LITHIUM ABUNDANCES IN WIDE BINARIES WITH SOLAR-TYPE TWIN COMPONENTS

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ABSTRACT

We present high-resolution spectroscopic observations of the Li i resonance line in a sample of 62 stars that belong to 31 common proper motion pairs with twin F- or G-type components. Photospheric abundances of lithium were derived by spectral synthesis analysis. For seven of the pairs, we have measured large lithium abundance differences. Eleven other pairs have components with similar lithium abundances. We cannot determine if the remaining 13 pairs have lithium differences because we did not detect the Li i lines, and hence we can only provide upper limits to the abundances of both stars. Our results demonstrate that twin stars do not always share the same lithium abundances. Lithium depletion in solar-type stars does not only depend on age, mass, and metallicity. This result is consistent with the spread in lithium abundances among solar-type stars in the solar-age open cluster M67. Our stars are brighter than the M67 members of similar spectral type, making them good targets for detailed follow-up studies that could shed light on the elusive mechanism responsible for the depletion of lithium during the main-sequence evolution of the Sun and solar-type stars.

Subject headings: binaries: visual — stars: abundances — stars: evolution — stars: fundamental parameters — stars: late-type

1. INTRODUCTION

Lithium has a rich life. It is created in many environments (primordial nucleosynthesis, cosmic ray spallation in the interstellar medium, spallation and fusion reactions around compact relativistic objects, flares, and red giant thermal pulses), and it is destroyed in the interior of stars by collision (primordial nucleosynthesis, cosmic ray spallation in the interstellar medium, spallation and fusion reactions around compact relativistic objects, flares, and red giant thermal pulses), and it is destroyed in the interior of stars by collision (primordial nucleosynthesis, cosmic ray spallation in the interstellar medium, spallation and fusion reactions around compact relativistic objects, flares, and red giant thermal pulses), and it is destroyed in the interior of stars by collision (primordial nucleosynthesis, cosmic ray spallation in the interstellar medium, spallation and fusion reactions around compact relativistic objects, flares, and red giant thermal pulses), and it is destroyed in the interior of stars by collision (primordial nucleosynthesis, cosmic ray spallation in the interstellar medium, spallation and fusion reactions around compact relativistic objects, flares, and red giant thermal pulses), and it is destroyed in the interior of stars by collision (primordial nucleosynthesis, cosmic ray spallation in the interstellar medium, spallation and fusion reactions around compact relativistic objects, flares, and red giant thermal pulses), and it is destroyed in the interior of stars by collision. The Sun has a lithium abundance more than 2 orders of magnitude lower than meteoritic material (Mueller, Peytremann, & de la Reza 1975), which reflects the composition of the presolar nebula. The Sun probably did not deplete lithium during the pre–main-sequence evolution, but rather during the slow main-sequence evolution, although the exact mechanism has not yet been identified (Martin 1997, 2001). Recent models of lithium depletion in solar-type stars suggest that two types of mixing may be at work during main-sequence evolution, namely, overshooting and rotational mixing (Umezu & Saio 2000). The history of rotational mixing may be strongly influenced by the initial conditions of angular momentum distribution in the protoplanetary disk. Thus, it is conceivable that there could be a connection between the rate of lithium depletion by rotational mixing and the presence of companions (stellar or substellar) to the stars.

Binary stars with twin components are interesting for understanding binary formation and evolution. Common proper motion (CPM) pairs of twins allow us a test of the validity of stellar evolution models because their separations are so large (more than 100 AU) that each member has probably evolved independently. If all the properties of stars are determined by age, mass, and chemical composition, twins should be identical. If the lithium abundance of a main-sequence star is determined by its age, mass, and chemical composition, pairs of twins should show the same lithium abundances. In the early work of Herbig (1965), it was already apparent that there was a scatter in lithium abundances among pairs of twins. Herbig’s study included 53 UMa A and B, where lithium was detected in A but not in B; 16 Cyg A and B, where lithium was detected in A but not in B; and 53 Aqr A and B, where lithium was detected in both stars.

