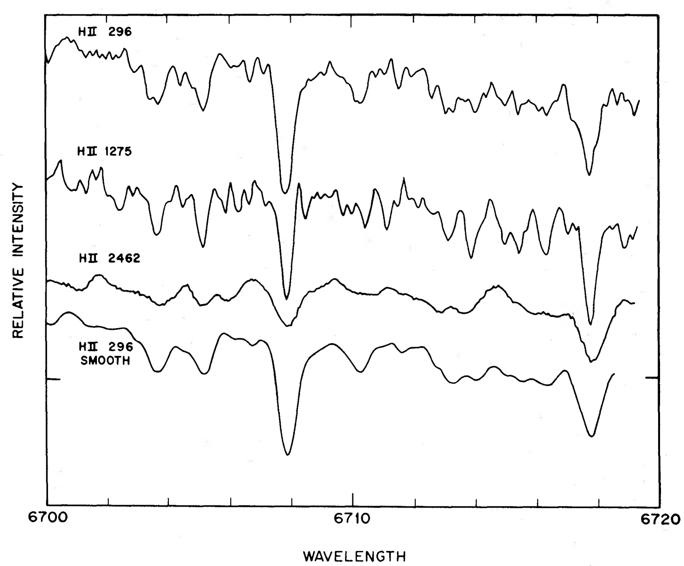


Fig. 2.—Spectra of three Pleiades stars with $T = 5200$ K, showing the wide range in the Li I strength. The upper two were taken with the MMT, resolution 0.3 Å, the third with the Mount Palomar coudé, resolution 0.5 Å. The bottom is the first spectrum with resolution degraded to 0.5 Å. The horizontal tick marks are zero intensity for the top spectrum.

Comparison of the two temperature scales for the 23 Pleiades stars with *UBVRI* colors indicates a very slight offset between them: $\langle T(B-V)-T(R-I)\rangle = 40 \pm 120$ K, independent of temperature. When both $B-V$ and $R-I$ temperatures were available, they were averaged. When only a $B-V$ temperature was available, it was lowered by 20 K. For the 24 Hyades stars, $\langle T(B-V)-T(R-I)\rangle = 34 \pm 120$ K, and in all cases the two temperatures were averaged.

Measured Li equivalent widths were converted into abundances using curves of growth computed with the WIDTH5 subsection of the code ATLAS (Kurucz 1970). Li was assumed to be entirely $^7$Li. The Li resonance line actually consists of two components, λ6707.761, $\log gf = 0.00$ and λ6707.912, $\log gf = -0.30$ (Grevesse 1968). The WIDTH5 Voigt profile line opacity subroutine was modified to take this fine-structure splitting into account. The input model atmospheres were those of Bell (1975, 1976, 1980), which include effects due to molecules. They covered the temperatures 4500–6000 K, with solar composition of metals and $\log g = 4.50$. We also computed a curve of growth for 6500 K by first computing curves of growth using the Kurucz (1979) models for 6000 K and 6500 K, and using the differences between these to incrementally change the curve of growth computed with the Bell 6000 K model. Several models with $\log g = 3.75$ and with metals underabundant by 0.5 dex were also used. Microturbulence was taken to be 1.5 km s$^{-1}$, and the damping constant, $C = -31.20$. As the Doppler velocity of Li is of the order of 4 km s$^{-1}$ in the line-forming region in solar-type stars, calculated abundances are insensitive to either of these two parameters.

Several of the curves of growth are shown in Figure 3. The 5000 K and 6000 K curves give abundances larger by approximately 0.3 dex and 0.1 dex, respectively, than those of Duncan (1981), which were based on Kurucz (1979) ATLAS model atmospheres. There are two reasons for this. The primary one is that Kurucz's atmospheres do not contain molecules, which become increasingly important at cooler temperatures. A second reason is that the 5000 K ATLAS6 models extend only to continuum optical depths of approximately $\log \tau = -3.0$, and their uppermost level is unphysically cool. In the case of a line arising from the neutral species of an atom which is predominantly ionized, such as Li (or Fe), spurious opacity may be added by this layer, leading to larger equivalent widths being computed for a given abundance, or smaller abundances being inferred from a given equivalent width. The present curves of growth based on Bell (1980) atmospheres are in excellent agreement with detailed computations of the solar Li abundance made by Müller, Peytremann, and de la Reza (1975).

