LITHIUM ABUNDANCES IN A SAMPLE OF PLANET-HOSTING DWARFS*

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ABSTRACT

This work presents a homogeneous determination of lithium abundances in a large sample of giant-planet-hosting stars (N = 117) and a control sample of disk stars without detected planets (N = 145). The lithium abundances were derived using a detailed profile fitting of the Li i doublet at 6708 Å in LTE. The planet-hosting and comparison stars were chosen to have significant overlap in their respective physical properties, including effective temperatures, luminosities, masses, metallicities, and ages. The combination of uniform data and homogeneous analysis with well-selected samples makes this study well suited to probe for possible differences in the lithium abundances found in planet-hosting stars. An overall comparison between the two samples reveals no obvious differences between stars with and without planets. A closer examination of the behavior of the Li abundances over a narrow range of effective temperature (5700 K ≤ Teff ≤ 5850 K) indicates subtle differences between the two stellar samples; this temperature range is particularly sensitive to various physical processes that can deplete lithium. In this Teff range, planet-hosting stars have lower Li abundances (by ~0.26 dex on average) than the comparison stars, although this segregation may be influenced by combining stars from a range of ages, metallicities, and masses. When stars with very restricted ranges in metallicity ([Fe/H] = 0.00 to +0.20 dex) and mass (M ∼ 1.05–1.15 M☉) are compared, however, both stars with and without planets exhibit similar behaviors in the lithium abundance with stellar age, suggesting that there are no differences in the lithium abundances between stars with planets and stars not known to have planets.

Key words: line: profiles – planetary systems – planets and satellites: formation – stars: abundances – stars: atmospheres

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The physical processes that both create and destroy lithium lead to a complex behavior of its chemical abundance in a variety of astrophysical sites. The abundance of Li in stellar photospheres, in particular, holds important clues to the understanding of various processes, from big bang nucleosynthesis to the formation and evolution of planetary systems (see, e.g., Meléndez et al. 2010b; Santos et al. 2010). The determination of lithium abundances in FGK dwarfs is challenging as it requires high-resolution and high-signal-to-noise (S/N) stellar spectra. In addition, the interpretation of the results is not straightforward as lithium abundances are known to depend on several variables, such as the effective temperature (Teff), metallicity ([Fe/H]) stellar mass, age, rotation, and activity level.

This complexity in the interpretation of lithium abundance results has led to conflicting conclusions concerning possible differences between lithium abundances in planet-hosting stars when compared with stars not known to host giant planets. In this introduction, we briefly discuss the results in these previous studies. One of the first papers to focus on the element lithium in stars with planets was Gonzalez & Laws (2000). This study compared Li abundances in a sample of eight stars with planets to a sample of field stars taken from the literature. After correcting for systematic differences in Teff, [Fe/H] and the Ca ii H+K emission index, log RHK (which is a measurement of the chromospheric emission), from the different studies, the conclusion was that stars with planets have lower Li abundances than non-planet hosts. This initial result, however, was not confirmed by Ryan (2000), who compared Li abundances (from the literature) of planet-hosting stars with those of open cluster and field stars carefully selected to span similar intervals in temperature, age, and chemical composition and found no differences in A(Li)5.

As more planet-hosting stars were discovered, the work by Israelian et al. (2004) obtained lithium abundances for a larger sample of 79 stars hosting planets and 38 stars without planets. This study did not find significant differences between the Li abundances in the two samples but noted that the control sample had too few stars with detectable Li to be used as a comparison. The authors then compared their Li abundances for their sample of planet-hosting stars with a sample of 157 field stars from Chen et al. (2001) and concluded that planet-hosting stars with effective temperatures in the range between 5600 K and 5850 K exhibit an excess of Li depletion. Two possible hypotheses were proposed for explaining this result: increased mixing due to rotational breaking caused by the interaction (during pre-main-sequence evolution) of the host stars with their protoplanetary disks and effective mixing generated by tidal forces resulting from planet migration.

The findings of Israelian et al. (2004) were further confirmed by Takeda & Kawanomoto (2005) with Li abundances derived for a sample of 160 FGK dwarfs and subgiants in the Galactic disk, among which there were only 27 planet-hosting stars. The lithium abundance distributions for planet-hosting and

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5 Here, we adopt the usual notation [Fe/H] = log(NFe/NH)⊙ − log(NFe/NH)⊙.

5 A(Li) = log[(N(Li))/N(H)] + 12.
non-planet-hosting stars in that study were found to be very similar; the size of the planet-hosting stellar sample in Takeda & Kawanomoto (2005), however, was not large enough in order to make meaningful statistical comparisons. If instead of using their own sample of planet-hosting stars, the authors adopted the Li results from Israeli et al. (2004), for planet-hosting stars only, a similar tendency of finding an excess of Li depletion in this sample was obtained, although this was only observed for stars within the narrow range in effective temperature between 5800 K and 5900 K. The study by Chen & Zhao (2006) analyzed smaller samples but also found a higher frequency of Li poor stars within their sample of 16 planet-hosting stars in comparison with 20 control stars, but in this case for stars with effective temperatures ranging between 5600 K and 5900 K.

Contrary results to these findings were obtained by Luck & Heiter (2006), continuing the controversy about Li in planet-hosting stars. This study derived Li abundances homogeneously for a sample of 216 nearby dwarf stars, 55 of which host close giant planets. They found no differences between lithium abundances of stars with and without planets and argued that the low-Li tendency observed by Israeli et al. (2004) was caused by a systematic difference between the temperature scales adopted in the latter work and the study of Chen et al. (2001) (from which the control sample was drawn).