The system 16 Cyg has received some attention recently. The two stars of the pair are nearly identical. The primary has $V = 5.96$, $T_{\text{eff}} = 5785$ K, and $\log g = 4.28$. The secondary has $V = 6.20$, $T_{\text{eff}} = 5747$ K, and $\log g = 4.35$. Despite those similarities, the members of this pair have two fundamental differences. King et al. (1997) have shown that the primary has a lithium abundance higher than that of the Sun [log $N$(Li) = 1.27 ± 0.05 in the customary scale of log $N$(H) = 12], while the secondary has a much lower lithium abundance [log $N$(Li) < 0.60]. The large difference in lithium abundance is surprising because both stars should be the same age and have very similar masses. Another significant difference between the two stars is that the secondary harbors a giant planet with a minimum mass of 1.5 $M_\text{J}$, an eccentricity of $e = 0.63$, and a period of 808.08 days (Cochran et al. 1997). On the other hand, no giant planet has yet been detected around 16 Cyg A. However, such nondetection does not rule out the presence of giant planets with long periods or smaller planets with short periods.

Gonzalez & Laws (2000) and Ryan (2000) have studied the distribution of lithium abundances among planet-harborining stars and have reached opposite conclusions. While Gonzalez & Laws claim that lithium is overdepleted in stars with giant planets, Ryan claims that it is normal.
The disagreement comes from the choice of stars to be compared with the host stars of extrasolar planets. This is a difficult task because the ages of most field stars are not well known.

Pairs of twins offer the possibility of comparing stars that are coeval and have nearly the same mass and metallicity. Thus, we might expect that the systematic study of binaries may shed light on whether there is any connection between the presence of giant planets and lithium depletion. Gratton et al. (2001) have recently reported an abundance analysis for six wide binaries. They find that the primary star of the binary HD 219542 has higher iron and lithium abundances than the secondary star, which leads them to suggest that the primary has ingested a planet.

In this paper we report lithium abundances for a sample of 31 visual binaries. The targets have been chosen to be as similar as possible to 16 Cyg in spectral type and magnitude. The paper is organized as follows: In § 2 we describe the observations. In § 3 we present the abundance analysis. In § 4 we discuss each pair of twins individually when we could detect the Li I line in at least one of the stars, and we compare them with lithium abundances in open clusters and theoretical models. Section 5 contains the discussion, and in § 6 we present our conclusions.

2. OBSERVATIONS

We selected our targets from the list of CPM pairs compiled by Halbwachs (1986). We filtered the sample by requiring that the difference in $V$ magnitudes should be less than 0.4 and that the spectral type should be between F8 and K0. The declination of the stars had to be north of $-30^\circ$. Our sample is listed in Table 1.

Observations were obtained during several observing runs at Lick and Keck observatories between 1998 January and 2001 March. The binaries BD+08 4386, BD+69 0993, BD+74 0718, and BD+76 0835 were observed at Keck. All the other binaries were observed at Lick. The observing log is given in Table 1.

The Lick observations were carried out using the Hamilton echelle spectrograph on the Shane 3 m telescope. This instrument provides 92 orders covering the spectral range from 490 to 890 nm at a resolution of 48,000. A standard reduction was performed (Valenti 1994), which included background subtraction, cosmic ray removal, and flat fielding. Wavelength calibration was made using ThAr lamp exposures.

The Keck observations were obtained with the HIRES echelle spectrograph (Vogt et al. 1994). The resolution was 67,000, and the coverage was from 600 to 850 nm. Data reduction was performed using IDL routines similar to those used for the Lick data.