As a final check, curves of growth were also produced for the Ca I λ6717 line, whose equivalent width was measured in addition to Li λ6707. A solar abundance

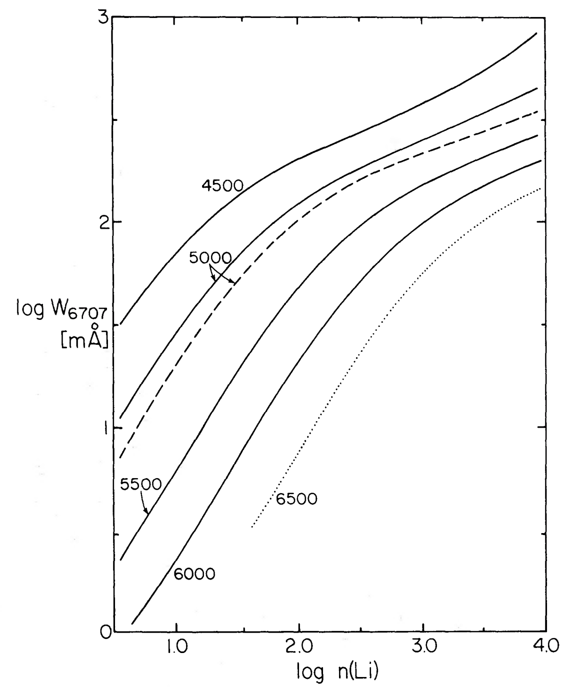


FIG. 3.—Li I λ6707.9 curves of growth for temperatures between 4500 K and 6500 K, computed as indicated in the text. The solid lines are for $\log g = 4.5$, the dashed line for $\log g = 3.75$. The dotted line is an approximation for 6500 K as indicated in the text.

curve fits the measured widths well for temperatures from 6000 K down to about 5200 K. Below this temperature the theoretical curve predicts larger equivalent widths than are observed. Therefore, the absolute normalization of the Li abundances we derive for the coolest program stars should be considered somewhat uncertain. However, for the differential comparison of Hyades and Pleiades, the main point of the present investigation, the Li curves of growth should be adequate.

## III. DISCUSSION

Figure 4 shows the Li abundance in the Hyades (nuclear age $7 \times 10^8$ yr; Patenaude 1978) derived from our new observations and from those of Zappala reanalyzed by the methods of the present observation. Li depletion increases monotonically toward lower temperatures, and the maximum abundance is approximately $\log n(\text{Li}) = 3.1$ [on a scale of $\log n(\text{H}) = 12.00$], which is typical of the primordial value (Duncan 1981). Also indicated is the expected pre-main-sequence depletion according to calculations of Bodenheimer (1965), which should define the ZAMS Li abundance curve.

Figure 5 shows the Pleiades Li abundances. Large symbols indicate more precise measurements with a standard deviation in the determination of $\log n(\text{Li})$ of

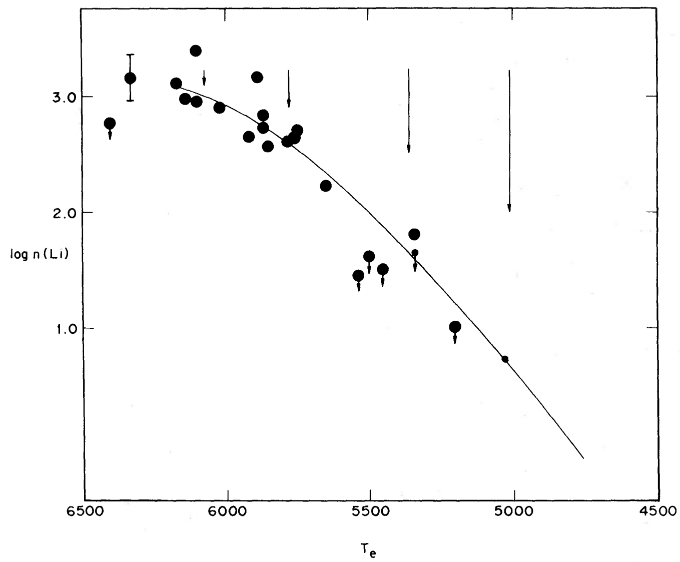


FIG. 4.—Hyades Li abundances [on a scale of log $n$(H) = 12.0]. Arrows represent the expected pre-main-sequence depletion according to Bodenheimer (1965). Large symbols have a standard deviation of approximately 0.2 (error bar plotted), and small symbols, approximately 0.3. The solid line is a freehand fit to the data.