The topic was revisited by Gonzalez (2008) who combined samples of stars from the literature (gathering a total of 37 stars with planets and 147 stars without planets) and corrected for systematic offsets between the $T_{\text{eff}}$, log $g$, [Fe/H], and A(Li) from the different published analyses. Gonzalez (2008) found that planet-hosting stars with $T_{\text{eff}} \sim 5800$ K tend to have lower Li abundances compared to stars not hosting planets. It was suggested in that study that stars with planets also exhibit larger Li abundances near $T_{\text{eff}} \simeq 6100$ K, with the transition occurring at $T_{\text{eff}} \simeq 5950$ K, and that $v \sin i$ and log $R'_{\text{HK}}$ seem to correlate with the lithium abundance.

More recently, Meléndez et al. (2010b), on the other hand, presented results for 4 and 6 stars with and without planets, respectively, with effective temperatures near $T_{\text{eff}} \sim 5800$ K (the same effective temperature regime for which Gonzalez 2008 finds differences). Based on this much smaller but homogeneous set of results, Meléndez et al. (2010b) argue that stars with planets do not show anomalously low Li abundances. A much larger sample observed with HARPS (Guaranteed Time Observations; Sousa et al. 2008) has been analyzed by Israeli et al. (2009). Lithium abundances were obtained for 451 stars, among which there are 70 stars which host planets. This sample was extended to include 16 stars hosting planets and 13 stars without planets (with $5600 \text{K} \lesssim T_{\text{eff}} \lesssim 5900$ K). The results obtained from this sample confirmed the low-Li tendency for planet-hosting stars with effective temperatures in the range between $5600$ K and $5900$ K and $T_{\text{eff}} = 5777 \pm 80$ K (solar analogues). The question about differences in other parameters being responsible for the effect was addressed by Sousa et al. (2010), who showed that differences in mass and age could not be responsible for this enhanced depletion and proposed that the low lithium abundance is directly related to the presence of planets.

Revisiting the topic, Gonzalez et al. (2010) performed a homogeneous analysis and derived Li abundances and $v \sin i$ for a large sample of stars with and without planets (with 90 and 60 stars, respectively). They basically confirm the results of Gonzalez (2008), although finding a lower temperature ($T_{\text{eff}} = 5850$ K) for the transition region between low and high Li abundances in stars with planets (relative to comparison stars). Finally, Baumann et al. (2010) analyzed a sample of 117 solar-like stars, among which there are 14 planet-hosting stars that do not exhibit an enhanced lithium depletion relative to stars without planets. The differences between lithium abundances of stars with and without planets previously found in the literature were attributed to a systematic effect that arises from the comparison of samples with different stellar properties, more specifically age and metallicity.

From a theoretical point of view, recent calculations by Baraffe & Chabrier (2010) predict that episodic large accretion events from protoplanetary disks can enhance Li destruction in stars which host planetary systems. They suggest that this is a possible mechanism for depleting lithium in stars with large planets when compared to stars without.

In Ghezzi et al. (2010b, hereafter Paper I), we performed a homogeneous determination of stellar parameters and metallicities for a large sample of dwarf stars hosting giant planets close in, as well as a sample of control disk stars not known to host large planets. The spectra analyzed in that study had high S/N and covered the spectral region containing the Li i feature at 6707.8 Å. The present study presents the homogeneous determination of lithium abundances for all the stars in Paper I based on a detailed profile fitting of the Li i resonance doublet at 6707.8 Å. This paper is organized as follows. In Section 2, the sample and observational data are briefly described. The profile fitting techniques and resulting lithium abundances are presented in Section 3. Section 4 contains the discussion and interpretation of the results. Finally, concluding remarks are presented in Section 5.

## 2. SAMPLE AND OBSERVATIONAL DATA

The sample of stars analyzed in this study is comprised of 117 stars hosting large planets and 145 comparison disk stars. The target stars were previously analyzed in Paper I, where stellar parameters and iron abundances were derived. The sample of main-sequence stars with planets was selected (until 2008 August) from the Extrasolar Planet Encyclopaedia given the constraints on object observability from La Silla Observatory. In addition, a control sample of main-sequence stars without detected planets so far was compiled from the subset of 850 nearby FGK stars in Fischer & Valenti (2005), which has been monitored in planet search programmes. The selection criteria were such that the stellar properties of the control stars matched those of stars with planets (which makes this comparison sample adequate for the lithium study presented here).

High-resolution ($R \sim 48,000$) and high signal-to-noise ($S/N \sim 200$) spectra were obtained with the Fiber-fed Extended Range Optical Spectrograph (FEROS; Kaufer et al. 1999) attached to the MPG/ESO-2.2 m telescope (La Silla, Chile) during six observing runs between 2007 April and 2008 August. The data reduction was done with the FEROS Data Reduction System (DRS) and followed standard procedures for echelle spectra. A complete description of the sample selection, observations, and data reduction can be found in Paper I and we refer to this previous study for details.

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6. Available at http://exoplanet.eu

7. Under the agreement ESO-Observatório Nacional/MCT

8. Available at http://www.eso.org/sci/facilities/lasilla/instruments/feros/tools/DRS/index.html
3. ANALYSIS

The determination of Li abundances from synthetic spectra requires a line list for the spectral region around the Li i feature at 6707.8 Å. The line list adopted here was taken from Ghezzi et al. (2009), but removing the \(^6\)Li components (not measurable at the resolution of FEROS spectra). The model atmospheres adopted in the calculations were interpolated from the ODFNEW grid of ATLAS9 models\(^9\) (Castelli & Kurucz 2004). Stellar parameters and metallicities ([Fe/H]) for the target stars were taken from Table 3 of Paper I. Briefly, the atmospheric parameters (\(T_{\text{eff}}, \log g, [\text{Fe/H}],\) and \(\xi\)) were derived in local thermodynamic equilibrium (LTE) following standard spectroscopic methods (excitation and ionization equilibria based on Fe i and Fe ii lines; see Paper I for all the details on these determinations). The 2002 version of the code MOOG\(^10\) (Sneden 1973) was used to compute synthetic spectra in the Li region. The limb darkening coefficient was varied between 0.0 and 1.0 (Van Hamme 1993), however, the choice of this coefficient has little, if any, effect on the Li i line profile and the impact on the derived lithium abundances is negligible.

