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The Host Stars of Extrasolar Planets Have Normal Lithium Abundances

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ABSTRACT

The lithium abundances of planet-harbouring stars have been compared with those of open clusters and field stars. Young (chromospherically active) and subgiant stars have been eliminated from the comparison because they are at different stages of evolution and Li processing to the planet-harbouring stars, and hence have systematically higher Li abundances. The analysis showed that the Li abundances of the planet-harbouring stars are indistinguishable from those of non-planet-harbouring stars of the same age, temperature, and composition. This conclusion is opposite to that arrived at by Gonzalez & Laws (2000); it is believed that the field star sample used by them contained too wide a range of ages, evolutionary types, and temperatures to be accommodated by the model they adopted to describe the dependence on parameters. Li does not appear set to provide key insights into the formation and evolution of planetary systems.

Key words: planetary systems — stars: abundances — solar system: formation

1 INTRODUCTION

The discovery of tens of extra-solar planets over recent years (Wolszczan 1994; Mayor & Queloz 1995; Marcy & Butler 2000) has re-invigorated efforts to understand the processes by which planetary systems form. The existence of more than one system — the solar system — to study and the prospect of many more being discovered has spurred this effort.

One way to help understand the formation of planetary systems is to discover characteristics which distinguish planet-harbouring stars from lone stars. They are more metal rich than the general stellar population (Fuhrmann, Pfeiffer & Bernkopf 1997; Gonzalez 1997, 1999), and the difference between solar photospheric and meteoritic abundances correlates with elemental condensation temperature, consistent with self-enrichment of the solar surface (Gonzalez 1997). Gonzalez (1999) discusses the anomalously small velocity of the sun relative to the local standard of rest (LSR), but the explanations are based on anthropic arguments which do not tell us about other planetary systems. Genuine characteristics not only provide information to help understand the formation of these systems, but could also help bias future searches towards planet-harbouring systems of that type.

Perusal of the characteristics of exoplanet hosts can give the impression that they are unusually Li deficient compared to lone stars. Several stars now known to have planetary systems were flagged as having low Li abundances *prior* to the discovery of their companions. HR 5968 (ρ CrB) was singled out by Lambert, Heath & Edvardsson (1991), and Friel et al. (1993) commented on the large Li difference between 16 Cyg A and B despite their similar temperatures, though they did not suggest that processes other than normal single-star evolution would be needed to explain the lower abundance in 16 Cyg B. As a third example, the low Li abundance in the solar photosphere (A(Li) = 1.10±0.10; Grevesse & Sauval 1998) compared with the pre-solar nebula (A(Li) = 3.31±0.04 in meteorites) has long challenged standard stellar evolution models (e.g. Deliyannis 1995). ($A(\mathrm{Li}) \equiv \log_{10}(n(\mathrm{Li})/n(\mathrm{H})) + 12.00$.)

Lithium is special because stars destroy it during pre-main sequence and main-sequence evolution, depending on their mass and metallicity. When surface material is mixed down to depths where the temperature exceeds 2.5×10^6 K, Li-purged material is returned to the surface. Li survival therefore reflects the mixing history, and in the context of planet-harbouring stars could provide information on the accretion of material and the angular-momentum evolution of the system as a whole.

Li deficiency in planet hosts was assessed by King et al. (1997) and Gonzalez & Laws (2000). King et al. examined 16 Cyg A and B, and commented on six other systems. HD 114762, 70 Vir, and τ Boo. They concluded that "the data are too few at this point to establish a connection between alleged planetary companions and photospheric Li abundances", whilst acknowledging "It is possible, in principle anyway, that the low Li abundances ... may be related to the presence of a planetary companion." Gonzalez & Laws concluded more positively that "stars with planets tend to