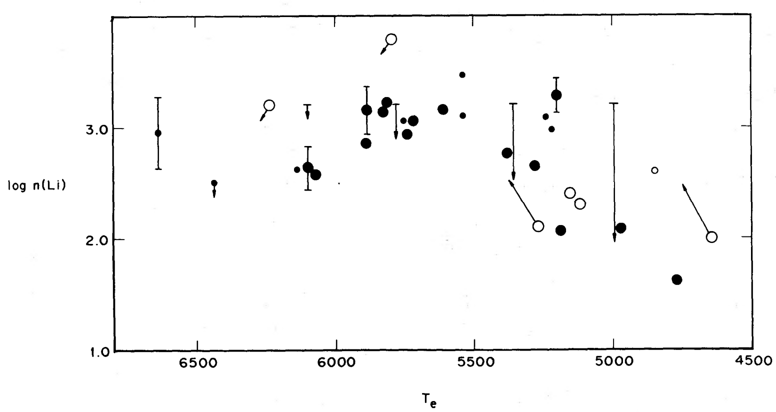


FIG. 5.—Pleiades Li abundances. Symbols are as for Fig. 4, except that unfilled circles indicate expected binaries. Several typical error bars are plotted. The arrows on unfilled circles are explained in the text.

$0.17 < \sigma < 0.24$. Small symbols represent less precise values with $0.26 < \sigma < 0.34$. Typical (1 $\sigma$) error bars are shown. Unfilled circles represent stars which lie 0.5–0.75 mag above the main sequence and which are probably binaries. If all the Pleiades stars in this temperature range were approximately one-tenth the age of the Hyades, then they should have suffered inconsequential main-sequence Li depletion and should lie on the ZAMS line with scatter due only to measuring errors.

Multiplicity could affect the observed Li abundance in at least two ways. If two stars are close enough that mutual interaction alters their physical structure (e.g., convection zone depth), the rate of Li depletion could change. To our knowledge, no calculations of such effects have been made. A second and more likely instance is from the contamination of the light of the primary by the secondary, which changes both the color and the λ6707 equivalent width. In a statistical way, both of these effects can be estimated.

For binaries in which the secondary is not identical to the primary, the primary's $B - V$ color will be reddened. Assuming a main-sequence slope of $\Delta V/\Delta(B-V) = -6.0$, cases were considered of secondaries 0–3.0 mag fainter than the primary. Over a wide range of secondary magnitudes, approximately $\Delta V = 0.4$–$2.3$, the combined light is redder than that of the primary by

$0.04 \pm 0.01$ mag, and the binary lies 0.7–0.04 mag above the main sequence. Thus the estimated primary temperature would be approximately 100 K too cool, and thus the Li abundance would be slightly underestimated.

The observed Li equivalent width may be increased or decreased owing to light from the secondary, as $W_{obs} = W_1 F_1 + W_2 F_2$, where $F_1$ and $F_2$ are the fractions of the total continuum flux near λ6707 contributed by the primary and secondary, respectively. The fractions $F_1$ and $F_2$ should be close to the flux fractions in the $R$ bandpass. Various combinations of $W_1$ and $W_2$ can produce a given $W_{obs}$, but the most likely combination may be inferred from Figure 6, which is a plot of Li I λ6707 equivalent widths of Pleiades stars which are not above the main sequence and which presumably are single. This plot shows in a general way how the equivalent width varies as a function of color, as shown by the freehand dotted line. Using Figure 6, for a primary and secondary of any color, one can crudely estimate the ratio of equivalent widths. One can also estimate $F_1$ and $F_2$, and thus from the observed total λ6707 equivalent width, one can estimate the equivalent width in the primary. For primaries blueward of $B-V=0.7$, the effect of the secondary increases the observed λ6707 equivalent width, and for stars redward of $B-V=0.8$, the effect decreases the observed equivalent width. The amount of this effect does not depend critically on the magnitude of the secondary. At $B-V=0.55$, the overestimate in the abundance is about 0.15 dex, and for $B-V=0.8$, the underestimate is about $-0.40$ dex. Arrows in Figure 5 indicate the compensation for this error in the case of four binaries.

