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Lithium in stars with exoplanets[*]

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Abstract. We present a comparison of the lithium abundances of stars with and without planetary-mass companions. New lithium abundances are reported in 79 planet hosts and 38 stars from a comparison sample. When the Li abundances of planet host stars are compared with the 157 stars in the sample of field stars of Chen et al. (2001) we find that the Li abundance distribution is significantly different, and that there is a possible excess of Li depletion in planet host stars with effective temperatures in the range 5600–5850 K, whereas we find no significant differences in the temperature range 5850–6350 K. We have searched for statistically significant correlations between the Li abundance of parent stars and various parameters of the planetary companions. We do not find any strong correlation, although there are may be a hint of a possible gap in the Li distribution of massive planet host stars.

Key words. stars: abundances – stars: chemically peculiar – stars: planetary systems

1. Introduction

The extrasolar planetary systems detected to date are probably not a representative sample of all planetary systems in the Galaxy. Indeed, the detection of a giant planet with a mass $M_\mathrm{p} \sin i = 0.47\ M_\mathrm{J}$ (Jupiter masses) orbiting the solar-type star 51 Peg at 0.05 AU (Mayor & Queloz 1995) was not anticipated. The Doppler method, which formed the basis of the discovery of more than 100 extrasolar planets, is clearly biased, being most sensitive to massive planets orbiting close to their parent stars. These surveys have established that at least ∼7% of solar-type stars host planets (Udry & Mayor 2001). On the other hand, we can learn a lot about the formation and evolution of planetary systems by studying in detail properties of stars with planets. Although extrasolar planetary systems differ from the Solar System, the host stars themselves do not appear to be distinguished by their kinematic or physical properties. They are normal main sequence stars that are metal-rich relative to nearby field stars (Gonzalez 1998; Santos et al. 2000, 2001, 2003a; Gonzalez et al. 2001). Possible explanations for the high metallicities of the stars with exoplanets involve primordial effects (Santos et al. 2001, 2003a; Pinsonneault et al. 2001) and

the ingestion of rocky material, planetesimals and/or metal-rich gaseous giant planets (Gonzalez 1998; Gonzalez et al. 2001; Laughlin & Adams 1997; Murray et al. 2001a; Murray & Chaboyer 2002). While our recent discovery (Israelian et al. 2001, 2003) of a significant amount of ^{6}Li in the planet host HD 82943 clearly suggests that the accretion of planetesimals or maybe entire planets has indeed taken place in some stars, we cannot state that this effect is responsible for the metallicity enhancement in planet-harbouring stars. This question can possibly be answered if we analise the abundances of Li, Be (beryllium) and the isotopic ratio ^{6}Li/^{7}Li in a large number of planet-bearing stars. Combined with precise abundance analyses of Fe and other elements, these studies may even allow us to distinguish between different planet formation theories (Sandquist et al. 2002). The light elements Li and Be are very important tracers of the internal structure and pre-main sequence evolution of solar type stars. In some way, studies of Be and Li complement each other. Lithium is depleted at much lower temperatures (about 2.5 milion K) than Be. Thus, by measuring Li in stars where Be is not depleted (early G and late F) and Be in stars where Li is depleted (late G and K) we can obtain crucial information about the mixing, diffusion and angular momentum history of exoplanet hosts (Santos et al. 2002).

Gonzalez & Laws (2000) presented a direct comparison of Li abundances among planet-harbouring stars with field stars and proposed that the former have less Li. However, in a critical analysis of this problem Ryan (2000) concludes that planet hosts and field stars have similar Li abundances. Given the large number of planet-harbouring stars discovered to date, we

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[*] Based on observations collected at the La Silla Observatory, ESO (Chile), with the CORALIE spectrograph at the 1.2 m Euler Swiss telescope, and with the FEROS spectrograph at the 1.52 m ESO telescope, and using the UES spectrograph at the 4.2 m William Herschel Telescope (WHT) and SARG spectrograph at the 3.5 m Telescopio Nazional Galileo on La Palma (Canary Islands).

have decided to investigate the Li problem and look for various statistical trends. We have attempted to remove and/or minimize any bias in our analysis following the same philosophy as Santos et al. (2001). Here, we present the results of Li analyses in 79 stars with planets and 38 stars from a comparison sample consisting of stars without detected planets from a CORALIE sample (Santos et al. 2001). Comparison of Li abundance in planet hosts and a sample of 157 solar-type stars from Chen et al. (2001) is presented and different physical processes that can affect the evolution of the surface abundance of Li in stars with exoplanets are discussed.

2. Observations and analysis

The spectroscopic observations of our targets were carried out during different runs using the 4.2 m WHT/UES (La Palma), the 3.5 m TNG/SARG (La Palma), the 1.52 m ESO (La Silla) and the 1.2 m Swiss/CORALIE (La Silla). The same data were used in recent papers by Santos et al. (2003a) and Bodaghee et al. (2003). Observations with the WHT/UES were obtained using the E31 grating and a 1.1 arcsec slit providing a resolving power 55 000. The TNG observations were carried out with the SARG spectrograph and a two EEV CCD mosaic of 4096 × 2048 pixels of size 15 μm × 15 μm. Resolving power ~57 000 was achieved with 1 arcsec slit. All the WHT and TNG images were reduced using standard IRAF routines. Normalized flats created for each observing night were used to correct the pixel-to-pixel variations and a ThAr lamp was used to find a dispersion solution. The ESO 1.52 m/FEROS (La Silla, Chile) observations were carried out using two EEV detector mosaic of 4096 × 2048 pixels (size 15 μm × 15 μm). Automatic spectral reduction was carried out using special FEROS software. In the present analysis we used the same spectral synthesis tools as in Santos et al. (2001, 2002, 2003a) and Israelian et al. (2001, 2003). The stellar parameters (Tables 1 and 2) were taken from Santos et al. (2003a) and Bodaghee et al. (2003). The orbital parameters of planets were obtained from the Extrasolar Planets Encyclopaedia (http://www.obspm.fr/encycl/encycl.html) compiled by Jean Schneider.

3. Lithium in solar-type stars

The light element Li provides information regarding the redistribution and mixing of matter within a star. Standard evolutionary models predict that the Li abundance in main sequence stars should depend uniquely on the stellar effective temperature, age (chromospheric activity) and metallicity (see for example D'Antona & Mazzitelli 1994). Mass (or T_{eff}) is the first parameter that governs the Li depletion in solar-type stars. Age is the second parameter which accounts for a MS (main sequence) depletion and is also linked with chromospheric activity. A third parameter(or perhaps parameters) might be a metallicity and/or rotation. This is confirmed by the analysis of the correlation matrix for the parameters governing the surface abundance of Li (Pasquini et al. 1994). On the other hand, we know that classical models of stellar evolution neglect several important physical processes that are important

for interpreting the photospheric Li abundance in solar-type stars. Gravitational settling (downward motions), thermal diffusion (downward motions) and radiative acceleration (upward) are among the most important. Main sequence mass loss and slow mixing via gravity waves (García López & Spruit 1991; Montalbán & Shatzman 2000) and rotation via angular momentum loss (e.g. Pinsonneault et al. 1990; Vauclair et al. 1978; Maeder 1995; Zahn 1992) make the physics of depletion even more complicated.