Table 1. Host stars to planetary systems in which lithium has been measured

Star			$T_{\rm eff}$ K	ϵ_T K	[Fe/H]	$\epsilon_{\rm [Fe/H]}$	age Gyr	M_V mag	$\epsilon_{M{\rm v}}$ mag	A(Li)	$\epsilon_{A({\rm Li})}$	$\log R'_{\rm HK}$	Refs[a]
HR5185	HD120136	τ Boo	6420	80	0.32	0.06	1.5	3.53	0.03	1.68	0.25		a,b,c
HR3947	HD75289		6140	50	0.28	0.05	2.1	4.04	0.04	2.76	0.05	–5.00	a
HR458	HD9826	υ And	6140	60	0.12	0.05	3.3	3.45	0.03	2.26	0.07	–4.97	a,d
HR810	HD17051		6074	100	–0.04			4.22	0.02	2.39		–4.65	e
HR4277	HD95128	47 UMa	5882	40	0.01		6.9	4.29	0.02	<1.70		–4.95	b,f,g
HD114762			5870	40	–0.74	0.03	13.8	4.26	0.13	1.92			d,f,h
HD187123			5830	40	0.16	0.05	4	4.43	0.08	1.20	0.20		a i
HR8729	HD217014	51 Peg	5777	40	0.06		8.5	4.52	0.03	1.16	0.05	–4.97	b,f,j
Sun			5770		≡0.00	≡0	4.5	4.72		1.10	0.10		a,b
HR5968	HD143761	ρ CrB	5750	50	–0.35	0.06	11	4.18	0.03	1.30	0.10	–5.02	f,d,k
HD186427	16CygB		5747	20	0.05	0.06		4.60	0.02	<0.60			l,b
HR8734	HD217107		5597		0.30		10	4.71	0.03	<0.64			m
HD210277			5540	60	0.24	0.05	12	4.90	0.05	<0.80			a i
HR5072	HD117176	70 Vir	5500		–0.11			3.68	0.03	1.12		–5.11	g,b
HD145675	14 Her		5300	90	0.50	0.05	6	5.32	0.03	<0.70		–5.10	i,a
HR3522	HD75732	ρ^1 55 Cnc	5250	70	0.45	0.05		5.47	0.02	<0.46	0.15	–4.97	n,a
HR637	HD13445	GJ86	5072					5.93	0.01	< -0.24		–4.74	o

[a] References: (a) Gonzalez & Laws 2000; (b) King et al. 1997; (c) Boesgaard & Lavery 1986; (d) Lambert et al. 1991; (e) Pasquini et al. 1994; (f) Edvardsson et al. 1993; (g) Duncan 1981; (h) Rebolo et al. 1988; (i) Gonzalez et al. 1999; (j) François et al. 1996; (k) Gonzalez 1998; (l) Friel et al. 1993; (m) Randich et al. 1999; (n) Gonzalez & Vanture 1998; (o) Favata et al. 1997.

have smaller Li abundances when corrected for difference in $T_{\rm eff}$, [Fe/H], and $R'_{\rm HK}$" (where $R'_{\rm HK}$ is a chromospheric emission measure).

The current study was prompted by the cases of HR 5968, 16 Cyg A and B, and the Sun, independently of the work by King et al. and Gonzalez & Laws. However, the opposite conclusion was reached compared to that of Gonzalez & Laws. Instead it showed that the Li abundances of planet-harbouring stars are indistinguishable from those of otherwise similar lone stars. The arguments leading to this negative conclusion will be presented in this paper.

2 DATA

All data in this study were taken from the literature. Extensive use was made of *Simbad* and the online *Hipparcos* catalog (ESA 1997) provided by the CDS. Planet-harbouring stars[⋆] for which Li abundances have been published are listed in Table 1. Where Li abundances are available from more than one source, the most recent has been adopted. Most have $-0.35 \leq$ [Fe/H] ≤ 0.45. Figure 1(a) gives the HR diagram based on accurate *Hipparcos* parallaxes, while Figure 1(b) shows A(Li) vs $T_{\rm eff}$.

Open clusters and field stars of appropriate age, temperature and metallicity can be used to reveal the "normal" evolution of Li. Shown in Figure 1(b) are fiducial lines (Hobbs & Pilachowski 1988; Ryan & Deliyannis 1995) for the Pleiades, Hyades, NGC 752 and M67, whose parameters are given in Table 2. Field stars whose Li abundances are known from Lambert et al. (1991), Pasquini, Liu & Pallavicini (1994), Favata, Micela & Sciortino (1996, 1997), and Randich et al. (1999) are also shown. Two other stars have been added for reasons that will become clear later: 16 Cyg A and α Cen A.

⋆ see http://cfa-www.harvard.edu/planets/catalog.html

Table 2. Open cluster ages and metallicities

Cluster	Age/Gyr	[Fe/H]
Pleiades	0.08	0.0
Hyades	0.7	0.1
NGC 752	1.7	0.0
M67	5	0.0

Several criteria have been to restrict the field stars used in the comparison sample. Firstly, only objects with absolute magnitudes from *Hipparcos*, typically accurate to ± 0.03–0.10 mag, have been admitted. This is so their evolutionary states are known. Secondly, the most luminous of the planet-hosting stars has $M_{\rm V} = 3.45 \pm 0.03$, so field stars having $M_{\rm V} < 3.20$ were excluded. Thirdly, stars lying outside the range $-0.35 \leq$ [Fe/H] ≤ 0.45, the same as the majority of the planet-harbouring sample, have been rejected to reduce the impact of stars having formed at different stages of Galactic chemical evolution (e.g. Ryan et al. 2000). Favata et al. (1996, 1997) do not tabulate metallicities; values from Cayrel de Strobel et al. (1997) have been used where possible.

