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 the lithium abundances 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 than 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; 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 that they adopted to describe the dependence of Li on the parameters. The Li abundance does not appear set to provide key insights into the formation and evolution of planetary systems.

Key words: planets and satellites: general – Solar system: formation – stars: abundances.

1 INTRODUCTION

The discovery of tens of extrasolar planets over recent years (Wolszczan 1994; Mayor & Queloz 1995; Marcy & Butler 2000), and the prospect of many more being discovered, has spurred the efforts to understand the processes by which planetary systems form.

One way to help us understand the formation of planetary systems is to discover characteristics that distinguish planet-harbouring stars from lone stars. These stars 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 the elemental condensation temperature, and is 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 that 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 with 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, although 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).

Lithium is special because stars destroy it during pre-main-sequence and main-sequence evolution depending on the mass and metallicity of the star. When surface material is mixed down to depths where the temperature exceeds 2.5 × 10⁶ 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: 47 Uma, 51 Peg, the Sun, 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 have smaller Li abundances when corrected for differences in Teff, [Fe/H] and R′HK’ (where R′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, independent of the work by King et al. and Gonzalez & Laws. However, the opposite conclusion was

1 A(Li) = log₁₀ [n(Li)/n(H)] + 12.00.
reached compared with that of Gonzalez & Laws. Instead, this study shows that the Li abundances of planet-harbouring stars are indistinguishable from the Li abundances 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 (European Space Agency 1997) provided by the Centre de Données astronomiques de Strasbourg. 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 \(-0.35 \leq \text{[Fe/H]} \leq 0.45\). Fig. 1(a) gives the Hertzsprung–Russel (HR) diagram based on accurate Hipparcos parallaxes whereas Fig. 1(b) shows \(A(\text{Li})\) versus \(T_{\text{eff}}\).

Open clusters and field stars of appropriate age, temperature and metallicity can be used to reveal the ‘normal’ evolution of Li. Fiducial lines are shown in Fig. 1(b) (Hobbs & Pilachowski 1988; Ryan & Deliyannis 1995) for the Pleiades, Hyades, NGC 752 and M67, the parameters of which are given in Table 2. Field stars of which the Li abundances are known (from Lambert et al. 1991; Pasquini, Liu & Pallavicini 1994; Favata, Micela & Sciortino 1996, 1997; 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.

Several criteria have been applied to restrict the field stars used in the comparison sample. First, only objects with absolute magnitudes from the Hipparcos catalogue, typically accurate to \(\pm 0.03–0.10\) mag, have been admitted. This is so the evolutionary states of the objects are known. Secondly, the most luminous of the planet-hosting stars has \(M_V = 3.45 \pm 0.03\), so field stars with \(M_V < 3.20\) were excluded. Thirdly, stars lying outside the range \(-0.35 \leq \text{[Fe/H]} \leq 0.45\) that corresponds to 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) did 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, \(dA(\text{Li})/dT_{\text{eff}}\), 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\(\text{ii}\), H and K line-core emission diagnostic, \(log R'_{\text{HK}}\) in the study by Henry et al. (1996, fig. 8) is strongly bimodal. Some 70 per cent of the stars of their sample constitute an inactive peak from \(-5.50 < \log R'_{\text{HK}} < -4.65\), the remainder having higher activity levels \(-4.65 < \log R'_{\text{HK}} \leq -4.0\). 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 \(\log R'_{\text{HK}} = -4.65\) (HD 17051) at the local minimum in the bimodal distribution. Measurements are also available for many of the non-planet-harbouring stars.