For solar-type stars, two important observational facts need to be explained: the high dispersion in Li abundance for stars of similar temperature, age and metallicity in open clusters (Pasquini et al. 1994) and the large Li deficiency in the Sun. On the other hand, observations indicate that rapidly rotating stars preserve more Li than slow rotators of the same mass (Randich et al. 1997; Stauffer et al. 1997; García López et al. 1994). However, this is not enough to explain the large Li scatter since several Li rich stars in the Pleiades are slow rotators (King et al. 2000). It has also been shown that tidally locked binaries in the Hyades have much higher Li abundances than single stars in the same cluster (Thorburn et al. 1993; Deliyannis et al. 1994). Nevertheless, Ryan & Deliyannis (1995) found close binaries in Pleiades with normal Li abundances, but, given the young age of the cluster, this may not be conclusive. Numerous observations strongly indicate that there must be an additional parameter, or parameters, to control the surface abundance of Li in solar-type stars.

Lithium destruction is sensitive to the detailed chemical composition of the stellar matter. Depletion of Li anticorrelates with helium and deuterium content because of opacity effects. The increase of metal opacities in solar-type stars is responsible for the transition between radiative and convective energy transport. The main contributors to the total opacity at BCZ (base of the convection zone) of the present Sun are oxygen (36%) and iron (20%) (see Table 3 of Piau & Turck-Chieze 2002). However, observations show no clear correlation between Li and [Fe/H] in the metallicity range $-1 <$ [Fe/H] < 0.2 (e.g. Pasquini et al. 1994; Chen et al. 2001) and Li and [O/H] in the range $-0.5 <$ [O/H] < 0.4 (Pompéia et al. 2002).

Li depletion already takes place in the pre-main sequence (PMS) phase of stellar evolution and increases with decreasing stellar mass. During the PMS, stars slowly contract towards the zero-age main sequence (ZAMS) in quasi-hydrostatic equilibrium within the Kelvin–Helmoltz timescale. The PMS lifetime varies from 30 to 100 Myr for stars with 1.4 and 0.8 $M_\odot$, respectively. The stars pass several stages of light-element burning during contraction. Initial energy production is provided by deuterium fusion at 5×10^5 K. According Palla & Stahler (1991), this phase stops the contraction at radius 5–6 $R_\odot$ for a 1 $M_\odot$ star. For solar-mass stars deuterium fusion starts at the age of $\sim 4 \times 10^4$ yr and continues for $\sim 2 \times 10^5$ yr. The Li depletion starts 1.4 Myr before the appearance of a radiative core. The temperature at the BCZ for a 1 $M_\odot$ star rapidly increases from 10^6 to 4×10^6 at 2 Myr and then slowly decreases toward the value almost equal to that observed in the present Sun (i.e. 1.2×10^6 K). This results in rapid burning of Li within 2–20 Myr.

Mass accretion in the T Tauri phase can affect surface abundance of Li in several ways. First of all, it modifies the stellar mass and therefore alters the stratification. Second, it adds matter with ISM abundances to the surface of the star thus modifying the chemical composition of the atmosphere. And finally, accretion changes the boundary conditions. Mass accretion rates in T Tauri stars vary between 10^{-6} and 10^{-8} $M_\odot$ yr^{-1} (Hartigan et al. 1995). Global accreted mass could be of the order of few times 10^{-2} $M_\odot$ (Hartmann 1998). During the accretion process the star depletes both its initial Li and also the Li it receives from accretion. It is clear that accretion will enhance surface Li abundance if it could last long enough, i.e. after PMS depletion. More than 90% of the final stellar mass is accreted during less than 1 Myr before the classical T Tauri phase (Andre et al. 1999). This phase is followed by slow (but most probably variable) accretion during some 30–50 Myr. Recent computations (Piau & Turck-Chieze 2002) suggest that the more the star accretes the more it depletes Li because of the dominant structural effects. Apparently, accreted Li does not compensate for the additive burning because of the lower mass of the star. Accretion rates as low as 10^{-9} $M_\odot$ (or even lower) are required in order to counteract the mass effect. Let us also note that internal rotation on the PMS also has an important effect on Li as the core and surface may have different rotation rates.

The existence of strong Li depletion in the Sun is inconsistent with classical models. In order to explain the observations, lithium must be transported from the convection zone to the hot layers where the temperature is more than 2.5×10^6 K. However, the overall effect must be small in order to allow for some Li preservation in the solar atmosphere after 4.5 Gyr of MS evolution. The real problem is how the Li nuclei can cross the gap between the hot layers and the BCZ. Overshooting convection (Ahrens et al. 1992) and anisotropic turbulence stabilized by the radial temperature gradient (Zahn 1992) are among the mechanisms most commonly discussed in the literature. This transport is less effective in rapidly rotating stars. The amount of Li depletion in the Sun cannot be explained by rotation and convective diffusion since the timescales of these processes are 12 days (Noyes et al. 1984) and 100 yr (Rüdiger & Pipin 2001), respectively. This clearly indicates that any nonconvective mixing must be very slow.

The presence of a large (~1 dex) Li gap in solar-type stars with 5600 K $< T_{\rm eff} <$ 5900 K has been suggested by different authors (see for example Pasquini et al. 1994; Chen et al. 2001). The Sun belongs to the group with low Li abundance with $\log \epsilon({\rm Li}) = 1.16$ (Müller et al. 1975) and according Pasquini et al. (1994), about 50% of these stars having similar $T_{\rm eff}$ and age as the Sun have suffered an equally severe Li depletion during their MS lifetime. Main-sequence depletion appears to be a slow and more complicated process.

In summary, a large spread of Li abundance exists in solar-type stars of similar age, mass and metallicity. This spread cannot be explained solely in terms of these parameters. The large Li dispersion may be produced during MS evolution by a still an unknown mechanism. Rotationally induced mixing and MS mass-loss could produce different Li abundance in stars with similar mass, age and chemical composition. What is not clear is why these non-standard mixing processes produce a "gap" on the Li morphology for stars with 5600 K $< T_{\rm eff} <$ 5900 K but not a large scatter.

4. Evolution of Li in stars with exoplanets

4.1. Accretion of planets and planetesimals

A large number of comets that plunge into the Sun have been discovered by SOHO (Raymond et al. 1998). There is almost no doubt that the flux of resonant asteroids that strike the Earth and the Sun was much higher in the past. The sweeping of mean motion resonances was caused by a dissipation of a protoplanetary gas disc and the migration of Jupiter and Saturn to their current positions. These processes led to the depletion of the outer belt and the accretion of rocky matter on to the Sun. The belt between Earth and Jupiter was more massive in the past as is evidenced by the interpolation of the surface density of iron material in the Solar System planets (Weidenschilling 1977). Other independent evidence comes from the accretion of the asteroids over short time scales as indicated by the analysis of meteorites (Wetherill 1989). It is believed that up to 5 Earth masses would have been between Mars and Jupiter, about half of which have accreted in the Sun.