3 ANALYSIS

The open cluster fiducials show that the youngest clusters have higher Li abundances, despite having similar metallicities. The steepness of the depletion curve, $dA({\rm Li})/dT_{\rm eff}$, also depends on age. Table 1 shows that age estimates (where they exist) for the planet host stars range from 1.5 – 14 Gyr, so they should lie below the NGC 752 fiducial. However, the ages of field stars are difficult to derive accurately. A useful surrogate for age in *young* Population I stars is chromospheric activity; the youngest stars show greater activity. The distribution of the Ca II H and K line-

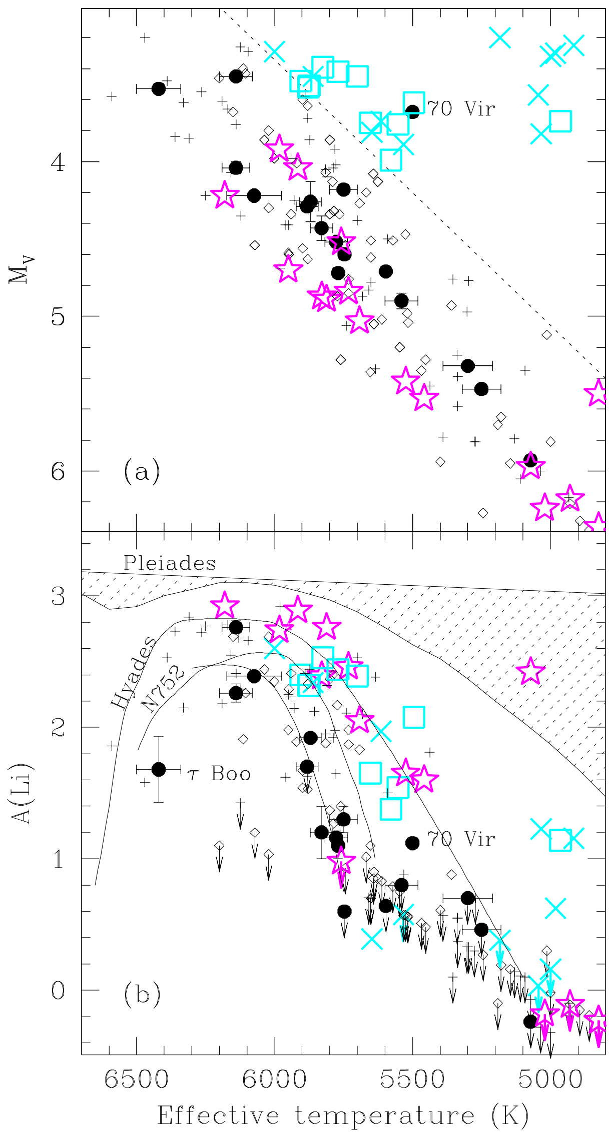

Figure 1. (a) HR diagram for: *solid symbols* planet host stars; *squares* and *crosses* field subgiants of low and unknown chromospheric activity; *diamonds* and *plus-signs* main-sequence field stars of low and unknown activity; and *five-pointed stars* known chromospherically active objects. The dotted line separates main-sequence and subgiant stars. (b) Li abundances for sample in (a). The shaded zone is the region occupied by Pleiades dwarfs. The other fiducials are (in descending order) for the Hyades, NGC 752, and M67. In both panels, error bars are shown only for the planet hosts, to aid clarity. Subgiants and chromospherically-active stars, which have been emphasised, have higher Li abundances; see text.

core emission diagnostic, log $R'_{\rm HK}$, in the study by Henry et al. (1996, Fig. 8) is strongly bimodal. Some 70% of the stars of *their* sample constitute in an inactive peak from $-5.50 <$ log $R'_{\rm HK} < -4.65$, the remainder having higher activity levels $-4.65 <$ log $R'_{\rm HK} \lesssim -4.0$. Measures of chromospheric activity from Soderblom (1985) and Henry et al. (1996) are available for ten of the planet hosts, and all fall within the lower activity peak, the highest level being log $R'_{\rm HK} = -4.65$ (HD 17051) at the local minimum in the bimodal distribution. Measurements are also available for many of the non-planet-harbouring stars. (Pasquini et al. (1994) measure a different chromospheric emission measure, F'_k. A least squares fit to stars in both surveys yielded the transformation log $R'_{\rm HK} = 0.755\ F'_k - 9.141$.)