3. ANALYSIS

We have compiled the available photometry in the literature for our program stars, and we provide it in Table 2. The $V$ magnitudes, $B-V$ colors, and spectral types were taken from SIMBAD, except for the particular cases listed in § 4 and for the notes to Table 2. This photometric database is rather heterogeneous. Some of our stars are included in the 2MASS second incremental release point-source catalog (PSC). Their 2MASS $J-K$ colors are included in Table 2. Temperatures were derived using the empirical scale of Alonso, Arribas, & Martinez-Roger (1996) for solar metal-
TABLE 2
Photometric Data for Program Stars

| HD/BD       | V      | B−V   | Spectral Type | J   | J−H   | J−K   | b−y  | ml  | cl  | References |
|-------------|--------|-------|---------------|-----|-------|-------|------|-----|-----|------------|
| HD 4552     | 8.87   | 0.53  | F8            | 7.84| 0.22  | 0.29  | ... | ... | ... |           |
| BD+12 0990  | 9.20   | 0.56  | G0            | 8.07| 0.30  | 0.34  | ... | ... | ... |           |
| HD 6872 A   | 8.06   | 0.41  | F8            | 7.16| 0.16  | 0.23  | 0.291| 0.169| 0.421| 1        |
| HD 6872 B   | 8.53   | 0.87  | F8            | 7.50| 0.24  | 0.32  | 0.336| 0.155| 0.376| 1        |
| HD 8624     | 8.01   | 0.67  | G0            | 7.84| 0.22  | 0.34  | 0.424| 0.234| 0.330| 2        |
| HD 8610     | 8.01   | 0.60  | F8            | 7.50| 0.24  | 0.32  | 0.400| 0.191| 0.405| 2        |
| HD 60269    | 8.56   | 0.48  | F8            | 7.74| 0.28  | 0.36  | 0.376| 0.187| 0.337| 3        |
| HD 60272    | 9.08   | 0.49  | F8            | 7.74| 0.28  | 0.36  | 0.466| 0.247| 0.425| 3        |
| HD 31208    | 9.60   | 0.83  | K0            | 8.02| 0.31  | 0.34  | 0.515| 0.424| 0.307| 3        |
| HD 39274    | 8.96   | 0.51  | G0            | 8.02| 0.31  | 0.34  | 0.336| 0.142| 0.419| 4        |
| HD 39275    | 8.99   | 0.84  | G0            | 7.60| 0.36  | 0.44  | 0.336| 0.142| 0.419| 4        |
| HD 54046    | 7.72   | 0.64  | F8            | 7.16| 0.16  | 0.23  | 0.291| 0.169| 0.421| 1        |
| HD 54100    | 7.72   | 0.53  | F8            | 7.16| 0.16  | 0.23  | 0.291| 0.169| 0.421| 1        |
| BD+15 2080  | 9.01   | 0.68  | G5            | 8.36| 0.24  | 0.36  | 0.424| 0.234| 0.330| 2        |
| BD+15 2079  | 8.77   | 0.59  | G0            | 8.16| 0.21  | 0.24  | 0.466| 0.247| 0.425| 3        |
| BD+34 2091 A| 9.71   | 0.51  | G0            | 8.02| 0.31  | 0.34  | 0.515| 0.424| 0.307| 3        |
| BD+34 2091 B| 9.79   | 0.49  | G0            | 8.02| 0.31  | 0.34  | 0.515| 0.424| 0.307| 3        |