Slow accretion of planetesimals was invoked in order to explain the [Fe/H] distribution of planet-harbouring stars. Based on an analysis of 640 solar-type stars Murray et al. (2001) have suggested that the main sequence accretion of a chondritic matter is a common process in MS stars. These authors have proposed that most, if not all, solar-type stars accreted 0.4 Earth masses of iron after they reached the main sequence. In a different paper Murray & Chaboyer (2002) conclude that an average of 6.5 Earth masses of iron must be added to the planet-harbouring stars in order to explain the mass–metallicity and age–metallicity relations. Given that a small fraction of protostellar discs have masses around 0.1 $M_\odot$, such discs would contain at least 10 Earth masses of iron even if their metallicity is [Fe/H] $= -0.5$. It is of course not clear which fraction of planetesimals will be accreted in stars with different atmospheric parameters or when. But in principle, one can be sure that there is a large amount of iron available in protoplanetary discs in the form of planetary embryos, asteroids and planetesimals. In some planetary systems, this matter may be accreted during MS evolution making the parent stars metal rich. Observational biases and poorly known convection zone masses of stars with $M > 1.2$ $M_\odot$ are responsible for the current debate on the source of metal enrichment in planet host stars (Santos et al. 2001, 2003a; Pinsonault et al. 2001; Murray & Chaboyer 2002).

Accretion of a few Earth masses of planetesimals during early MS evolution will strongly modify ^{7}Li abundances in these stars. Moreover, in stars with $T_{\rm eff} >$ 5900 K a large amount of the added ^{6}Li may avoid destruction via mixing given the depth of the convection zone (Montalbán & Rebolo 2002). Following the estimates of Murray et al. (1998, 2001) and Murray & Chaboyer (2002), we would expect a large amount of ^{6}Li in the atmospheres of late F/early G main sequence metal-rich planet hosts. Our detection of ^{6}Li

in HD 82943 (Israelian et al. 2001, 2003) certainly suggests that this test should be continued in other systems.

Numerical simulations of inward migration suggest that planets may be ingested in some systems. Different physical mechanisms may lead to planet engulfment and each of them have their characteristic timescales. Classical migration caused by tidal interaction (Lin et al. 1996) operates on short time scales (a few Myr) and will add planetary Li to the star when the latter is still evolving towards the main sequence. This may not have a large affect on the surface abundance of ^{7}Li and ^{6}Li since these nuclei will be destroyed in hot stellar interiors owing to the efficient convection. The time scale of planet accretion brought about by multi-body interactions may be much longer (up to 100 Myr, Levison et al. 1998) compared with the pre-MS evolution lifetime; therefore, this process may modify surface abundances of both Li isotopes. Dynamical friction is another possibility for the accretion of a large amount of rocky matter during several hundreds of Myr or even Gyr.

We conclude that there are various physical process that may lead to the accretion of matter by stars with extrasolar planets during their MS lifetime. These processes will modify surface abundance of Li.

4.2. Stellar activity caused by interaction with exoplanets

It is well know that stellar chromospheric or coronal activity increases when two stars interact with each other (e.g. RS CVn systems). This effect is mostly caused by enhanced dynamo activity brought about by rotational synchronization and spin-up. Activity can also be triggered by tidal effects (Catalano et al. 1996). Resulting flares may be a source of Li just as it is produced in the Sun (Livshits 1997). The effects of tidal and magnetic interaction are also expected to occur in stars with exoplanets. These effects have recently been considered by Cuntz et al. (2000). We also note that Shkolnik et al. (2003) have detected the synchronous enhancement of Ca II H and K emission lines with the short period planetary orbit in HD 179949. Another example of the stellar activity triggered by a star-planet interaction was presented by Santos et al. (2003b) in HD 192263.

Present exoplanet surveys are targeting old, chromospherically inactive, slowly rotating stars. This observational bias does not allow us to discover any possible relationship between rotation, chromospheric activity and Li in planet-harbouring stars. The reason for avoiding young and active stars lies in surface spots, which introduce systematic variations in the Doppler velocities of stellar absorption lines. While solar flares produce Li in spallation reactions, the amount of Li and the dynamics of flares are such that no Li atoms are accreted in the stellar photosphere (Ramaty et al. 2000). However, the so called *superflares*, if they exist, may modify the surface abundance of Li in cool stars and planet hosts, in particular. There have been nine observations of old solar-type stars indicating very strong flares with durations from minutes to days (Rubenstein & Shaefer 2000; Schaefer et al. 2000). There is

no clear theoretical interpretation of these events while the link with hot jupiters has already been put forward (Rubenstein & Shaefer 2000). Strong magnetic fields of short period giant planets may become entangled with the magnetic fields of their parent stars and release large amounts of energy in superflares via magnetic reconnection. The amount of energy created in these flares is large (10^{33}–10^{38} erg) enough to create a substantial amount of Li (Livshits 1997; Ramaty et al. 2000).

If strong flares are able to enhance atmospheric Li in planet hosts, then we may expect parent stars in short period systems to have more Li on average. Such flares will create not only ^{7}Li but also ^{6}Li.

4.3. The tidal effects in short-period systems

Engulfment of planets and brown dwarfs has been suggested as the cause of the high rotational velocities in some field red giants (Stefanik et al. 2001) and blue horizontal branch stars (Peterson et al. 1983; Soker & Harpaz 2000). A theoretical examination of the effects of planet engulfment on angular momentum evolution and mass loss rates from giants was recently carried out by Livio & Soker (2002).

Various observations confirm a correlation between the lithium content and the angular momentum lost by solar-type stars (García López et al. 1994; Randich et al. 1998). The physics of this relationship was explored by different authors (Pinsonneault et al. 1990; Zahn 1992, 1994). A link between lithium depletion and angular momentum loss is also predicted for binary systems. Viscous dissipation of time-dependent tidal effects may produce the circularization of the binary system orbit and synchronization between stellar rotation and orbital motion (Zahn 1977). While single stars spin down because of angular momentum lost via stellar winds, stars in binary systems may spin up as a result of the momentum gained from orbital migration. Many observations (De Medeiros et al. 1997; Costa et al. 2002) show that stars in binary systems with a period less than the critical period for synchronization generally have enhanced rotation compared with their single counterparts. There are strong indications that lithium is less depleted in short-period binary systems with enhanced rotation.

It is well known that short-period planets have tidal interactions with their parent stars. If a star's rotation period is greater than that of the planets, the star will spin up because of tidal friction. This may prevent strong Li depletion. Momentum conservation will lead to a decrease in the semimajor axis of the planet's orbit. This interaction was invoked in order to explain the absence of massive planets at $a < 0.1$ AU (Pätzold & Rauer 2002). A critical test for this scenario would be a comparison of rotational velocities of stars in short and long period planetary systems. However, this may not be easy given the complex and time-dependent nature of the core–envelope evolution and the star–planet interaction. The orbital angular momentum of the close-in planets transferred to the star may influence the angular momentum evolution of the remaining planets in the system. The rotationally decoupled convective layer may spin up and force the remaining planets to spiral outward. The enhanced angular momentum of the convective layer may create a large

shear instability at the interface between the convective and radiative zones that may result in mixing between the convection zone and stellar interior by a decreasing surface abundance of Li. Planetary migration and/or consumption may also enhance magnetic activity via the dynamo effect. Consequently, the star will spin down because of enhanced magnetic breaking.