In this study, we adopted the following procedure in order to determine Li abundances for the target stars. First, it was assumed that the broadening of spectral lines was represented by a single Gaussian smoothing function which combined the effects of stellar rotation, macroturbulence, and instrumental profile. A grid of synthetic spectra was then computed for combinations of the Gaussian full width at half-maximum (FWHM\(_{\text{Gauss}}\)) and lithium abundance. The best fit between the synthetic and observed profiles was obtained through a reduced \(\chi^2\)-minimization in the spectral interval between 6707.3 and 6708.4 Å (including mainly, besides the Li i doublet, an Fe+CN and a Ca+CN feature). Small adjustments in the continuum level were allowed in order to compensate for possible errors in the continuum normalization. Also, wavelength shifts of the observed spectra were needed in order to account for radial velocity shifts. The abundances of Fe, CN, Si, Ca, and V were kept as free parameters in this first step in order to properly match their contributions and improve the overall quality of the fits. Such adjustments in the elemental abundances, however, do not affect the derivation of the Li abundances, as their contributions to the global feature are clearly distinguishable from the Li i line. This first step provided the best-fit lithium abundance, as well as values of \(r\) (continuum displacement), \(w\) (wavelength shift), and FWHM\(_{\text{Gauss}}\). Such quantities were then kept fixed but the broadening was then separated into the contributions of macroturbulence and instrumental profile (combined as a single Gaussian) and the stellar rotational velocity profile. A new grid of synthetic spectra was computed. The best fit between synthetic and observed profiles was again obtained through a reduced \(\chi^2\)-minimization in the spectral interval between 6707.3 and 6708.4 Å. Given the intrinsic spectrograph resolution of FWHM\(_{\text{Inst}}\) = 6.25 km s\(^{-1}\), with typical macroturbulence velocities of \(\sim\)4.00 km s\(^{-1}\), the combined broadening is equivalent to 7.40 km s\(^{-1}\). Tests reveal that for the majority of stars sampled, which rotate rather slowly, this analysis technique cannot distinguish between macroturbulence velocities and projected rotational velocities \(v \sin i\); because of the large relative uncertainty in almost all of the values of \(v \sin i\) derived in this way, we do not include any further discussion of \(v \sin i\) values determined here.

\(^9\) Available at http://kurucz.harvard.edu/

\(^{10}\) Available at http://www.as.utexas.edu/~chris/moog.html

The determination of Li abundances described above was done in an automated way with the aid of BASH and FORTRAN codes: lithium abundances for the entire sample of 262 stars studied here could be derived in \(\sim\)2 days. All automatically obtained fits were inspected visually and manual corrections were needed for approximately 10% of the cases. The stars with non-optimum fits generally had spectra with low S/N values, or extremely weak or non-measurable Li lines for which only upper limits to the Li abundances could be derived. Figure 1 shows the best fit between observed and synthetic spectra obtained for target star HD 52265 as an example. Table 1 lists the values of FWHM\(_{\text{Gauss}}\) (Column 2) which include instrumental profile, macroturbulence, and stellar rotation, and derived \(A(\text{Li})\) (Column 3) for all studied stars. The Li abundance in the Sun was also derived using a solar spectrum observed with the FEROS spectrograph on 2008 August 20. The result obtained for the Sun is \(A(\text{Li}) = 0.99 \pm 0.16\), which is in agreement with recent solar abundance determinations which are based on three-dimensional (3D) hydrodynamical models and take non-LTE effects into account (\(A(\text{Li}) = 1.05 \pm 0.10\) from Asplund et al. 2009; \(A(\text{Li}) = 1.03 \pm 0.03\) from Caffau et al. 2010).

We compared the results obtained here with those from Ghezzi et al. (2009), which were based on much higher quality...
bHROS spectra ($R \sim 150,000$ and $S/N \gtrsim 700$). For the six stars in common (namely, HD 17051, HD 36435, HD 74156, HD 82943, HD 147513, and HD 217107), we find the average difference (in the sense “FEROS − bHROS”) to be $\langle \Delta(A(Li)) \rangle = 0.01 \pm 0.09$. The agreement between these two sets of results is very good.

### 3.1. Uncertainties

The formal uncertainties in the derived best-fit lithium abundances can be calculated by varying $A(Li)$ around its best value and computing $\chi^2$, for each lithium abundance tested, the quantity $\Delta \chi^2 = \chi^2 - \chi^2_{\min}$. The difference between $A(Li)$ and $A(Li)_{\text{best}}$ that gives $\Delta \chi^2 = 1$ is taken as the 1σ uncertainty. The derived lithium abundances and their formal uncertainties are presented in Column 3 of Table 1. The lithium abundances, however, are also sensitive to uncertainties in the effective temperature parameter: $\delta T_{\text{eff}} = \pm 100$ K introduces an uncertainty of $\sim 0.1$ dex in the derived lithium abundances for most sample stars; for the cooler stars ($T_{\text{eff}} \sim 5000$ K) the sensitivity to $T_{\text{eff}}$ is slightly larger ($\sim 0.15$ dex). The sensitivity of $A(Li)$ to variations in the adopted log $g$'s and microturbulent velocities is only marginal: a change in log $g$ of $\pm 0.5$ dex changes the lithium abundance by $0.01$−$0.02$ dex, with a slightly larger sensitivity of $\sim 0.05$ dex for the coolest stars in our sample. A change in the microturbulent velocity by $\pm 0.5$ km s$^{-1}$ has virtually no effect on the derived $A(Li)$. The total uncertainties in the derived lithium abundances are then calculated by the addition of all these uncertainties in quadrature, assuming that the errors are independent. The total estimated uncertainties in the derived $A(Li)$ abundances in this study are in Column 4 of Table 1.