Attempting to account for variations in the Li abundance with age, metallicity and effective temperature, Gonzalez & Laws (2000) performed a fitting to a similar sample of field stars using an equation \(A(\text{Li}) = a_0 + a_1 \text{[Fe/H]} + a_2 \log R'_{\text{HK}} + a_3 \log T_{\text{eff}}\). 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 with parameters that do not coincide with the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
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Star & \(T_{\text{eff}}\) & \(\text{[Fe/H]}\) & \(M_V\) & \(M_\text{bol}\) & \(A(\text{Li})\) & \(\log R'_{\text{HK}}\) & Refs\footnote{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, Molaro & Beckman 1988; (i) Gonzalez, Wallerstein & Saar 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.}
\hline
HR5185 & HD120136 & 3.45 & \(\pm 0.03\) & 1.5 & 3.53 & 0.03 & 1.68 & 0.25 & a,b,c
HR3947 & HD75289 & 3.17 & \(\pm 0.04\) & 2.1 & 4.04 & 0.04 & 2.76 & 0.05 & -5.00 & a
HR458 & HD9826 & 3.34 & \(\pm 0.03\) & 3.3 & 4.35 & 0.03 & 2.26 & 0.07 & -4.97 & a,d
HR810 & HD17051 & 2.97 & \(\pm 0.04\) & 4.22 & 0.02 & 2.39 & -4.65 & e
HR4277 & HD95128 & 4.70 & \(\pm 0.04\) & 6.9 & 4.29 & 0.02 & 1.90 & -4.95 & b,f,g
HD114762 & 5.87 & \(\pm 0.04\) & 13.8 & 4.26 & 0.13 & 1.92 & d,f,h
HD187123 & 5.83 & \(\pm 0.16\) & 4.43 & 0.08 & 1.20 & 0.20 & a
HR8729 & HD217014 & 51 Peg & 8.5 & 4.52 & 0.03 & 1.16 & 0.05 & -4.97 & b,f,j
Sun & 5770 & \(\pm 0.06\) & 4.5 & 4.72 & 0.03 & 1.10 & 0.10 & a,b
HR5068 & HD143761 & 50 CrB & 5.75 & 0.35 & 11 & 4.18 & 0.03 & 1.30 & 0.10 & -5.02 & f,d,k
HR186427 & 56CygB & 5747 & 20.05 & 4.60 & 0.02 & <0.60 & l,b
HR8734 & HD217107 & 5597 & 0.30 & 10 & 4.71 & 0.03 & 0.64 & m
HR210277 & 5540 & 60.24 & 12 & 4.90 & 0.05 & <0.80 & a,i
HR5072 & HD17176 & 5500 & -0.11 & 3.68 & 0.03 & 1.12 & -5.11 & g,b
HD145625 & 14 Her & 5300 & 50.50 & 6 & 5.32 & 0.03 & <0.70 & -5.10 & i,a
HR3522 & HD75372 & 555 Cnc & 5250 & 70.45 & 0.05 & 5.47 & 0.02 & <0.46 & 0.15 & -4.97 & n,a
HR637 & HD13445 & 5072 & 5.93 & 0.01 & <0.24 & -4.74 & o
\hline
\end{tabular}
\caption{Host stars to planetary systems in which lithium has been measured.}
\end{table}
Lithium in host stars of extrasolar planets

planet-host sample, and then to compare the stars in the A(Li) versus $T_{\text{eff}}$ 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, Fig. 1(b) seems to justify the belief that planet hosts have lower Li abundances. However, the non-planet-harbouring sample in Fig. 1(b) is not broadly similar to that of the planet hosts. Two groups of unrepresentative stars have been highlighted. Star symbols indicate objects with activity in excess of $\log R'_{\text{HK}} = 4.65$ (or $F'_{\text{eff}} = 6.12$), which is the highest measurement for planet hosts (HD 17051). This coincides with the local minimum in the bimodal distribution of Henry et al. (1996). Fig. 1(a) verifies that these stars are generally less luminous, which is typical of young stars lying closer to the zero-age main sequence. Fig. 1(b) shows that the lithium abundances of these stars are amongst the highest in the sample. Although Gonzalez & Laws (2000) attempted to fit this dependence, the approach here is, instead, to eliminate these stars entirely. This reduces the chance of comparing non-alike samples. Furthermore, it is unclear whether A(Li) depends linearly on this parameter. There are examples in Fig. 1(b) where ‘active’ stars with the same $T_{\text{eff}}$ have very different A(Li) values; a linear model cannot fully capture the effect. Instead, such stars are eliminated here because they are 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 stars 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 the destruction of their Li 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 the surface Li as deepening convection mixes Li-purged material up to the surface; dilution without additional destruction occurs initially. In Fig. 1(a) stars are defined as subgiants if they fall in the region at the upper right of the panel defined by $M_V < 13.63 - 1.7143 \times 10^{-3}T_{\text{eff}}$, and are shown as squares and crosses depending on whether or not, respectively, chromospheric-activity measurements are available (chromospheric activity is not expected in normal subgiants). They are seen (Fig. 1b) to have higher A(Li) values than the main-sequence stars. The two groups must be analysed separately; there is no indication whether Gonzalez & Laws (2000) made this distinction.

There is only one subgiant planet host in this study, 70 Vir. With $T_{\text{eff}} = 5500$ K, it lies along the trend towards diminishing A(Li) at lower $T_{\text{eff}}$, coincidently close to the Hyades fiducial. The subgiants with $T_{\text{eff}} < 5700$ 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 have arisen because some of them lay in the wings of the F-star Li dip when they were on the main sequence. As Gonzalez & Laws recognized, the low Li abundance of $\tau$ Boo is certainly a consequence of the Li dip.