References.—(1) Mechler 1976. (2) Olsen 1994. (3) Schuster, Parrao, & Contreras Martinez 1993. (4) Duncan 1984. (5) Mechler & McGinnis 1978. (6) Cuypers & Seggewiss 1999.
| HD/BD       | $T_{\text{eff}}$ (K) | $T_{\text{eff,fit}}$ (K) | [M/H] | EW (Li i) (mÅ) | log $N$(Li)$_{\text{COG}}$ | log $N$(Li)$_{\text{fit}}$ |
|-------------|----------------------|--------------------------|-------|---------------|---------------------------|--------------------------|
| HD 4552 A  | 6140                 | 6000                     | −0.2  | <2            | <1.7                      | <1.6                     |
| BD +12 0090| 5837                 | 5750                     | −0.2  | 99 ± 3        | 2.2                       | 2.3                      |
| HD 6872 A  | 6543                 | 6250                     | −0.2  | <3            | <2.0                      | <1.8                     |
| HD 6872 B  | 5954                 | 6250                     | −0.2  | 36 ± 3        | 2.4                       | 2.6                      |
| HD 8624    | ...                  | 5250                     | −0.2  | 31 ± 4        | ...                       | 1.6                      |
| HD 8610    | ...                  | 5500                     | −0.2  | 17 ± 3        | ...                       | 1.6                      |
| BD +60 269 | ...                  | 6250                     | 0.0   | 49 ± 4        | ...                       | 2.6                      |
| BD +60 271 | ...                  | 6250                     | 0.0   | <3            | ...                       | <1.8                     |
| HD 31208   | ...                  | 5000                     | −0.1  | <2            | ...                       | <1.0                     |
| BD +07 754 | ...                  | 5000                     | −0.1  | <2            | ...                       | <1.0                     |
| HD 39274   | 5836                 | 6000                     | 0.0   | 61 ± 3        | 2.4                       | 2.6                      |
| HD 39275   | 5305                 | 5750                     | −0.1  | 79 ± 3        | 2.1                       | 2.5                      |
| HD 54046   | ...                  | 6000                     | −0.5  | 38 ± 3        | ...                       | 2.4                      |
| HD 54100   | ...                  | 6250                     | −0.5  | 39 ± 3        | ...                       | 2.6                      |
| BD +28 1698| ...                  | 6000                     | −0.2  | 65 ± 2        | ...                       | 2.7                      |
| BD +28 1697| ...                  | 6000                     | −0.2  | 67 ± 2        | ...                       | 2.7                      |
| BD +15 2080| ...                  | 5750                     | −0.2  | <2            | ...                       | <0.7                     |
| BD +15 2079| ...                  | 6000                     | −0.2  | 9 ± 2         | ...                       | 1.7                      |
| BD +34 2091 A | 5723       | 5750                     | −0.1  | 88 ± 4        | 2.6                       | 2.6                      |
| BD +34 2091 B | 5954       | 5750                     | −0.1  | 63 ± 3        | 2.6                       | 2.5                      |
| HD 92222 A | 5257                 | 5500                     | −0.1  | 24 ± 3        | 1.4                       | 1.7                      |
| HD 92222 B | 5404                 | 5500                     | 0.0   | 8 ± 2         | 1.4                       | 1.4                      |
| BD +13 2311 A | 6403       | 6500                     | 0.0   | 37 ± 3        | 2.8                       | 2.8                      |
| BD +13 2311 B | 6403       | 6500                     | 0.0   | <2            | <1.9                      | <2.0                     |
| HD 98744   | 6077                 | 6250                     | −0.2  | <2            | <1.5                      | <1.5                     |
| HD 98745   | 6140                 | 6250                     | −0.2  | 36 ± 3        | 2.4                       | 2.5                      |
| HD 111484 A| ...                  | 6000                     | −0.2  | 64 ± 3        | ...                       | 2.6                      |
| HD 111484 B| ...                  | 6000                     | −0.2  | 92 ± 3        | ...                       | 2.8                      |
| HD 124257 A| 6139                 | 6500                     | 0.0   | 65 ± 3        | 2.7                       | 2.6                      |
| HD 124257 B| 5954                 | 5750                     | 0.0   | 11 ± 3        | 1.9                       | 1.7                      |