Attempting to account for variations in the Li abundance with age, metallicity, and effective temperature, Gonzalez & Laws (2000) performed a fit to a similar sample of field stars using an equation $A({\rm Li}) = a_0 + a_1[{\rm Fe/H}] + a_2$ log $R'_{\rm HK} + a_3$ log $T_{\rm eff}$. The approach adopted in the present work differs; a polynomial of this form is regarded as inappropriate. Instead, an effort is made to eliminate stars whose parameters do not coincide with the planet-host sample, and then to compare the stars in the A(Li) vs $T_{\rm eff}$ plane directly. As will be shown below, the approach adopted here leads to the opposite conclusion to the one reached by Gonzalez & Laws.

At first glance, Figure 1(b) seems to justify the belief that planet hosts have lower Li abundances. However, the non-planet-harbouring sample in Figure 1(b) is *not* broadly similar to that of the planet hosts. Two groups of unrepresentative stars have been highlighted. *Star* symbols indicate objects whose activity exceeds log $R'_{\rm HK}$ = 4.65, or $F'_k = 6.12$, the highest measurement for planet-hosts (HD 17051). This coincides with the local minimum in Henry et al's bimodal distribution. Figure 1(a) verifies that these are generally less luminous, typical of young stars lying closer to the zero age main sequence. Figure 1(b) shows that their lithium abundances are amongst the highest in the sample. Although Gonzalez & Laws (2000) attempted to fit this dependence, the approach here is instead to eliminate those stars entirely. This reduces the chance of comparing un-alike samples. Furthermore, it is unclear that A(Li) depends linearly on this parameter. There are examples in Figure 1(b) where "active" stars having the same $T_{\rm eff}$ have very different A(Li) values; a linear model cannot fully capture the effect. Instead, here such stars are eliminated as unrepresentative of the population of less-active planet hosts. Note, however, that this elimination is incomplete, as there are stars for which chromospheric diagnostics are lacking. They are shown as *crosses* and *plus* signs for subgiant and main-sequence stars. It is likely that some of the latter with low luminosities and high Li abundances would be eliminated if more complete data were available.

Secondly, Hipparcos parallaxes allow us to distinguish main sequence stars from subgiants, which owe their Li destruction to different processes Ryan & Deliyannis (1995). The former mix surface material to depths, greater in cooler stars, where it is *destroyed* at $T > 2.5 \times 10^6$ K. Subgiants had higher temperatures when they were on the main sequence, and either may have experienced less Li destruction, or at the other extreme may have depleted Li extensively if located between 6400 and 6900 K at the F-star Li gap (Boesgaard & Tripicco 1986). Once on the subgiant branch, they *dilute* surface Li as deepening convection mixes Li-purged material up to the surface; *dilution* without additional *destruction* occurs initially. In Figure 1(a), stars are defined as subgiants if they fall in the region at upper right defined by $M_{\rm V} < 13.63 - 1.7143 \times 10^{-3} T_{\rm eff}$, and are shown as *squares* and *crosses* depending on whether or not chromospheric-activity measurements are available. (Chromospheric activity is not expected in normal subgiants.) They are seen (Figure 1(b)) to have higher A(Li) values than main-sequence stars. The two groups must be analysed separately; there is