Fig. 2, from which known chromospherically active stars and subgiants (but not 70 Vir) have been eliminated, contains main-

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**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    |

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sequence stars. If we adopt $\log R'_{\text{HK}} = -4.9$ (the modal value of the activity distribution in Henry et al. 1996) as being characteristic of inactive stars, and compute the Li abundance from the fitting in Gonzalez & Laws (2000, equation 1) for [Fe/H] = −0.3 and +0.2, assuming chromospheric inactivity ($\log R'_{\text{HK}} = -4.9$). The model is a poor match to this sample (see text).

The remaining planet hosts follow the steep decline of $A(\text{Li})$ with decreasing $T_{\text{eff}}$ 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 stars with low values of Li abundance. Moreover, many of the stars 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 $T_{\text{eff}} = 5900$ K, one has a higher value of $A(\text{Li})$, one has a Li abundance between the abundances 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, and this brings the tally of Li-deficient planet hosts to zero out of the seven discussed so far.

The five planet hosts in the ‘solar’ group at $T_{\text{eff}} = 5800$ 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 Li abundances (although two are only marginally higher with values within the errorbars), two within the $A(\text{Li})$ range of the solar group (one of which is obscured in Fig. 2) and one yielding only a low upper limit of Li abundance. However, three notes of caution are required.

Firstly, the planet-hosting 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 $\rho$ CrB at 11 Gyr. All of these planet hosts lie close to the fiducials for NGC 752 (2 Gyr) and M67 (5 Gyr), so the Li abundances would be interpreted as normal for their ages. Perhaps the high $A(\text{Li})$ 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 $T_{\text{eff}}$ 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, $A(\text{Li})$ falling by 0.33 dex per 50 K. The ‘expected’ location of a star in the $A(\text{Li})$ versus $T_{\text{eff}}$ plane is clearly very sensitive to the uncertainties in its $T_{\text{eff}}$. 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 $\alpha$ Cen A ($T_{\text{eff}} = 5800 \pm 20$ and $A(\text{Li}) = 1.37 \pm 0.06$; King et al. 1997), and between the coeval pair $16$ Cyg A and B ($T_{\text{eff}} = 5785$ and 5747 K, respectively, and $A(\text{Li}) = 1.27 \pm 0.05$ and <0.60; King et al. 1997). The differences in $T_{\text{eff}}$ and $A(\text{Li})$ between the first pair run parallel to the NGC 752 and M67 fiducials at this temperature, so the difference in $A(\text{Li})$ is entirely consistent with the different temperatures. The rate $dA(\text{Li})/dT_{\text{eff}}$ 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 suggests a greater loss of Li in the coolest of these four stars would not be outrageous. The emphasis on normal stellar evolutionary processes by Friel et al. (1993) 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, $\rho$ CrB and the Sun. The first two planet masses and semimajor axes are $M \sin i = 0.50$ $M_{\odot}$ and =0.045 au, whereas $\rho$ CrB has values 1.1 $M_{\odot}$ and 0.23 au. The parameters for the Sun are obvious. One would be challenged to explain why three diverse configurations arrive at similar Li abundances if all are depleted compared to non-planet-hosting stars. The alternative that the four systems have the same Li abundance because this 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 $T_{\text{eff}} < 5600$ K, so there is no information on the relative abundances of planet-hosting stars compared with 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 $T_{\text{eff}}$, but are significantly younger (more active) than the planet-harbouring stars, and so were eliminated from the sample. An examination of the $A(\text{Li})$ versus $T_{\text{eff}}$ 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 show no differences between the Li abundances of the planet host and other samples in the case of the planet-harbouring subgiant, or in the case of the six hosts with $T_{\text{eff}} > 5850$ 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 $A(\text{Li})$. 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 known coeval field stars. In particular, the difference in $A(\text{Li})$ between $\alpha$ Cen A and the Sun is consistent with the decline rate of $dA(\text{Li})/dT_{\text{eff}} = 0.33$ dex per 50 K inferred from 2–5-Gyr open clusters. While the decline rate from 16 Cyg A to 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 neither strong evidence that planet-harbouring stars have lower Li abundances than open cluster stars of similar mass, age and metallicity, nor that the abundances are 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 they used contained too wide a range of ages, evolutionary types and temperatures to be accommodated by the model that they adopted to explain the dependence of the Li abundance on the parameters.

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

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