| HD 124913 A| 6472                 | 6500                     | 0.0   | <4            | <2.0                      | <2.2                     |
| HD 124913 B| 6763                 | 6500                     | −0.1  | <4            | <2.3                      | <2.1                     |
| BD +02 2820 A | ...                 | 6000                     | 0.0   | <3            | ...                       | <1.5                     |
| BD +02 2820 B | ...                 | 5500                     | 0.0   | <3            | ...                       | <1.2                     |
| BD +35 2576 A | ...                 | 6000                     | 0.0   | 8 ± 2         | ...                       | 1.8                      |
| BD +35 2576 B | ...                 | 6000                     | 0.0   | 4 ± 2         | ...                       | 1.7                      |
| BD +13 2830 A | 5668                 | 5750                     | −0.2  | <5            | <1.3                      | <1.7                     |
| BD +13 2830 B | 5354                 | 5750                     | −0.2  | <3            | <1.0                      | <1.4                     |
| BD +15 2867 B | 5210                 | 5250                     | −0.2  | <3            | <1.0                      | <1.0                     |
| BD +15 2867 C | 5070                 | 5250                     | −0.2  | <2            | <0.8                      | <0.9                     |
| HD 155674  | ...                  | 5250                     | −0.2  | <5            | ...                       | <1.1                     |
| BD +54 1862 | ...                  | 5250                     | −0.2  | <3            | ...                       | <1.1                     |
| BD +65 1043 | 4615                 | 5250                     | 0.0   | <2            | <0.4                      | <1.2                     |
| BD +65 1044 | 6688                 | 6500                     | 0.0   | <3            | <1.6                      | <1.5                     |
| BD +74 0718 | ...                  | 5500                     | −0.1  | <3            | ...                       | <1.2                     |
| BD +74 0719 | ...                  | 5500                     | −0.1  | <3            | ...                       | <1.2                     |
| HD 167215  | ...                  | 6500                     | −0.2  | 43 ± 3        | ...                       | 2.8                      |
| HD 167216  | ...                  | 6500                     | −0.2  | 34 ± 3        | ...                       | 2.7                      |
| BD +69 0993 A | ...                 | 6500                     | 0.0   | 30 ± 3        | ...                       | 2.7                      |
| BD +69 0993 B | ...                 | 6500                     | 0.0   | 34 ± 3        | ...                       | 2.7                      |
| BD +08 4386 A | ...                 | 6000                     | 0.0   | <2            | ...                       | <1.6                     |
| BD +08 4386 B | ...                 | 5500                     | 0.0   | <3            | ...                       | <1.2                     |
| BD +03 4428 A | ...                 | 5500                     | −0.2  | <3            | ...                       | <1.2                     |
| BD +03 4428 B | ...                 | 5500                     | −0.2  | <3            | ...                       | <1.4                     |
| BD +76 0835 A | ...                 | 6000                     | −0.2  | <2            | ...                       | <1.5                     |
| BD +76 0835 B | ...                 | 5750                     | −0.2  | <2            | ...                       | <1.3                     |
| BD +01 4575 A | ...                 | 5750                     | −0.2  | <3            | ...                       | <1.2                     |
| BD +01 4575 B | ...                 | 5750                     | −0.2  | <3            | ...                       | <1.6                     |
| BD +11 5033 A | 5162                 | 5250                     | −0.1  | <3            | <1.0                      | <1.2                     |
| BD +11 5033 B | 5779                 | 5000                     | −0.1  | <3            | <1.4                      | <1.1                     |
| HD 224984  | ...                  | 6000                     | −0.1  | 35 ± 3        | ...                       | 2.3                      |
| HD 224994  | ...                  | 6000                     | −0.1  | 33 ± 3        | ...                       | 2.3                      |
LITHIUM ABUNDANCES IN WIDE BINARIES