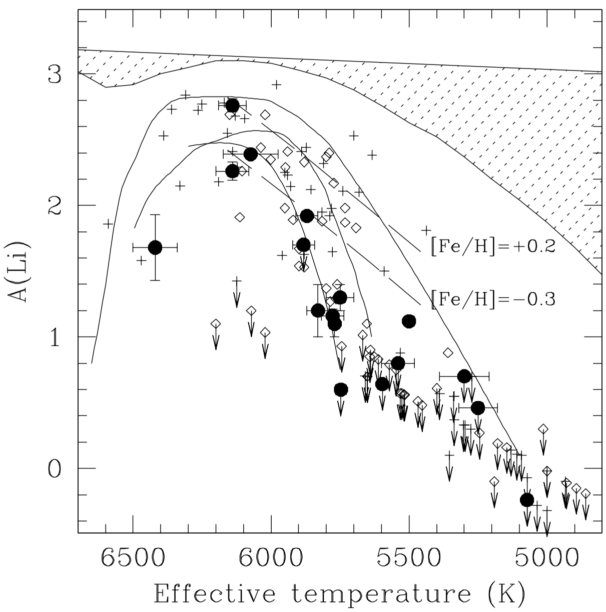

Figure 2. As for Figure 1(b), but with subgiants and *known* chromospherically active stars eliminated. Dashed lines give the model of Gonzalez & Laws (2000, eq. 1) for [Fe/H] = −0.3 and +0.2, assuming chromospheric inactivity (log $R'_{\rm HK}$ = − 4.9). The model is a poor match to this sample; see text.

no indication whether Gonzalez & Laws (2000) made this distinction.

There is only one subgiant planet-host in this study, 70 Vir. With $T_{\rm eff}$ = 5500 K, it lies along the trend towards diminishing A(Li) at lower $T_{\rm eff}$, coincidentally close to the Hyades fiducial. The subgiants with $T_{\rm eff}$ < 5700 K exhibit a wide range of Li abundances; 70 Vir sits in the middle of that range, giving no indication that it is abnormally Li-poor. The wide range of Li abundances in these subgiants may arise because some of them lay in the wings of the F-star Li dip when they were on the main sequence. As Gonzalez & Laws recognised, the low Li abundance of τ Boo is certainly due to the Li dip.

Figure 2, from which *known* chromospherically active stars and subgiants (but not 70 Vir) have been eliminated, contains main-sequence stars. If we adopt log $R'_{\rm HK} = -4.9$ (the modal value of Henry et al's activity distribution) as characteristic of inactive stars, and compute the Li abundance from Gonzalez & Laws' (2000, eq(1)) fit for [Fe/H] = −0.3 and +0.2, the dashed lines in Figure 2 are obtained. These fail to fit the decreasing Li abundance in the cooler main-sequence field or open cluster stars. This is almost certainly due to the elimination of inappropriate objects (known chromospherically-active stars and subgiants) in the present work. The fit upon which Gonzalez & Laws based their conclusion was not appropriate to main-sequence, inactive stars.

Figure 2 can be used to reexamine whether the Li abundances in the planet-harbouring stars are distinguishable from those of otherwise similar stars. 70 Vir and τ Boo have been discussed above and no evidence of abnormal Li deficiency found. The three planet hosts with $T_{\rm eff} \simeq 6100$ K are completely consistent with similar stars in the field and the open cluster fiducials. The planet host with the lowest Li abundance is also the most luminous, and could be an early subgiant descended from the wing of the F-star Li dip. There is no evidence in these three planet hosts for abnormally low Li abundances.

The remaining planet hosts follow the steep decline of A(Li) with decreasing $T_{\rm eff}$ that both the field star samples and the older open cluster fiducials (NGC 752 and M67) exhibit. Whilst there exist some field stars with higher Li abundances, there also exist many low values. Moreover, many of those with higher values have unknown chromospheric activity levels, and it is plausible that many of these are in fact relatively young. Considering chromospherically-inactive stars within ±50 K of the two planet hosts at $T_{\rm eff} \simeq 5900$ K, one has higher A(Li), one has a lithium abundance between those of the planet hosts, and three have lower Li abundances. Widening the interval to ±100 K would change the count to six above, two between, and five below. Clearly there is nothing to distinguish these two planet hosts as having abnormally low Li abundances, bringing the tally to zero Li-deficient planet hosts out of seven discussed so far.

The five planet hosts in the "solar" group at $T_{\rm eff} \simeq 5800$ K provide the only hint of possibly lower Li abundances. A count of chromospherically-inactive stars within ±50 K of the solar temperature gives eight with higher abundances (though two only marginally and within the error-bars), two within the A(Li) range of the solar group (one of which is obscured in Figure 2), and one yielding only a low upper limit. However, three notes of caution are required.

Firstly, the planet-harbouring stars are an excellent fit to the older open cluster fiducials. The youngest of these five planet hosts is HD 187123 at 4 Gyr, and the oldest is ρ CrB at 11 Gyr. All lie close to the fiducials for NGC 752 (2 Gyr) and M67 (5 Gyr), so their Li abundances would be interpreted as normal for their ages. Perhaps the high A(Li) field stars within ±50 K of the sun are younger and retain more Li, although not so young as to remain chromospherically active.