Several important discrepancies from prediction are apparent in Figure 5. A number of stars lie above the ZAMS line predicted by the Bodenheimer (1965) models. Pre–main-sequence depletion of Li must be less than his calculations predict; the models may be too convective. The dispersion in Li abundances in the Pleiades at a given temperature is clearly greater than in the Hyades, and not only at cooler temperatures. There appears to have been depletion in some of the hottest Pleiades stars. This depletion in the hotter stars is probably due to a different mechanism than that which operates in the cooler stars. Duncan (1981) has noted Li depletion in field stars of mid-F spectral type and also in cluster stars of early to mid-F type, and he has argued that this depletion is due to a different cause than that which operates in solar and later type stars. Boesgaard (1976) has also observed Be and Li depletion in some early F-type stars whose convection zones should be too thin for the operation of the same mechanism that depletes Li in the Sun and later type stars.

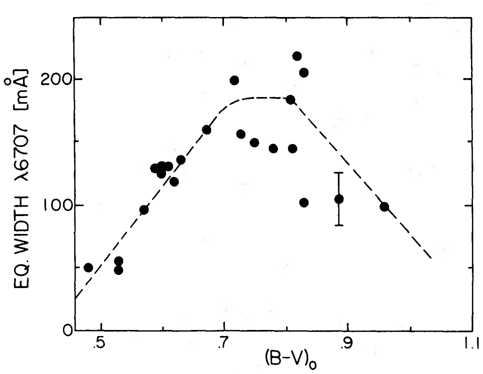


FIG. 6.—Li I λ6707 equivalent widths for nonbinary Pleiades stars.

Cooler than $T_e = 5500$ K, Li abundances in the Pleiades decrease, and for temperatures of 5200 K and cooler, the dispersion in Li abundance also increases. The dispersion in Li abundances of the stars of $T_e \sim 5200$ K is far greater than the measuring error. Spectra of three of these stars are shown in Figure 2. None of these three are above the main sequence in a color-magnitude diagram. These differences cannot be due to instrumental effects. Although the Pleiades data were gathered on many different instruments, there are no systematic differences for the stars that were observed on more than one instrument. The Mount Palomar spectra have the lowest resolution and might be expected to produce systematically lower equivalent widths owing to the lowering of the continuum from unresolved lines, though the continuum was measured in regions known to be line free in the Sun. As a check on this, several MMT spectra were numerically smoothed to degrade their resolution to that of the Mount Palomar spectra. Equivalent widths were lowered from 0% to 10%, a negligible amount. The last spectrum in Figure 2 is an example of this check.

The dispersion in Li abundance of the cooler Pleiades stars thus appears to be cosmic, but does it necessarily represent a dispersion in ages? Other explanations for the dispersion might be that (1) it is primordial; (2) it arises during pre–main-sequence contraction; or (3) the rate of main-sequence depletion differs among stars of the same mass, possibly through different degrees of mass loss or different rotation rates.

Alternative (1) appears unlikely for several reasons. The dispersion is large for stars of $T_e \sim 5200$ K, but it is as small as the measurement error for all but one of the stars near the peak abundance. Moreover, this same peak abundance is seen in the Pleiades, Hyades, the UMa cluster, and the field stars (Duncan 1981).

We cannot rule out alternatives (2) and (3) on the basis of the available evidence. If alternative (3) is correct, the dispersion for Hyades stars of $T_e \sim 5200$ K should be much greater than that of the corresponding Pleiades stars. High-accuracy observations of these Hyades stars could test this possibility.

Is there any independent evidence whether an age spread or one of the other alternatives is more likely?