1 We refer to the solar abundances given by Grevesse (1984) using the convention $M/H = 0$. The temperatures obtained from the $J-K$ colors are given in Table 3. Typical error bars in $J-K$ colors are ±0.03, corresponding to ±180 K in $T_{\text{eff}}$. These temperatures were derived to compare with our, presumably more reliable, temperatures obtained from synthetic spectra fitting to the observed spectra in the lithium region. This comparison is shown in Figure 1 for 26 stars that have available 2MASS J-K photometry. The mean difference between the $T_{\text{eff}}$ derived from $J-K$ and from fits is −65 K, and the standard deviation is 270 K. We conclude that there is no significant systematic deviation of the $T_{\text{eff}}$ derived from $J-K$ colors with respect to those derived from synthetic fits.

For each spectrum, we determined the continuum level using the DECH20 software (Galasutdinov 1992). To detect the real continuum level, we smoothed the observed spectra using three loops of a three-point smoothing boxcar. Then the continuum points were fitted by splines to use in the fine analysis procedure. The S/N pixel$^{-1}$ given in Table 1 were obtained by measuring the standard deviation of the normalized continuum in the spectral range 669.3–669.5 nm. We carried out the computations using the LTE spectral synthesis program WITA6 (Pavlenko 2000), which is a modified version of the program used by Pavlenko et al. (1995). Our computations of synthetic spectra were carried out using plane-parallel model atmospheres in LTE, with no energy divergence. The model atmospheres were taken from Kurucz’s grid, which is available on the Web.

We used metallicities in the range $[M/H] = 0.0$ to $-0.2$ for fitting the observed spectra except for HD 54046 and HD 54100, which are known metal-poor stars (Norris 1986). Chemical equilibrium was computed for the mix of ≈100 molecular species, with data taken from Tsuji (1973). ATLAS9 (Kurucz 1993) grids of continuum opacity sources were used in our computations. We used VALD (Piskunov et al. 1995) for the atomic line list and damping constants. For some lines the damping data are missing; in that case, we used Unsöld (1955) approach to compute them. We had to increase the log $gf$ of the Fe i line at 670.510 nm by a factor of 2 (from 0.0319 given by VALD to 0.0640) to find good fits to the observed spectra of the Sun as a star (Kurucz et al. 1984). Computations were carried out for a fixed microturbulent velocity of $\nu = 2$ km s$^{-1}$ and a Voigt profile for every absorption line.

Synthetic spectra were computed with a step of 0.002 nm. Instrumental profile and macroturbulence broadening effects were modeled by convolution with a Gaussian of half-width in the range 0.010–0.018 nm. For most stars we could describe the profile with instrumental broadening only, without any rotation. That provides upper limit of $\nu \sin i = 3$ km s$^{-1}$. No enhanced van der Waals broadening was used. For two stars rotational broadening was taken into account (HD 6872 A and BD+65 1044; $\nu \sin i = 14$ km s$^{-1}$). For each star we found the best-fitting synthetic spectrum using a least-squares minimization algorithm. Figures 2, 3, and 4 show typical examples of synthetic fits to the echelle spectra.

For each LTE lithium abundance, we determined NLTE abundance corrections using the grid of curves of growth of Pavlenko & Magazzù (1996). In Table 3 we summarize our results. We give the temperatures, metallicities, and lithium abundances (including NLTE corrections) that we used in the best fits to the observed spectra. Equivalent widths of the Li i line measured by direct integration of the line profile in the observed spectrum are given in Table 3 as well. They can be used to derive lithium abundances from curve-of-growth (COG) computations. For the stars with 2MASS photometry, we have obtained COG Li abundances using the temperatures derived from the $(J-K) - T_{\text{eff}}$ calibration of Alonso et al. (1996) and the WITA code. Those abundances are listed in Table 3 for comparison with the abundances obtained from the synthetic spectra. Figure 5 illustrates this comparison for the same 26 stars that were used in Figure 1.
The mean difference between the lithium abundances derived using these two methods is \( \log N(\text{Li})_{\text{COG}}/C0 - \log N(\text{Li})_{\text{fit}} = 0.08 \) dex, and the standard deviation is 0.17 dex. We conclude that there is no significant systematic discrepancy between the two methods of obtaining lithium abundances. We adopt the uncertainty of \( 1 \sigma = 0.17 \) dex in our absolute lithium abundances. In our computations we have assumed that our stars are dwarfs. A variation of \( \log g \pm 0.5 \) dex provides a maximum \( \Delta \log N(\text{Li}) < 0.1 \) dex.