Non-LTE effects have not been considered in this Li abundance analysis and these will contribute to the total error budget. Takeda & Kawanomoto (2005) calculated non-LTE Li abundances for their sample of stars with effective temperatures ranging between 5000 K and 7000 K and metallicities $-1.0 < [\text{Fe/H}] < +0.40$ dex. The non-LTE corrections in that study were found to range between $-0.1$ dex $< \Delta < +0.1$ dex. Stars in restricted ranges in effective temperatures and metallicities, however, have similar non-LTE corrections. The stars with detected Li i lines in this study have effective temperatures roughly between 5700 K and 6200 K (as will be shown in Figure 6). For these hotter dwarfs, with $A(Li) < 3.00$, the non-LTE corrections are found to be small in the recent study of Lind et al. (2009).

### 4. DISCUSSION

#### 4.1. Comparisons within the Samples: Metallicities, Masses, Ages, and Activity

As mentioned previously, interpreting lithium abundances can be a complex process because these abundances depend on a number of parameters, such as effective temperature, metallicity, mass, age, rotation, as well as the stellar activity level. The behavior of Li with $T_{\text{eff}}$ can only be isolated if samples with similar metallicities, masses, ages, and activity levels are compared. The stars in the sample considered here are dwarfs, as shown in Figure 2; all targets lie on the main sequence.

The metallicity distributions of the studied stars are shown in panel “a” of Figure 3 (same as Figure 9 of Paper I). As discussed in Paper I, there is a visible offset between the distributions of stars with and without planets; the average metallicity of stars hosting giant planets is 0.15 dex higher than that of the comparison stars. This metallicity offset, however, has a negligible effect on the Li abundances, as can be noted from panel “b” of Figure 3 where Li is shown versus [Fe/H]. The samples of stars with and without planets have considerable overlap with no significant trend of the lithium abundance with metallicity found over the roughly 1.0 dex change in [Fe/H] for the stars studied here. Also, the Sun does not exhibit any peculiarity in this plot.

Panel “c” of Figure 3 presents the mass distributions for the two studied samples. The adopted values for the stellar masses correspond to the $M_{\text{track}}$ values presented in Table 4 of Paper I (see that paper for details on the derived masses). The samples of stars hosting planets (represented by the red solid line histogram) and without planets (represented by the blue dashed line histogram) overlap closely in mass. The average masses for stars with and without planets are, respectively, $\langle M \rangle = 1.05 \pm 0.16$ and $1.02 \pm 0.17 M_\odot$; there is a probability of 92%, based on a two-sample Kolmogorov–Smirnov (K-S) test that they are drawn from the same parent population of mass distributions. Panel “d” of Figure 3 reveals a tendency of higher Li abundances with increasing mass. This is expected (see, e.g., Lambert & Reddy 2004), as lower mass stars have deeper convective zones in which Li is destroyed more efficiently. The location of the Sun in this diagram (represented by the black star symbol) indicates it to be a normal star when compared to the samples of stars with and without planets.

The age distributions for the sample stars are shown in panel “a” of Figure 4. The stellar ages were taken from Table 4 of Paper I (see that paper for details). An inspection of the two histograms in this panel (red solid line representing stars with planets and blue dashed line representing stars without planets) indicates that overall there is not a significant difference between the age distributions of the two samples; the average values are: $\langle \text{Age}_{\text{HStars}} \rangle = 5.24 \pm 2.48$ Gyr and $\langle \text{Age}_{\text{NonP–HStars}} \rangle = 5.41 \pm 2.86$ Gyr. The probability that these two samples belong to the same parent population (from a K-S test) is 84%. In panel “b” of Figure 4, we observe an expected slight dependence of $A(Li)$ upon age, with lower abundances being found for older stars.
Figure 3. (a) Metallicity distributions of planet-hosting (solid red line) and comparison (blue dashed line) stars from Paper I. (b) Lithium abundances vs. metallicity for stars with (red symbols) and without (blue symbols) planets. Open circles are detected abundances and inverted triangles denote upper limits. The Sun is represented by a black star. (c) Same as panel (a) but for masses. (d) Same as panel (b) but replacing metallicity with mass.

(A color version of this figure is available in the online journal.)

However, the behavior of stars with and without planets seems indistinguishable.

Panel “c” of Figure 4 shows histograms comparing the chromospheric activity indices (log $R'_{HK}$) for the two samples studied here. The values of log $R'_{HK}$ for the target stars were taken, whenever available, from Henry et al. (1996), Tinney et al. (2002), and Wright et al. (2004). An evaluation of possible systematic differences between the chromospheric activity indices in these studies follows. Tinney et al. (2002) find that the activity indices in their study are consistent with those from Henry et al. (1996). A comparison of indices for 13 stars in our sample which appear in both studies finds good agreement: the linear fit to the two data sets has a slope of 0.98 ± 0.12, a correlation coefficient $R = 0.92$, and a mean difference (in the sense “Tinney et al. − Henry et al.”) of −0.01 dex. The works of Henry et al. (1996) and Wright et al. (2004) have 17 stars in common which are also present in our sample. A linear fit for these values reveals no significant trend, having a slope of 0.99 ± 0.04 and a correlation coefficient $R = 0.99$. There is just an offset in the averages of −0.04 dex, with the indices from Henry et al. (1996) being higher than those in Wright et al. (2004).