The angular momentum history of solar-type stars is strongly influenced by the formation and evolution of planetary systems. The wide dispersion in rotation rates of cluster stars has been explained (Edwards et al. 1993) by invoking disk interactions in the pre-MS. This phenomenon, as well as the formation of planets, may prevent some stars from ever passing through a fast rotator phase near the ZAMS. It is believed that magnetic interactions between pre-MS stars and their discs, and the formation of planetary systems with different characteristics, create a wide range of initial rotation periods that virtually converge on the main sequence. Thus, stars with similar age, mass and metallicity may arrive on the MS with similar rotation velocities but different amounts of Li.

Barnes (2003) has recently proposed that rotating solar-type stars lie primarily on two sequences. Stars evolve from a core–envelope decoupled state to a coupled state. It is interesting to investigate whether the physics behind the two rotational sequences of Barnes (2003) has anything to do with the Li gap of Chen et al. (2001) and Pasquini et al. (1994). The planetary migration may also leave their signatures on period–colour diagrams of clusters and field stars.

5. Correlation with stellar parameters

5.1. Comparison sample of Santos et al. (2001)

A first look at the of Li abundances in stars with and without exoplanets (Tables 1 and 2) from Santos et al. (2001) suggests that both samples have a similar distribution (Fig. 1). Plotting Li against metallicity in stars with and without planets, we found a large scatter. Our Fig. 2 shows no clear dependence on metallicity. Yet this can be hidden by the mass-related depletion. In fact, we observe old solar-type stars with metallicities 2–3 times solar and with abundance of Li similar to the Sun. This suggests that the metallicity is not the key parameter determining the Li abundance in these stars (Pasquini et al. 1994). On the other hand, our plot of Li against $T_{\rm eff}$ for the stars of both samples (Fig. 3) does not show anything peculiar. Except for a few stars occupying a small area between $1.0 < \log \epsilon({\rm Li}) < 2.2$ and $5300 \text{ K} < T_{\rm eff} < 5700 \text{ K}$, this morphology is not different from that observed in the field stars. However, the low number of stars in the comparison sample with detectable Li in their atmospheres (Table 2) does not allow us to arrive at any firm conclusions.

5.2. Comparison sample of Chen et al. (2001)

To make this comparison possible we have decided to use data from the literature. Lithium abundances in field stars from Chen et al. (2001) were used to compare stars with and without exoplanets. We have removed four stars with exoplanets from the list of Chen et al. and used their data as a

Table 1. Determined atmospheric parameters and Li abundances for a set of stars with planets and brown dwarf companions.

Star	$T_{\rm eff}$ (K)	$\log g$ (cm s^{-2})	ξ_t (km s^{-1})	[Fe/H]	$\log \epsilon({\rm Li})$
HD 142	6290	4.38	1.91	0.11	2.96
HD 1237	5555	4.65	1.50	0.11	2.24
HD 2039	5990	4.56	1.23	0.34	2.29
HD 4203	5650	4.38	1.15	0.40	<0.70
HD 4208	5625	4.54	0.95	−0.23	<0.69
HD 6434	5790	4.56	1.40	−0.55	<0.85
HD 8574	6080	4.41	1.25	0.05	2.71
HD 9826	6120	4.07	1.50	0.10	2.47
HD 10697	5665	4.18	1.19	0.14	1.98
HD 12661	5715	4.49	1.09	0.36	<0.99
HD 13445	5190	4.71	0.78	−0.20	<−0.1
HD 16141	5805	4.28	1.37	0.15	1.11
HD 17051	6225	4.65	1.20	0.25	2.63
HD 19994	6210	4.20	1.52	0.26	2.01
HD 20367	6100	4.55	1.31	0.14	3.02
HD 22049	5135	4.70	1.14	−0.07	<0.3
HD 23079	5945	4.44	1.21	−0.11	2.37
HD 23596	6125	4.29	1.32	0.32	2.93
HD 27442	4890	3.89	1.24	0.42	<−0.42
HD 28185	5705	4.59	1.09	0.24	1.55
HD 30177	5590	4.45	1.07	0.39	<0.35
HD 33636	5990	4.68	1.22	−0.05	2.60
HD 37124	5565	4.62	0.90	−0.37	<0.32
HD 38529	5675	4.01	1.39	0.39	<0.61
HD 39091	5995	4.48	1.30	0.09	2.33
HD 46375	5315	4.54	1.11	0.21	<0.02
HD 50554	6050	4.59	1.19	0.02	2.59
HD 52265	6100	4.29	1.31	0.24	2.88
HD 74156	6105	4.40	1.36	0.15	2.74
HD 75289	6135	4.43	1.50	0.27	2.84
HD 75732	5307	4.58	1.06	0.35	<0.02
HD 80606	5570	4.56	1.11	0.34	<0.62
HD 82943	6025	4.54	1.10	0.33	2.52
HD 83443	5500	4.50	1.12	0.39	<0.56
HD 89744	6338	4.17	1.55	0.30	2.07
HD 92788	5820	4.60	1.11	0.34	1.34
HD 95128	5925	4.45	1.24	0.00	1.8
HD 106252	5890	4.40	1.06	−0.01	1.65
HD 108147	6265	4.59	1.40	0.20	2.34
HD 108874	5615	4.58	0.93	0.25	<0.37
HD 114386	4875	4.69	0.63	0.00	<−0.47
HD 114729	5820	4.20	1.03	−0.26	1.96
HD 114762	5950	4.45	1.0	−0.60	2.26
HD 114783	5160	4.75	0.78	0.16	−0.12
HD 117176	5530	4.05	1.08	−0.05	1.85
HD 121504	6090	4.73	1.35	0.17	2.66
HD 128311	4950	4.80	1.00	0.10	<−0.37
HD 130322	5430	4.62	0.92	0.06	<0.16
HD 134987	5780	4.45	1.06	0.32	<0.74
HD 136118	6175	4.18	1.61	−0.06	2.40
HD 141937	5925	4.62	1.16	0.11	2.48
HD 143761	5750	4.10	1.2	−0.29	1.38
HD 145675	5255	4.40	0.68	0.51	<−0.02
HD 147513	5880	4.58	1.17	0.07	2.05
HD 150706	6000	4.62	1.16	0.01	2.75

Table 1. continued.

Star	$T_{\rm eff}$ (K)	$\log g$ (cm s^{-2})	ξ_t (km s^{-1})	[Fe/H]	$\log \epsilon$(Li)
HD 160691	5820	4.44	1.23	0.33	<0.86
HD 162020	4830	4.76	0.72	0.01	<−0.3
HD 168443	5600	4.30	1.18	0.10	<0.76
HD 168746	5610	4.50	1.02	−0.06	<0.85
HD 169830	6300	4.04	1.37	0.22	1.16
HD 177830	4840	3.60	1.18	0.32	<−0.50
HD 178911B	5650	4.65	0.85	0.28	<0.39
HD 179949	6235	4.41	1.38	0.21	2.63
HD 186427	5685	4.26	0.80	0.07	<0.60
HD 187123	5830	4.40	1.00	0.16	1.20
HD 190228	5325	3.95	1.10	−0.23	1.23
HD 190360	5590	4.48	1.06	0.25	<0.34
HD 192263	4995	4.76	0.90	0.04	<−0.35
HD 195019	5845	4.39	1.23	0.08	1.46
HD 196050	5905	4.41	1.40	0.21	2.15
HD 202206	5765	4.75	0.99	0.37	1.05
HD 209458	6120	4.56	1.37	0.03	2.70
HD 210277	5560	4.46	1.03	0.21	<0.32
HD 213240	5975	4.32	1.30	0.16	2.56
HD 216435	5905	4.16	1.26	0.22	2.72
HD 216437	5875	4.38	1.30	0.25	1.95
HD 217014	5805	4.51	1.22	0.21	1.30
HD 217107	5655	4.42	1.11	0.38	<0.41
HD 222582	5850	4.58	1.06	0.06	<0.59

Table 2. Li abundance in a volume-limited sample of stars without detected giant planets from Santos et al. (2001).