Strength of emission in the core of the Ca II H and K lines is another good indicator of age in late-type stars (Wilson 1963; Wilson and Skumanich 1964; Duncan 1981), since this emission decreases with age. It is difficult to observe since the violet continuum near the H and K lines is weak, and the emission arises from the core of the lines, which is weaker still. However, we have obtained spectra in the vicinity of the H and K lines of the three stars of Figure 2. These are shown in Figure 7. Resolution is approximately 1 Å, and some of the falloff toward the blue is instrumental. The spectra were obtained with the Double Spectrograph of the Mount Palomar 5 m telescope and an intensified Reticon detector (Shectman 1976, 1981). The H and K emission intensities seen in Figure 7 support the hypothesis of an age spread. H II 296 is the most Li-rich star, and shows the greatest H and K emission line strength. H II 2462 appears the oldest on both counts.

If an age spread is the cause of the observed dispersion in Li abundance among Pleiades stars of $T_e \sim 5200$ K, a rough estimate can be made of this spread. Pre-main-sequence depletion appears negligible at this temperature; some Pleiades stars have $\log n(\mathrm{Li}) = 3.1$. Hyades stars of the same temperature have $\log n(\mathrm{Li}) \sim 1.2$. Modeling the Li decrease with time as an exponential (Duncan 1981) and taking the age of the Hyades to be approximately $0.7 \times 10^9$ yr implies an $e$-folding time of $0.17 \times 10^9$ yr for Li depletion at this temperature. Li-rich Pleiades stars such as H II 296 must be significantly younger than this. The Li in H II 2462 is depleted by over 1.0 dex, suggesting an age of about $0.4 \times 10^9$ yr, more than 5 times the nuclear age of the cluster.

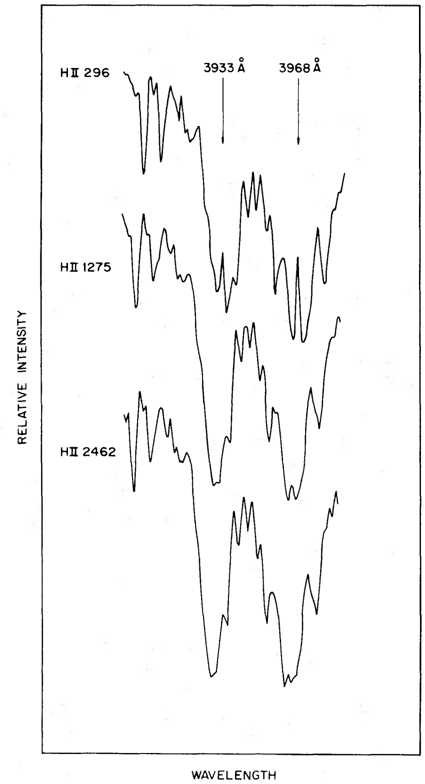


FIG. 7.—The same three stars as in Fig. 2 but showing approximately 100 Å in the region of the Ca II H and K lines. Chromospheric emission in the line core is indicated. Zero intensity is at the bottom for H II 2462, and all are at the same scale.

## IV. SUMMARY

The observed Pleiades main sequence covers more than 17 visual magnitudes, and the time scale for contraction of the lowest mass ($\sim 0.35\ M_\odot$) known main-sequence members is several times longer than the age derived from fitting isochrones to the upper main sequence. These considerations suggest that the Pleiades cluster might not be coeval.

We have attempted to gather independent information on the age of the Pleiades G and early K stars by determining their Li abundances and comparing them with the Hyades stars, and, for three stars, observing the strength of emission in the cores of the Ca II H and K lines. Both Li abundance and H and K emission generally decrease with age in late-type stars. A large range in Li abundance is seen among the latest Pleiades stars we surveyed. Other explanations can be devised, but the straightforward interpretation of our data is that the Pleiades G and K stars formed over an extended period of time—many times longer than the commonly accepted nuclear age of the cluster—and most are older than the high-mass cluster members. We thus lend strong support to a hypothesis first proposed by Herbig (1962).

Some of the later Pleiades stars have Li abundances equal to the primordial or cosmic value, contrary to the predictions of Bodenheimer (1965), which suggest that the convection should have been deep enough during pre-main-sequence contraction for significant amounts of Li to be destroyed. Our results indicate that such pre-main-sequence models may be overly convective.

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