Henry et al. (1996) and Wright et al. (2004) have 17 stars in common which are also present in our sample. A linear fit for these values reveals no significant trend, having a slope of 0.99 ± 0.04 and a correlation coefficient $R = 0.99$. There is just an offset in the averages of −0.04 dex, with the indices from Henry et al. (1996) being higher than those in Wright et al. (2004). Henry et al. (1996) derived an error of 0.052 for log $R'_{HK}$, while Wright et al. (2004) state that the uncertainties in log $R'_{HK}$ are not larger than 13% (which would correspond to ~0.057 for log $R'_{HK} \approx -4.90$). As the offset between the two studies is compatible with the errors in log $R'_{HK}$, no corrections in the indices were attempted in order to bring them to a consistent scale. In this study, whenever a star had more than one log $R'_{HK}$ value, the average value was adopted.

Panel “c” of Figure 4 indicates that there is a visible offset between the distributions of log $R'_{HK}$ for stars with and without planets, with a probability of $6.80 \times 10^{-5}$ that they are drawn from the same population. This result is a consequence of the greater number of planet-hosting stars with low activity levels. We note that this fact may be related to a bias in the Doppler detection method, which is more accurate for inactive stars. In spite of this offset, the average chromospheric activity indices for planet-hosting and comparison stars are, respectively, log $R'_{HK} = -4.94 \pm 0.16$ and $-4.87 \pm 0.17$ dex. The overall global difference of 0.07 dex is interesting but cannot be considered as significant since it is roughly of the same order of the uncertainties discussed above. Panel “d” of Figure 4 shows that there is no clear correlation between Li abundances and log $R'_{HK}$ and no visible difference in the behavior of stars with and without planets. Finally, the Sun (log $R'_{HK} = -4.96$; Wright et al. 2004) does not seem to be anomalous.

The comparisons of the various quantities discussed above show that the samples of planet host and comparison stars are similar in their mass and age distributions, although the metallicities do show a significant difference, with the planet-hosting stars being on average more metal rich (as discussed in Paper I). Small differences are found in their respective activity levels, but neither the metallicity nor the activity levels produce obvious trends with the lithium abundances.
4.2. Lithium Abundances

Possible differences between Li abundances in stars with and without planets remains an active topic of discussion (Israelian et al. 2009; Sousa et al. 2010; Gonzalez et al. 2010; Baumann et al. 2010). In order to investigate such possible differences, we first examine the lithium abundance distributions for all stars in our sample, which are shown as the histograms in panel “a” of Figure 5. In this initial discussion, upper limits were included in the construction of this plot. An inspection of panel “a” reveals two interesting features. First, we can clearly see a bimodal distribution, with peaks located at $A_{\text{Li}} \sim 0.5$ and 2.4 dex. Second, the similarity in the distributions of stars with and without planets is evident, with a significant difference being visible only in the bin centered at $A_{\text{Li}} = 0.4$ dex, which is dominated by upper limits; these facts become more evident if we analyze the cumulative distributions which are shown in panel “b” of Figure 5. The differences between the distributions are probably a result of the inclusion of those stars with only upper limits to the Li abundances. In fact, if only detected Li abundances are considered, the distributions become more similar, as can be seen in panels “c” (histogram) and “d” (cumulative distribution) of Figure 5. The average detected lithium abundances of stars with and without planets are $(A_{\text{Li}}) = 2.06 \pm 0.63$ and $2.06 \pm 0.60$ dex, respectively, and the probability that the two samples belong to the same parent population is 87% (K-S test). Therefore, this broad comparison of the entire sample does not seem to reveal any anomaly in the Li abundances of planet-hosting stars.

Differences between Li abundances in stars with and without planets have been reported in the effective temperature range $5600 \text{ K} \lesssim T_{\text{eff}} \lesssim 5900 \text{ K}$ (Israelian et al. 2009). In order to investigate this behavior in our samples, the lithium abundances derived in this study are plotted versus the effective temperatures of the target stars in Figure 6. This plot holds some interesting features. First, the detection limit of our method varies with $T_{\text{eff}}$ roughly as $0.07 \text{ dex}/100 \text{ K}$, increasing from $\sim 0.3$ dex at $\sim 4800 \text{ K}$ to $\sim 1.5$ dex at $\sim 6500 \text{ K}$. Also, the well known decrease in lithium abundances with declining temperatures is recovered (see, e.g., Takeda & Kawanomoto 2005; Luck & Heiter 2006). This behavior is ultimately a reflection of the trend seen in panel “d” of Figure 3, as higher mass stars on the main sequence also have higher effective temperatures. As there are three clearly distinct Li regimes in Figure 6 (hotter stars with high $A_{\text{Li}}$; intermediate $T_{\text{eff}}$ stars with $A_{\text{Li}}$ declining; and low $T_{\text{eff}}$ stars with Li upper limits), in the following we discuss them separately (see Figure 7).

For $T_{\text{eff}} < 5600 \text{ K}$ (upper most panel of Figure 7), almost all stars have very low Li abundances ($\lesssim 0.7$–0.8 dex) and only upper limits could be derived in most cases. With only upper limits, it is not possible to probe any possible differences in $A_{\text{Li}}$ in stars hosting planets compared to stars not known to host planets. The exceptions to upper limits are: HD 1237, HIP 14810, AB Pic, HD 69830, and HD 181433 (stars with...
Figure 5. Distributions of lithium abundances for planet-hosting (red solid lines) and comparison (blue dashed lines) stars. Panels (a) and (b) show the frequency and cumulative distributions, respectively, for all stars in our sample. Panels (c) and (d) present the same plots, but only for those stars with detected Li abundances.

(A color version of this figure is available in the online journal.)