Star	$T_{\rm eff}$ (K)	$\log g$ (cm s^{-2})	ξ_t (km s^{-1})	[Fe/H]	$\log \epsilon$(Li)
HD 1581	5940	4.44	1.13	−0.15	2.35
HD 4391	5955	4.85	1.22	0.01	<1.16
HD 5133	5015	4.82	0.92	−0.08	<0.01
HD 7570	6135	4.42	1.46	0.17	2.91
HD 10360	5045	4.77	0.89	−0.19	<0.05
HD 10647	6130	4.45	1.31	−0.03	2.80
HD 10700	5370	4.70	1.01	−0.50	<0.43
HD 14412	5410	4.70	1.01	−0.44	<0.47
HD 20010	6240	4.27	2.23	−0.20	2.10
HD 20766	5770	4.68	1.24	−0.20	<1.00
HD 20794	5465	4.62	1.04	−0.36	<0.53
HD 20807	5865	4.59	1.28	−0.22	<1.09
HD 23356	5035	4.73	0.96	−0.05	<0.34
HD 23484	5230	4.62	1.13	0.10	<0.44
HD 26965A	5185	4.73	0.75	−0.26	<0.22
HD 30495	5880	4.67	1.29	0.03	2.45
HD 36435	5510	4.78	1.15	0.03	1.69
HD 38858	5750	4.56	1.22	−0.22	1.64
HD 40307	4925	4.57	0.79	−0.25	<−0.09
HD 43162	5630	4.57	1.36	−0.02	2.33
HD 43834	5620	4.56	1.10	0.12	2.32
HD 50281A	4790	4.75	0.85	0.07	<−0.27
HD 53705	5810	4.40	1.18	−0.19	1.04
HD 53706	5315	4.50	0.90	−0.22	<0.24
HD 65907A	5940	4.56	1.19	−0.29	<0.98
HD 69830	5455	4.56	0.98	0.00	<0.51
HD 72673	5290	4.68	0.81	−0.33	<0.52
HD 76151	5825	4.62	1.08	0.15	1.90
HD 84117	6140	4.35	1.38	−0.04	2.62
HD 189567	5750	4.57	1.21	−0.23	<0.81
HD 191408A	5025	4.62	0.74	−0.51	<0.13
HD 192310	5125	4.63	0.88	0.05	<0.24
HD 196761	5460	4.62	1.00	−0.27	<0.70
HD 207129	5910	4.53	1.21	−0.01	2.33
HD 209100	4700	4.68	0.60	0.01	<−0.39
HD 211415	5925	4.65	1.27	−0.16	1.95
HD 222237	4770	4.79	0.35	−0.22	<−0.26
HD 222335	5310	4.64	0.97	−0.10	<0.35

comparison sample of stars without planets. Most of the targets from Chen et al. are bright nearby solar-type stars which are part of various radial velocity surveys. Therefore, it is very unlikely that the sample contains more stars with exoplanets. Note also that most of the targets in this sample have solar metallicities or lower. Given the strong dependence between the presence of planets and the metallicity of the parent star (Santos et al. 2001, 2003a) we do not expect the sample of Chen et al. to contain more than one or two so far unknown planet hosts.

In Table 3, we show the effective temperature distribution of the stars in the planet host and comparison samples in the temperature range 5600–6350 K. The planet host sample is biased against lower and higher temperatures (Santos et al. 2003a); therefore, in what follows, we have not considered such stars in any of the two samples. The size of the bin used in the table has been chosen taking into account that the errors in the temperatures are of order 70 K. The three bins represent three major groups of stars according to the mass in their superficial convective zones. In the lower temperature bin the mass of the convective zone is a steep function of temperature, while in the other two bins, this mass does not change drastically. The third bin is just at a temperature below the Boesgaard & Tripicco gap (Boesgaard & Tripicco 1986). The table shows that the planet host and the comparison sample have comparable fractions of stars in each bin.

The lithium distribution in the planet host and Chen et al. comparison samples is shown in Fig. 4. The histogram reveals a marginally statistically significant excess of planet host stars

with $1.0 < \log \epsilon$(Li) < 1.6. It may be expected that these remarkably depleted stars come from the lower temperature bin (deeper superficial zones and potentially able to sustain a more efficient destruction mechanism). Looking at Table 3 we see that the planet host sample contains a slightly larger relative number of stars in this bin, which would favour a slightly larger relative fraction of lithium-depleted stars in the planet host sample, but this is not enough to explain the differences in the histograms of the two lithium distributions. Measurements of low lithium abundances require high S/N spectra as the equivalent width of the Li line in these stars varies between 2 and 8 mÅ. Our high quality spectra allow a clear detection of the Li line in all cases with $EW \geq 2$ mÅ. The S/N of spectra of Chen et al. (2001) is similar and therefore we have no reason to suspect that the excess of "Li-poor" stars with planets is
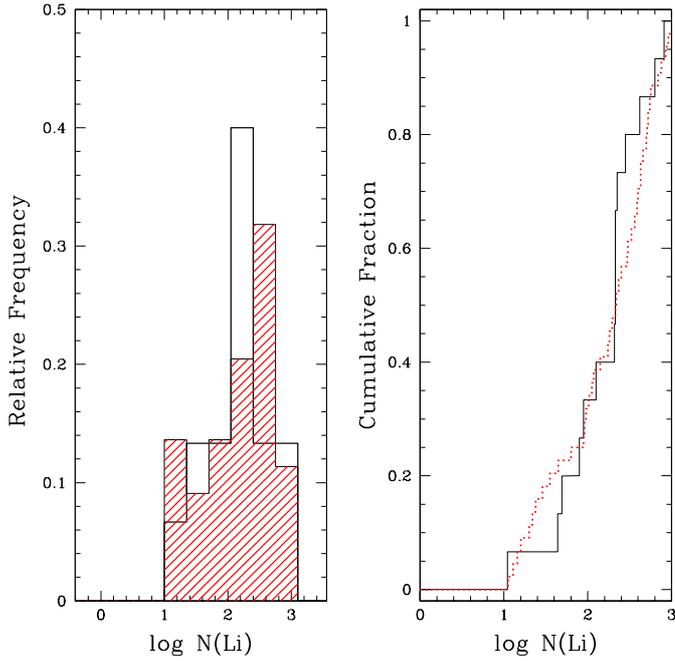
Fig. 1. Lithium distribution for stars with planets (hatched histogram) compared with the same distribution for the field stars (Table 2) without planets (empty histogram). A Kolmogorov–Smirnov test shows the probability for the two populations being part of the same sample to be 0.6.

Fig. 2. Lithium versus metallicity for stars with (filled dots) and without (empty circles) planets from Santos et al. (2001).