Secondly, this $T_{\rm eff}$ is the coolest for which Li detections, as opposed to upper limits, are routinely measurable. The open cluster fiducials indicate that Li depletion is a steep function of temperature, A(Li) falling by 0.33 dex per 50 K. A star's "expected" location in the A(Li) vs $T_{\rm eff}$ plane is clearly very sensitive to the uncertainties in its $T_{\rm eff}$. Furthermore, the range of Li abundances even in the field sample is 1.5 dex within this ±50 K interval. It is difficult to conclude that the planet hosts are anomalous in this circumstance. Of particular relevance to this point is the comparison between the Sun and α Cen A ($T_{\rm eff}$ = 5800±20, A(Li) = 1.37±0.06; King et al. 1997), and between the coeval pair 16 Cyg A and B ($T_{\rm eff}$ = 5785 and 5747 K respectively, and A(Li) = 1.27±0.05 and <0.60; King et al. 1997). The $T_{\rm eff}$ and A(Li) difference between the first two runs parallel to the NGC 752 and M67 fiducials at this temperature, so the difference in A(Li) is entirely consistent with the different temperatures. The rate dA(Li)/d$T_{\rm eff}$ for 16 Cyg A and B is steeper, but they are also marginally cooler, and as the prevalence of non-detections (upper limits) and the steep open cluster fiducials suggest, a greater loss of Li in the coolest of these four stars would not be outrageous. Friel et al's (1993) emphasis on normal stellar evolutionary processes in their comment that these two stars "may provide a powerful constraint to models of evolution of the Li content in solar type stars" is simpler than postulating an abnormal evolution of Li in stars harbouring planets.

Thirdly, if one supposes for a moment that the planet hosts are abnormally Li-deficient, one would be struck by the great similarity in the final abundances of the four systems 51 Peg, HD187123, ρ CrB, and the Sun. The first two planet masses and semi-major axes are M sin $i \simeq 0.50$ M_{Jup} and $\simeq 0.045$ AU, and ρ CrB has values 1.1 M_{Jup} and 0.23 AU. The parameters for the Sun are obvious. One would be challenged to explain why three diverse systems have similar Li abundances if all are depleted compared to non-planet-harbouring stars. The alternative, that the four systems have the same Li abundance because that is what is natural for stars of their mass, age, and composition, is in accord with Occam's razor.

For the planet hosts cooler than the solar group, only upper limits on lithium abundances are available. The same is true of almost all field star measurements at $T_{\rm eff} < 5600$ K, so there is no information on the relative abundances of planet-harbouring compared to sole stars.

4 CONCLUSIONS

The lithium abundances of planet-harbouring stars have been compared with the abundances in open clusters of known age and metallicity and with field stars. Young (chromospherically active) field stars have higher Li abundances than older stars of the same $T_{\rm eff}$, but are significantly younger (more active) than the planet-harbouring stars, so were eliminated. An examination of the A(Li) vs $T_{\rm eff}$ trends for the planet-host and field star samples were conducted separately for subgiants and main-sequence stars because of their different evolutionary and Li-processing histories. The comparisons showed no differences between the Li abundances of the planet-host and other samples in the case of the planet-harbouring subgiant or the six hosts with $T_{\rm eff} > 5850$ K. For the five solar-like planet hosts there are examples of chromospherically-inactive lone stars having much higher Li abundances, but covering a huge range ($\sim$1.5 dex) in A(Li). It is likely that some of these are old enough to show no chromospheric activity but have not yet depleted their Li abundances to the levels seen in the older open clusters. Furthermore, the temperature dependence of Li depletion is very high. The solar-temperature planetary systems have ages greater than 4 Gyr, and in this context their Li abundances are consistent with similarly old open cluster and with known coeval field stars. In particular, the difference in A(Li) between α Cen A and the Sun is consistent with the decline rate dA(Li)/d$T_{\rm eff}$ = 0.33 dex per 50 K inferred from 2-5 Gyr open clusters. While the decline rate between 16 Cyg A and B is larger, 16 Cyg B is cooler and very close to the temperature at which Li routinely vanishes in main-sequence stars. In summary, there is no strong evidence that planet-harbouring stars have lower Li abundances than open cluster stars of similar mass, age, and metallicity, and nor are they lower than in an appropriately constituted sample of field stars of similar age and evolutionary state. This conclusion is opposite to that arrived at by Gonzalez & Laws (2000); it is believed that the field star sample used by them contained too wide a range of ages, evolutionary types, and temperatures to be accommodated by the model they adopted to explain the dependence on parameters.

Li does not appear set to provide key insights into the formation and evolution of planetary systems.

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