Figure 6. Lithium abundances vs. effective temperatures for planet-hosting (red symbols) and comparison (blue symbols) stars. Determined abundances are represented by circles and upper limits are denoted by downward triangles. The dashed line shows the detection limit of our method. The black star represents the Sun.

(A color version of this figure is available in the online journal.)

planets); HD 17925, HD 36435, HD 118972, HD 128674, and HD 212291 (stars without planets). The two stars exhibiting extremely high Li abundances are AB Pic (A(Li) = 3.35 dex) and HD 17925 (A(Li) = 2.66 dex). As already noted by Takeda & Kawanomoto (2005), HD 17925 is a young star with high activity level (log $R'_\text{HK}$ = -4.30; Henry et al. 1996). AB Pic is a young star identified as a member of the Tucana–Horologium association (Song et al. 2003), which has an estimated age of $\sim$30 Myr. In Paper I, upper limits of 1 Gyr were derived for the ages of these two stars. The same upper limit is derived in Paper I for HD 1237, which has A(Li) = 2.16 dex and is also a young, active star (age of 0.02 Gyr and log $R'_\text{HK}$ = -4.27; Naef et al. 2001). The stars HD 36435 and HD 181433 have uncertain ages because they are located in crowded regions of their respective grids of isochrones. Based on its chromospheric activity level (log $R'_\text{HK}$ = -5.11; Bouchy et al. 2009) and does not seem to be young. Although consistent with the chromospheric activity level, its lithium abundance (A(Li) = 0.76 dex) is relatively high when compared to stars of the same temperature (difference of $\sim$0.35 dex). The lithium abundance of HD 212291 also seems to be higher (by $\sim$0.25 dex) than the typical value for stars with similar $T_{\text{eff}}$. Although its age is uncertain (the star is located in a crowded region of its grid of isochrones), its activity level (log $R'_\text{HK}$ = -4.82; Wright et al. 2004) shows that it may be younger than the Sun, which could explain the value of the Li abundance. Finally, the four remaining stars (HIP 14810, HD 69830, HD 118972, and HD 128674) have Li abundances consistent with those of other stars within the same temperature
range. In this lower temperature regime ($T_{\text{eff}} < 5600$ K), there are 41 and 34 stars with and without planets, respectively; this corresponds to the largest sample analyzed to date. If we do not consider the stars with high Li abundances (HD 1237 and AB Pic in the planet-hosting sample; HD 17925 and HD 36435 in the comparison sample), a general overlap of the two samples is clear. Taking the upper limits as real detections, we find that the average Li abundances of planet-hosting and comparison stars are, respectively, $\langle A(\text{Li}) \rangle = 0.37 \pm 0.25$ and $0.35 \pm 0.28$ dex.

In the hotter main-sequence stars in this sample, where $T_{\text{eff}} > 5900$ K (bottom most panel of Figure 7), most have $A(\text{Li}) \sim 1.5$–3.0. There are, however, a small number of stars with only upper limits, and we note that some of these stars (with low Li abundance and $T_{\text{eff}} \gtrsim 6300$ K) may be in the Li dip (see Boesgaard & Tripicco 1986; Balachandran 1995). In this temperature interval, there are 34 and 54 planet-hosting and comparison stars, respectively, with considerable overlap. It is clear that the number of stars with planets diminishes with increasing temperature, reflecting the limitation of radial velocity surveys. Also, we notice that eight comparison stars belong to the low-Li group, while only one star with a planet has an upper limit on its Li abundance. Although this feature can also be seen in Takeda & Kawanomoto (2005) and Luck & Heiter (2006), we are not sure if this is related to any physical effect or selection bias. Considering only detected lithium abundances, we obtain $\langle A(\text{Li}) \rangle = 2.42 \pm 0.31$ and $2.44 \pm 0.32$ dex for stars with and without planets, respectively. Thus, we do not find the excess Li abundances for planet-hosting stars with $T_{\text{eff}} \sim 6000$ K discussed in Gonzalez (2008) and Gonzalez et al. (2010), and find no detectable differences in the Li abundances between stars with and without planets in the most massive stars of the sample ($M \gtrsim 1.2 M_\odot$).

A more complicated behavior of the Li abundance occurs in the transition region between high and low Li, within the temperature interval $5600$ K $\lesssim T_{\text{eff}} \lesssim 5900$ K (middle panel of Figure 7). In this temperature regime, there are 42 and 57 stars with and without planets, respectively, in our sample. The overlap is considerable, except in the narrow range of $T_{\text{eff}} \sim 5700$–5800 K. Over the entire temperature range shown in this panel ($T_{\text{eff}} = 5600$–5900 K), 26 planet-hosting stars (or 62%) have detected Li abundances, with an average value of $A(\text{Li}) = 1.68 \pm 0.53$ dex. For the comparison stars, the average lithium abundance for 37 stars (65%) with detections is $A(\text{Li}) = 1.69 \pm 0.54$ dex. Treating the upper limits as actual detections, we derive $A(\text{Li}) = 0.58 \pm 0.11$ and $0.62 \pm 0.17$ dex for stars with and without planets, respectively. Finally, it is interesting to note that the Sun does not exhibit an excessive Li depletion; actually, it looks like a “normal” main-sequence star.