Fig. 3. Lithium versus effective temperature for stars with (filled dots) and without (empty circles) from Santos et al. (2001).

a bias. Thus, we think the effect is real. In Fig. 5 we find that the lithium abundances of planet host stars with effective temperatures between 5850 and 6350 K are similar to those in the Chen et al. comparison sample. While at lower effective temperatures the planet host stars show on average lower lithium abundances than stars in the comparison sample. The excess of Li poor planet host stars found in the histogram of Fig. 4 is concentrated in the range 5600 K $< T_{\rm eff} <$ 5850 K.

In Fig. 6 we can clearly see that the behaviour of the lithium abundances in the high metallicity planet host stars differ only with respect the comparison sample in the temperature range 5600 K $< T_{\rm eff} <$ 5850 K. In this temperature range we do not find a single example of planet host star with high lithium abundance (i.e. $\log \epsilon(\rm Li) \geq 2.0$) while in the comparison sample there are many. However, we should admit that the comparison sample of Chen et al. (2001) does not contain many stars with [Fe/H] $>$ 0. Future observations of metal-rich stars without planets (if there are any) may help to confirm our conclusions.

6. Correlation with orbital parameters

In Fig. 7 we plot the surface abundance of Li against the eccentricities of planetary orbits. As discussed above, consumption of a slowly migrated inner planet may increase the surface abundance of Li and modify the eccentricities of the remaining planet(s). A similar effect maybe produced if the ingestion of a planet is caused by multi-body interactions in the system. Except for a possible gap at 0.2 $< e <$ 0.4 and 1 $< \log \epsilon(\rm Li) <$ 1.6, our plot does not show any trends.

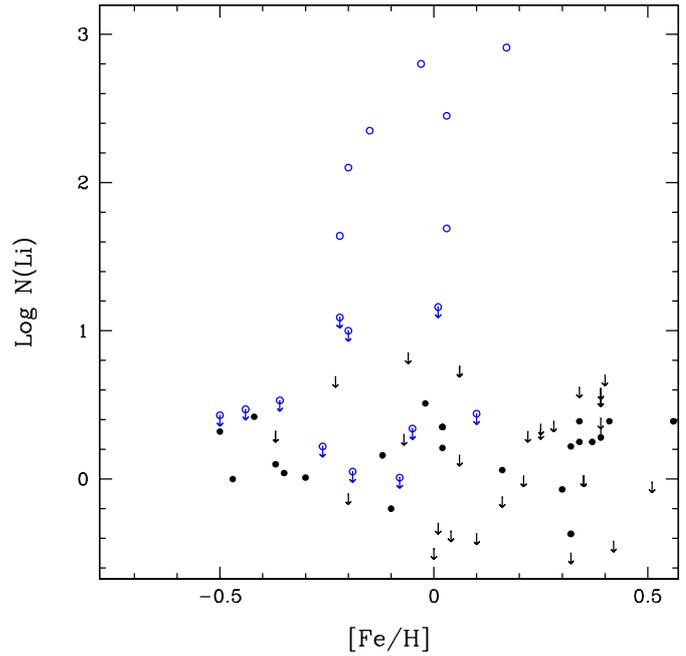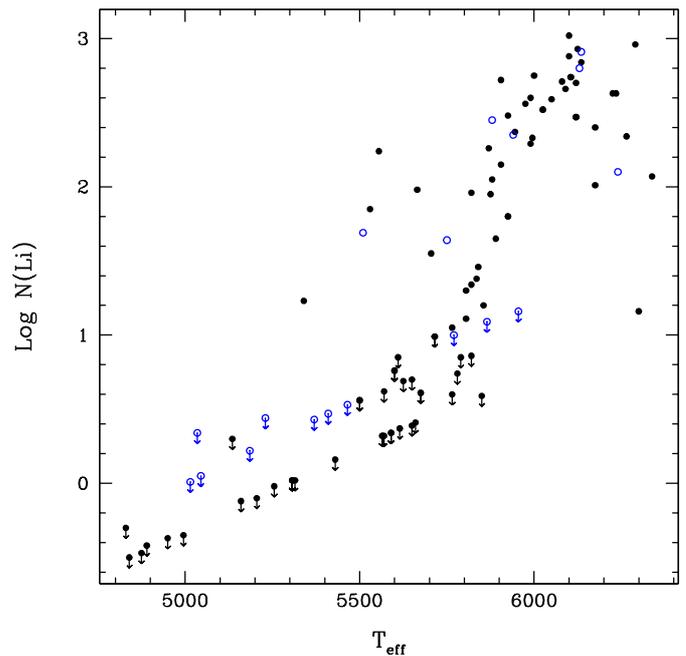Li abundance against the orbital period is shown in Fig. 8. As we can see, there seems to be a possible lack of

long-period planets orbiting Li-poor stars with 1 $< \log \epsilon(\rm Li) <$ 1.6. Apparently, all these planets, except one, have periods less than 500 days. All these short-period planets are orbiting their parent stars at less than 1 AU (Fig. 9). Considering stars with 1.6 $< \log \epsilon(\rm Li) <$ 3, we find that 50% have periods more than 500 days.

In Fig. 10 we plot the minimum mass for the planetary companions against Li. A first look at the plot immediately suggests a lack of massive planets with $M > 4\,M_{\rm J}$ orbiting
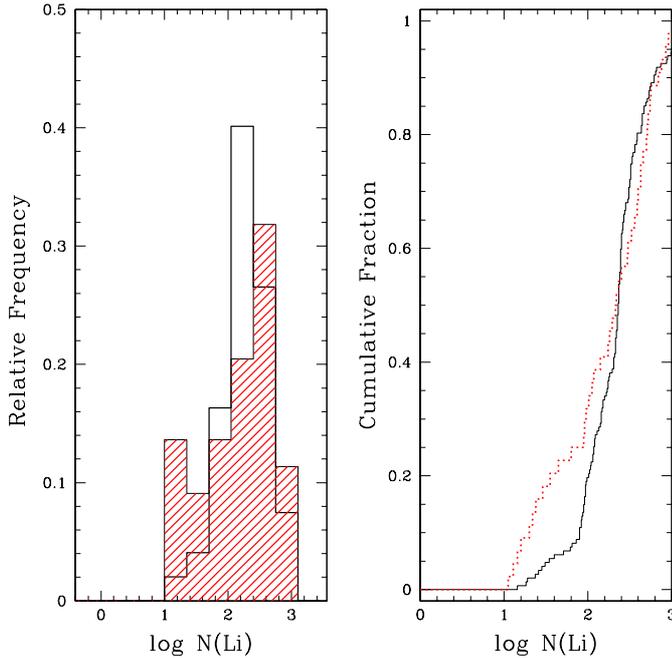
Fig. 4. Lithium distribution for stars with planets (hatched histogram) compared with the same distribution for the field stars from Chen et al. (2001). (empty histogram). A Kolmogorov–Smirnov test shows the probability for the two populations being a part of the same sample to be 0.2.

Table 3. Distribution of stars in the comparison samples of Chen et al. (2001) and planet hosts.