4. COMMENTS ON INDIVIDUAL STARS

The main goal of this paper is to determine whether stars with the same age and initial chemical composition and nearly equal masses have depleted lithium at the same rate. We limit our discussion to pair of twins for which we could detect the \( \text{Li}^i \) line in at least one of the stars. When we could not detect the \( \text{Li}^i \) line in any of the stars, we could not tell if the lithium abundances are different or similar, and therefore those pairs are not discussed any further. After a literature search using SIMBAD, we found that some of the pairs deserve individual comments:

1. HD 6872 A and B. — Oblak & Charette (1980) and Duncan (1984) included HD 6872 A and B among a sample of stars that are sufficiently evolved for the ages to be estimated from \( T_{\text{eff}} \) and absolute magnitudes using the displacement from the zero-age main sequence (ZAMS). Both groups obtained \( uvby \) photometry and derived \( T_{\text{eff}} \) of 6380 K (Oblak & Charette 1980) and 6300 K (Duncan 1984) for the primary. For the secondary, they gave 6251 K (Oblak & Charette 1980) and 6084 K (Duncan 1984). The discrepancy in \( T_{\text{eff}} \) is mainly due to their use of different equations of \( b-y \) index versus temperature. Soderblom, Duncan, & Johnson (1991) converted the \( b-y \) color of Duncan (1984) to \( B-V \) color. In Table 1, we adopt the Soderblom et al. (1991) color, which is different from the color provided by SIMBAD. Our best-fit temperatures are 6250 K for both stars. We find good synthetic fits to our spectra with the same \( T_{\text{eff}} \) for both stars (Fig. 3). The fainter star has a higher lithium abundance than the hotter star by at least 0.8 dex. Adopting the \( T_{\text{eff}} \) of either Oblak & Charette (1980) or Duncan (1984) does not change the conclusion that the ligh-
Lithium abundance is very sensitive to the mass (and thus \( T_{\text{eff}} \)) of stars. In the temperature range of our program stars (6500–5250 K), lithium abundances generally decrease with decreasing \( T_{\text{eff}} \), although at the hot end of this temperature range, the F-type lithium dip starts to kick in (Boesgaard & Tripicco 1987). If the lithium abundances of the components of pairs of twins were dominated by the mass dependence of lithium depletion, we would expect a correlation between the difference in \( T_{\text{eff}} \) and the difference in log \( N(\text{Li}) \), in the sense that the cooler components should show systematically lower lithium abundances than the hotter ones. Figure 6 shows that such correlation is not present in the data. We conclude that the observed pattern of lithium abundances in pairs of twins cannot be explained solely with the dependence of lithium depletion on stellar mass.

We have found five pairs with nearly identical \( T_{\text{eff}} \) and nearly identical log \( N(\text{Li}) \) and four pairs with nearly identical \( T_{\text{eff}} \) and very different log \( N(\text{Li}) \). Hereafter, we call these latter four pairs “16 Cyg analogs,” namely, HD 6872 A/B, BD+60 0269/BD+60 0271, BD+13 2311 A/B, and HD 98744/HD 98745. The common characteristics of 16 Cyg analogs is that they are pairs of twins with lithium abundance difference between the two stars of the pair that exceeds 0.5 dex (which corresponds to 3 \( \sigma \) significance in our synthetic fit analysis) and difference in \( T_{\text{eff}} < 200 \text{ K} \).

Figure 7 illustrates the comparison between the pairs of twins and the Hyades cluster in a \( T_{\text{eff}} \) versus log \( N(\text{Li}) \) diagram. The Hyades single star members define a tight relationship between \( T_{\text{eff}} \) and log \( N(\text{Li}) \). In general, the twins do not follow the Hyades relation. A possible explanation for this discrepancy could be that there are many tidally locked binaries (TLB) hidden among the twins. We do not know of any example of a TLB in our sample.

HD 8610 has a lithium abundance similar to Hyades members with the same \( T_{\text{eff}} \). The lithium-\( T_{\text{eff}} \) locus in the Hyades declines steeply from 5500 to 5250 K, so one would expect that HD 8624 should have a lithium abundance much lower than that of HD 8610, which is contrary to what we have found. HD 8624 is a double-lined spectroscopic binary with a period of 14.91 days (Tokovinin 1999) and an eccentricity \( e = 0.132 \). Even though it is not strictly a TLB because the orbit is not completely circularized, it may have preserved lithium in a manner similar to the TLBs studied by Barrado y Navascués et al. (1997), which show a trend of higher lithium abundances when compared to single stars. However, TLBs are relatively rare among the general population of solar-type stars. A program to monitor the radial velocity of 10 of our pairs has been started using HIRES.
with the iodine cell. There are already enough data for 16 of the stars to find TLBs, but none has been seen (G. W. Marcy 2002, private communication). We conclude that it is very unlikely that TLBs can account for most of the discrepancy between the pairs of twins and the Hyades.