Within this complex temperature transition region for Li, if we now follow the analysis of Israeli et al. (2009) and keep only stars within the very narrow range of $T_{\text{eff}} = 5777 \pm 80$ K, the sample here is left with 21 planet-hosting and 27 comparison stars. For the sample of stars with planets, the average is $A(\text{Li}) = 1.50 \pm 0.44$ dex for the 16 detections (76%) and $A(\text{Li}) = 0.65 \pm 0.08$ dex for the 5 upper limits. For the control sample, the average is $A(\text{Li}) = 1.76 \pm 0.48$ dex for the 19 detections (70%) and $A(\text{Li}) = 0.64 \pm 0.11$ dex for the 8 upper limits. Following the analysis of Gonzalez et al. (2010), on the other hand, we have 20 and 30 planet-hosting and comparison stars, respectively, in the temperature interval 5650–5800 K. For the former group, we obtain $A(\text{Li}) = 1.30 \pm 0.26$ dex for the 13 detections (65%) and $A(\text{Li}) = 0.63 \pm 0.08$ dex for the 7 upper limits. For the control sample, we derive $A(\text{Li}) = 1.45 \pm 0.47$ dex for the 16 detections (53%) and $A(\text{Li}) = 0.64 \pm 0.11$ dex for the 14 upper limits. These comparisons between Li abundances in planet-hosting stars and comparison stars using the different $T_{\text{eff}}$ boundaries as defined by Israeli et al. (2009) and Gonzalez et al. (2010) are intriguing, with averages differences of $+0.26$ dex and $+0.15$ dex, respectively. Note, however, that in the latter case, in particular, the average lithium abundances in the two samples overlap within our estimated uncertainties.

It is interesting to investigate in more detail the Li abundances derived here for stars falling in the narrow $T_{\text{eff}}$ range centered on the solar effective temperature as used by Israeli et al. (2009), since this temperature interval resulted here in the larger difference of $+0.26$ dex. The Israeli et al. sample in this $T_{\text{eff}}$ interval contains more stars than analyzed here, with 23 planet-hosting stars and 60 comparison stars, compared to 21 and 27 stars here. The Li abundance distribution from Israeli et al. (2009) is heavily influenced by non-detections of Li and thus, upper limits to $A(\text{Li})$, with 17 and 28 upper limits for planet-hosting stars and comparison stars, respectively. Taking the remaining Li detections from Israeli et al., which span values of $A(\text{Li}) \sim 1.0$–3.0, and examining the cumulative fraction of $A(\text{Li})$ reveals a shift toward larger Li abundances in the stars without planets, as discussed in Israeli et al. (2009). This same procedure is carried out for the samples of stars here, where there are only 5 upper limits in planet-hosting stars and 8 upper limits in comparison stars. The cumulative fractions of $A(\text{Li})$ in the two sets of stars also show that the comparison stars are shifted.
toward somewhat larger values of $A$(Li), but not as large a shift as found by Israelian et al. (2009). Taken together, we find the same effect as found by Israelian et al., however the difference in the samples here is not as large. It is worthwhile to probe for other differences between planet-hosting and comparison stars that might pertain to these possibly real differences in Li abundances between the two sets of stars.

Stellar rotation would be an obvious candidate on which to focus more closely in trying to understand why there might be differences in $A$(Li) between the planet-hosting and comparison star samples, however such a study is not feasible at the spectral resolution of the observed spectra studied here given the considerable degeneracy between macroturbulence and \( \sin i \).

Another observational variable to investigate is the stellar activity level in the different types of stars studied here for lithium. The index of stellar activity discussed in Section 4.1 is \( \log R'_{\text{HK}} \) and this index is plotted in Figure 8 versus \( T_{\text{eff}} \) over the limited range 5700–5850 K. Within this narrow temperature range, which was the focus of the discussion in Israelian et al. (2009), it is clear that the planet-hosting stars tend to fall toward lower values of \( \log R'_{\text{HK}} \) relative to the comparison stars.

The point noted above about differences in stellar activity levels is made clearer by the respective frequency distributions and cumulative fractions of \( \log R'_{\text{HK}} \) shown in the top and bottom panels of Figure 9, respectively. The comparison stars are shifted significantly toward larger levels of stellar activity when compared to planet-hosting stars. Within a sample of stars which have a restricted range in mass and effective temperature, such as the small subset of stars being discussed here, the value of \( \log R'_{\text{HK}} \) is likely related to both rotational velocity and age, with both the rotational velocities and chromospheric activity decreasing with increasing age. As noted above, all of the stars studied here within this range of \( T_{\text{eff}} = 5700$–5850 K are slow rotators, thus it is not possible to directly disentangle differences in rotation between stars with and without planets. The other main parameter associated with chromospheric activity and rotation is age; a detailed comparison of derived ages from Paper I between the planet-hosting and comparison stars reveals no significant difference in the age distributions, however it must be noted that the age estimates come with large uncertainties of typically $\pm 2$–3 Gyr.

Takeda et al. (2010) has already noted the difference in chromospheric activity levels between stars with and without planets and argue that the differences in activity levels are rooted in differences in the underlying rotational velocities. The picture put forth in Takeda et al. (2010) is that the stars with planets tend to rotate more slowly (with less stellar activity) due to the influence of giant planets or massive protoplanetary disks slowing down stellar rotation early in the evolution of the parent star.

Sousa et al. (2010) have also investigated the behavior of the Li abundance in stars with and without planets across the 5700–5850 K range in \( T_{\text{eff}} \) and find differences in the behavior of $A$(Li), with the stars with planets having smaller abundances of Li. They investigate the stellar parameters age and mass and conclude that neither the age distributions nor the mass distributions are different for stars with and without planets and thus suggest that the observed difference in lithium abundances is likely due to some process related to the formation of planetary systems (as also concluded by Takeda et al. 2010).

Most recently, Baumann et al. (2010), in a study of 117 solar-like stars, find strong correlations of a decrease in the lithium abundance with stellar age but do not find any differences in the behavior of Li in planet-hosting stars compared to stars without known planets when rather restricted ranges in stellar masses and metallicities are enforced. They suggest that the previously identified differences were due to systematic biases caused by combinations of age and metallicity in the samples.