Range	Planet hosts	Comparison sample
$5600 < T_{eff} \le 5850$	39% (22)	32% (50)
$5850 \le T_{eff} < 6100$	34% (19)	40% (64)
$6100 \le T_{eff} \le 6350$	27% (15)	28% (43)

"Li-poor" stars with $1 < \log \epsilon(Li) < 1.6$. The only exception is HD 202206, which hosts a brown dwarf with a mass 17.5 M_J. When considering stars with $\log \epsilon(Li)$ between 1.6 and 3, we find that about half host planets with $M > 4\ M_J$. Obviously, there is a link between Mass–Li and Period–Li relationships. This may be associated with the already proposed correlation between mass and period of planetary companions (Zucker & Mazeh 2002; Udry et al. 2002). It would be interesting to get higher quality Li measurements for stars with massive planets and investigate whether there are no long-period massive planets around Li-poor ($1 < \log \epsilon(Li) \le 1.6$) exoplanet hosts.

7. Discussion and conclusions

It has been proposed that stars with short-period planets have higher metallicities among planet hosts (Queloz et al. 2000). If confirmed, this fact could be interpreted in several ways. For example, inward migration can produce a metallicity excess (Murray et al. 1998) because of the accretion of planetesimals. One can also imagine that the formation of inner planets is favoured by the metallicity. Recently Santos et al. (2003a)
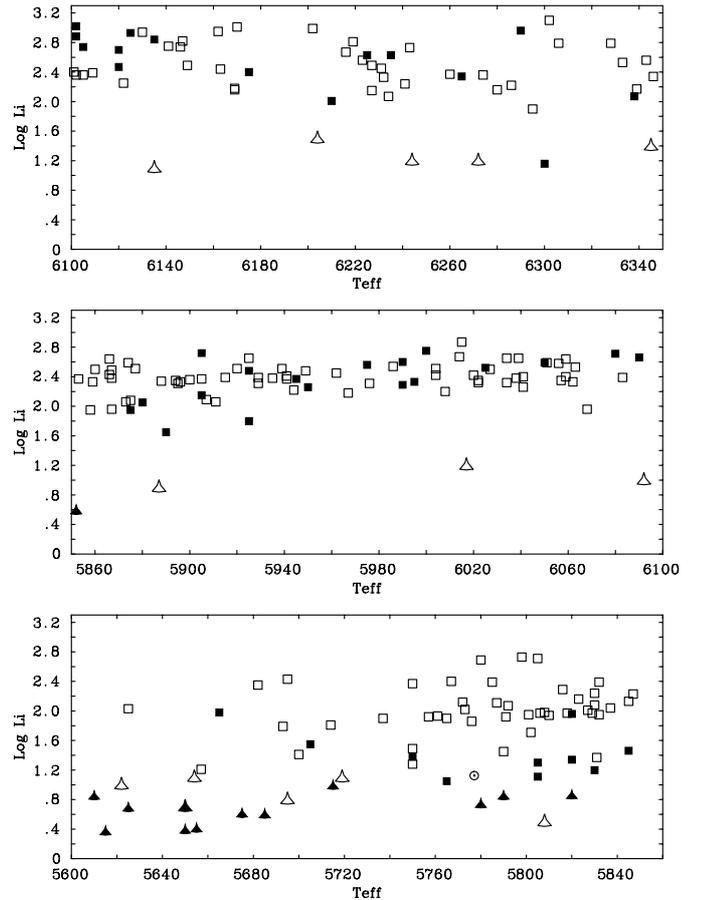

Fig. 5. Lithium versus effective temperature for stars with planets (filled squares) and the comparison sample of Chen et al. (empty squares). Upper limits are filled (planet hosts) and empty (comparison sample) triangles. The position of the Sun is indicated.

found an indication (which, however, is statistically not significant) that low mass planets mostly orbit metal-poor stars (e.g. Udry et al. 2002). Apparently, planet host stars more frequently show Li abundances in the range $\log N(Li) = 1.0-1.6$ than field stars. These abundances occur in stars with effective temperatures between 5600 and 5850 K, where we expect well developed convective zones and a significant depletion of Li. Are planet host stars in this temperature range more efficient at depleting lithium than single stars? What is the reason for their different behaviour in comparison with stars without planets? Why there are no significant differences with field stars in other Li abundance ranges?

Many processes discussed in this article may modify the surface abundance of Li in stars with exoplanets. By what amount and when depends on many parameters involved in the complex star–planet interaction. Given the depth of the convection zone, we expect that any effects on the Li abundance will be more apparent in solar-type stars. Lower mass stars have deeper convective zones and destroy lithium very efficiently, so we frequently only set upper limits to the abundance, which makes it difficult to find correlations with any parameter affecting Li abundance. On the other hand, the convective layers of stars more massive than the Sun are too far to reach the lithium burning layer. These stars generally preserve a significant
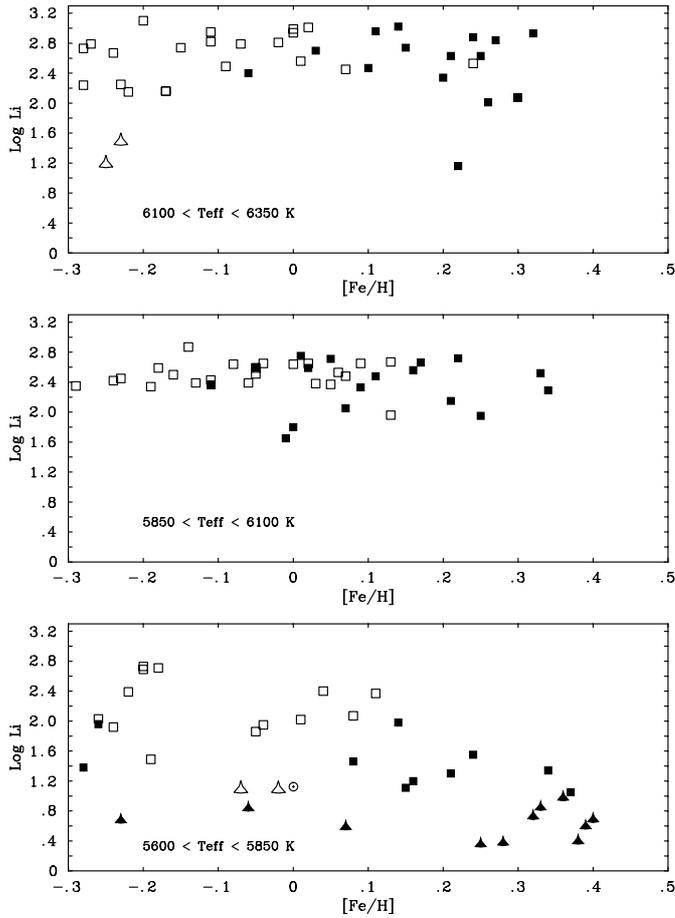
Fig. 6. Lithium versus metallicity for stars with planets (filled squares) and the comparison sample of Chen et al. (empty squares) for three regions of effective temperature. Upper limits are filled (planet hosts) and empty (comparison sample) triangles. The position of the Sun is indicated.
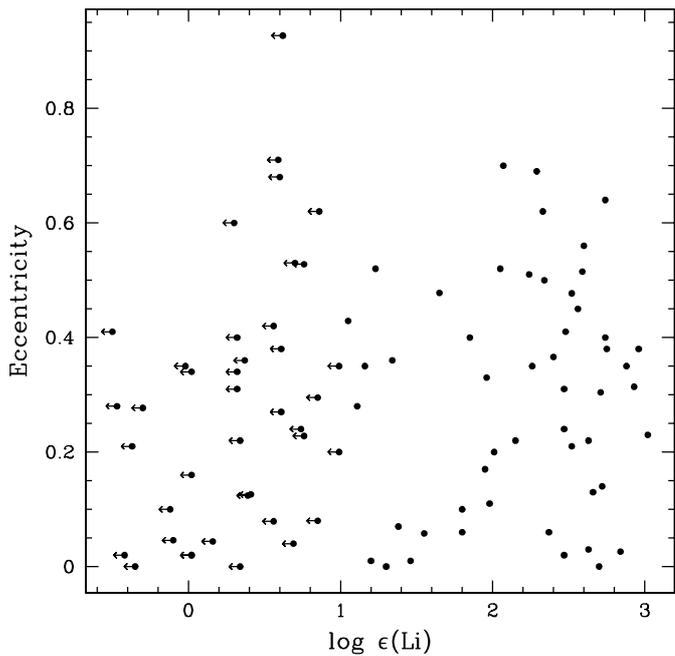