The average age of the pairs of twins is probably larger than the Hyades cluster age (~600 Myr). It is informative to compare the twins with the well-studied solar-age cluster M67. In Figure 7 we compare the pairs of twins with the members of M67. The M67 stars show a large spread of lithium abundances at a given $T_{\text{eff}}$, which is similar to the behavior exhibited by our binaries. The evolution of lithium from the Hyades to M67 implies a mechanism of lithium depletion during the main-sequence lifetime of solar-type stars that is not very mass dependent. We have not found in the literature any models that can explain the evolutionary pattern of lithium abundances implied by the comparison between the Hyades and the M67 solar-type stars. We conclude that there is currently not a good theoretical explanation for the lithium abundances observed in our pairs of twins and the open clusters. In future papers we plan to tackle this problem observationally via searches for connections between the lithium abundances in the pairs of twins and the presence of companions (stellar or substellar), chromospheric activity, rotation, and the abundances of other chemical elements. At the moment, it would be premature to suppose that the presence of planets had anything to do with the spread in lithium abundances.

6. FINAL REMARKS

We report high-resolution spectroscopy observations of 62 solar-type stars in 31 common proper motion pairs of twins. These binaries are sufficiently separated that the evolution of each star is not expected to be influenced by its stellar companion. Lithium abundances have been derived from theoretical fits to the observed spectra using model atmospheres. A comparison with COG abundances derived from Li i equivalent widths and temperatures obtained from near-infrared colors shows that the absolute lithium abundances are reliable to within 0.17 dex (1 $\sigma$).

We have found seven pairs of twins with large lithium abundance differences. The pattern of lithium abundances in our sample of twins seems to be midway between those of the Hyades (tight lithium-$T_{\text{eff}}$ relation) and M67 (large lithium spread for any $T_{\text{eff}}$) open clusters. We have not found any evolutionary models in the literature that provide a satisfactory explanation for the observed spread in lithium abundances in solar-type stars. We plan to follow up with additional studies of our sample of twins to obtain an overall understanding of all the effects that may come into play in the evolution of solar-type stars.

This paper is based on data collected with the 3 m Shane telescope at Lick Observatory, California and the Keck I telescope at the W. M. Keck Observatory, Mauna Kea, Hawaii. The Keck observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. The authors wish to extend special thanks to those of Hawaiian ancestry on whose sacred mountain of Mauna Kea we are privileged to be guests. Without their generous hospitality, the Keck telescope observations presented therein would not have been possible. We thank Louise Good for correcting the English of the manuscript and Geoff Marcy for communicating the results of the radial velocity program for a subset of our sample. We are also indebted to Ann Boesgaard and David Barrado y Navascués for sending data files for lithium abundances of M67 stars and to Nina Kharchenko for astrometric data. The project was partly supported by a SRG grant of AAS to Y. P.

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Fig. 7.—Lithium abundances vs. $T_{\text{eff}}$ for pairs of twins. Our lithium measurements are given as filled circles, with the components of each binary linked by a solid line. The effective temperatures of some pairs are shifted by 30 K to avoid confusion. The components of 16 Cyg are denoted with an open circle and a solid line. The locus of lithium abundances in single stars members of the Hyades cluster is shown with a dotted line. The Hyades data have been taken from Thorburn et al. (1993). Lithium abundances for M67 members are denoted with open hexagons for detected Li i lines, and asterisks denote upper limits. Data for M67 stars come from Hobbs & Pilachowski (1986), Spite et al. (1987), García López, Rebolo, & Beckman (1988), Deliyannis et al. (1994), Pasquini, Randich, & Pallavicini (1997), Jones, Fischer, & Søderblom (1999), Barrett et al. (2001), and D. Barrado y Navascués & S. Balachandran (2002, in preparation).