We investigate the conclusions from Baumann et al. (2010) by restricting the metallicity and mass of the sample of stars
studied here and comparing the $A$(Li)—stellar age relations for stars with planets and those stars without. Using a similar procedure as that in Baumann et al. (2010), we isolate a subset of stars from the already restricted range in effective temperature ($T_{\text{eff}} = 5700–5850$ K) with [Fe/H] = 0.00 to $+0.20$ dex. (or $+0.10 \pm 0.10$). Within this parameter range, there are 12 stars without planets having measured Li abundances (and an additional 3 with upper limits) and 6 planet-hosting stars. The parameters of these two sets are closely matched, with the means and standard deviations of stars with planets and stars without planets being, respectively, [Fe/H] = $+0.12 \pm 0.05$ and $+0.10 \pm 0.03$; $M = 1.12 \pm 0.05$ and 1.09 $\pm 0.06 M_\odot$; and age = 6.1 $\pm$ 1.5 and 5.4 $\pm$ 2.0 Gyr. The values of $A$(Li) versus stellar age are plotted in Figure 10 for the planet-hosting stars and stars without known planets. In this case, there is no significant difference in the behavior of $A$(Li) with stellar age between the two stellar samples. As noted by Baumann et al. (2010), when the stellar parameters which are known to influence Li abundances over time are restricted, the behaviors of $A$(Li) in stars with and without planets appear very similar.

Given that there remains some uncertainty in the detailed behavior of $A$(Li) and the underlying processes that shape this behavior, the observation noted here that stars with planets tend to exhibit lower stellar activity levels remains. However, at this point, this signature cannot be separated from observational biases which are present in planet detection from radial velocity measurements. Lower values of stellar activity may result in smaller intrinsic radial velocity variations, making the chromospherically quiet stars targets around which planets producing small RV amplitudes can still be detected.

5. CONCLUSIONS

This paper is the third in a series which analyzes chemical abundances in a sample of planet-hosting stars and a comparison sample of disk stars. Paper I presented metallicities, [Fe/H], for dwarf stars; Paper II (Ghezzi et al. 2010a) analyzed samples of subgiants and giant stars, and the present paper analyzes the element lithium in the same main-sequence targets as in Paper I. These targets consist of 117 planet-hosting stars and 145 comparison stars not known to host giant planets.

Lithium abundances are potentially important for a better understanding of processes involved in the formation and evolution of planetary systems. Several recent studies in the literature have looked into possible differences between Li abundances of stars with and without planets but so far have yet to reach a full consensus regarding a possible excess Li depletion in planet-hosting stars (see, e.g., reviews by Meléndez et al. 2010a and Santos et al. 2010). The combination of uniform data and homogeneous analysis with well-selected samples makes the results in this study well suited to investigate possible differences in the Li abundances found in planet-hosting stars.

Lithium abundances were derived through an automated profile fitting of the Li i resonance doublet at $\lambda$6707.8 Å. As a test, the automated analysis of the Sun as a normal target star yields a lithium abundance $A$(Li) = 0.99 $\pm$ 0.16 dex; this result is in good agreement with recent NLTE 3D abundance determinations done by Asplund et al. (2009) and Caffau et al. (2010). When compared to stars with similar properties in our sample (irrespective of the presence of planets), the Sun appears to have a normal Li abundance.

Lithium abundances were not found to exhibit significant trends with metallicity and stellar activity levels. It is possible, though, to identify a slight negative correlation with age. The most significant dependence is with effective temperature or, alternatively, mass. Hotter (more massive) stars have higher Li abundances. This is a well-known effect related to the variation of the depth of the convective zone as a function of mass.

The most suggestive difference between planet-hosting stars and the comparison stars occurs in the narrow $T_{\text{eff}}$ range from 5700 to 5850 K, where the behavior of the Li abundance is perhaps the most complex. Within this restricted temperature range, we find that the comparison stars tend to have on average somewhat larger Li abundances than the planet-hosting stars; this is similar to earlier results from Israelian et al. (2009) and Gonzalez et al. (2010), although the differences found here are smaller. Within this sample of stars, the planet-hosting stars also tend to exhibit lower levels of stellar chromospheric activity $\log R_{\text{HK}}$ relative to the comparison stars, thus mirroring the behavior of the lithium abundances. This difference in chromospheric activity could be due to planet-hosting stars being somewhat older or rotating more slowly (or a combination of both). Perhaps a more likely explanation is that this is a selection effect, as the chromospherically quieter stars exhibit smaller radial velocity jitter and thus represent easier stars around which to find Doppler-detected planets.

Within the effective temperature interval between 5700 and 5850 K, when more constrained samples of stars having quite restricted ranges in stellar mass and metallicity are compared, however, no differences in the behavior of $A$(Li) versus stellar age were found between stars with and without (known) planets. The results for lithium abundances presented here highlight the importance of comparing samples which are as restricted as possible in all parameters, however, in such cases conclusions are based on a much smaller number of objects and thus require further confirmation. As the number of planet-hosting stars continues to grow, larger samples with restricted masses and metallicities will be available to probe the real behavior of lithium and to fully understand the influence of planets on the lithium abundance of the host stars.
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Note added in proof. Lovis et al. (2010) recently announced the discovery of up to seven low-mass planets ($M < 65M_{\oplus}$) orbiting the solar-type star HD 10180, which is included in the comparison sample in this study. If this star is moved to the planet-hosting sample, negligible changes in the average lithium abundances ($\leq 0.01$ dex) are observed. Also, it has a $T_{\text{eff}} = 5933$ K and does not belong to the solar analogues sample, which is the main focus of our discussion. Thus, the consideration of HD 10180 as a planet-hosting star (instead of a comparison star) does not change any of the conclusions presented in this study.

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