Fig. 7. Eccentricity for the planetary companions against surface abundance of Li.
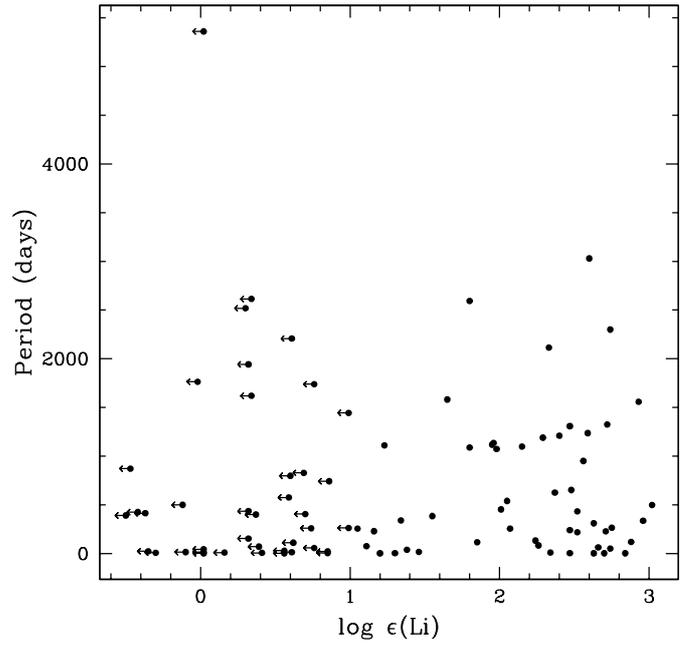

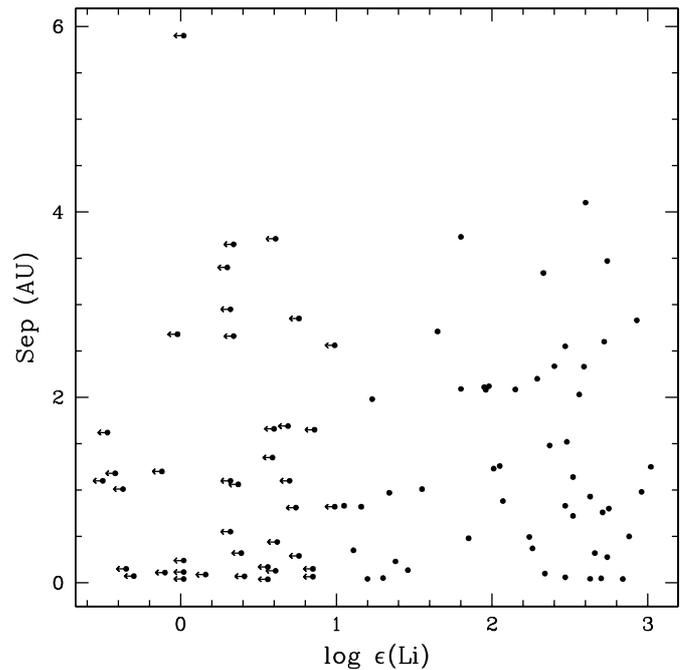**Fig. 8.** Orbital period for the planetary companions against surface abundance of Li.

Fig. 9. Separation (semimajor axis) for the planetary companions against abundance of Li.

fraction of their original lithium. The relatively small dispersion of lithium abundances in these hotter stars is clearly seen in Fig. 6. It is thus also more difficult to detect any external effects on the surface lithium.

Solar-type stars are possibly the best targets for investigating any possible effect of planets on the evolution of the stellar atmospheric Li abundance. In these stars we find a lower average Li abundance in planet host stars than in the field comparison sample (Fig. 6, lower panel). There are at least two possible
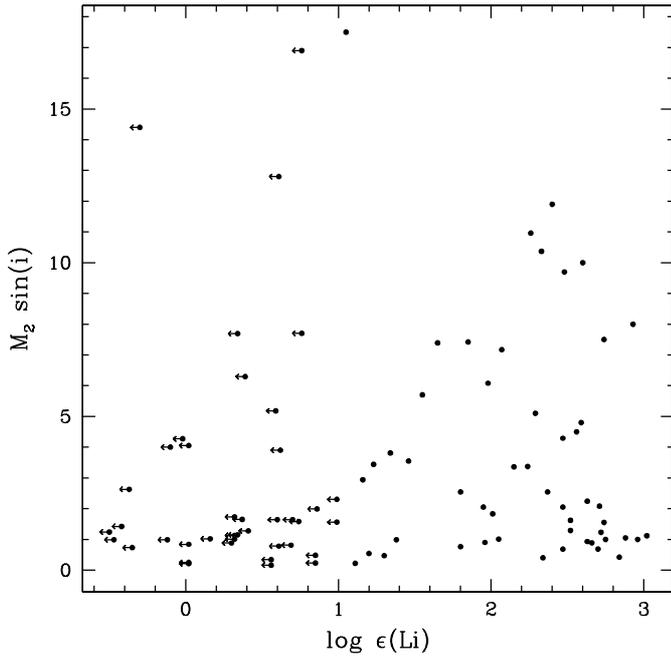
Fig. 10. Minimum mass for the planetary companions against surface abundance of Li.

hypothesis for the lower Li abundance in exoplanet hosts. It is possible that proto-planetary disks lock a large amount of angular momentum and therefore create some rotational breaking in the host stars during their pre-main sequence evolution. The lithium is efficiently destroyed during this process due to an increased mixing. The apparent extra depletion may be also associated with a planet migration mechanism at early times in the evolution of the star when the superficial convective layers may have been rotationally decoupled from the interior. Strong depletion may be caused by an effective mixing caused by Migration-triggered tidal Forces, which create a shear instability. The mass of the decoupled convection zone in these stars is comparable to the masses of the known Exoplanets; therefore, the migration of one or more planets could indeed produce an observable effect. The migration of planets may also produce the accretion of protoplanetary material and/or planets, inducing metallicity enhancement, and some fresh lithium could also be incorporated in the convective zone. However, if this takes place in the early evolution of the star, this lithium will most probably be destroyed.

Our observations suggest that Li abundances in stars with short-period planets may be influenced by the presence of planets. More observations would be welcome to tackle this problem.

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