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LETTER TO THE EDITOR

Higher depletion of lithium in planet host stars: no age and mass effect

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ABSTRACT

Recent observational work by Israelian et al. has shown that sun-like planet host stars in the temperature range 5700 K $< T_{\rm eff} <$ 5850 K have lithium abundances that are significantly lower than those observed for "single" field stars. In this letter we use stellar evolutionary models to show that differences in stellar mass and age are not responsible for the observed correlation. This result, along with the finding of Israelian et al., strongly suggest that the observed lithium difference is likely linked to some process related to the formation and evolution of planetary systems.

Key words. stars: evolution – stars: fundamental parameters – stars: abundances – stars: chemically peculiar – planetary systems

1. Introduction

The increasing number of discovered planets continues to give new insights into the planet formation processes (e.g. Udry & Santos 2007). The study of planet host stars is providing crucial observational evidence for this. The first large uniform studies (Santos et al. 2001, 2004b) have shown that stars with giant planets have chemical abundances that are distinctly different from those found in "single" stars, a result that was later confirmed by other authors (e.g. Fischer & Valenti 2005). This result provided important constraints for the models of planet formation and evolution (e.g. Pollack et al. 1996; Mordasini et al. 2009; Boss 2002).

Although most studies of chemical abundances in stars with planets have concentrated on the measurement of iron abundances as a metallicity proxy, several works have been made to study the abundances for a variety of refractory and volatile elements in planet host stars (e.g. Gilli et al. 2006; Ecuvillon et al. 2006; Takeda et al. 2007; Neves et al. 2009). Besides the general chemical enrichment found for stars hosting giant planets (interestingly not found for stars hosting very low mass planets, see: Sousa et al. 2008), none of these found compelling evidence for other chemical peculiarities.

The possibility that stars with planets present different abundances of the light elements lithium and beryllium has also been debated (King et al. 1997; Garcia Lopez & Perez de Taoro 1998; Deliyannis et al. 2000; Cochran et al. 1997; Ryan 2000; Gonzalez & Laws 2000; Gonzalez 2008; Israelian et al. 2004; Santos et al. 2004a; Takeda & Kawanomoto 2005; Takeda et al. 2007; Chen & Zhao 2006; Luck & Heiter 2006). Different abundances could indicate that planets or planetary material were engulfed by the star during its lifetime (and in which quantity) (e.g. Israelian et al. 2001), or suggest that the rotational history of the stars depends on the existence of planets or indirectly on the process for planet formation (Bouvier 2008; Castro et al. 2009).

Recently, Israelian et al. (2009) presented a large uniform study of lithium abundances in a sample of stars from the HARPS planet search programme (Mayor et al. 2003). In their work they reported a significant difference regarding the depletion of lithium for planet host stars when compared with stars with no detected planet in the range 5700 K $< T_{\rm eff} <$ 5850 K, confirming former suspicions (e.g. Israelian et al. 2004; Takeda et al. 2007). According to Israelian et al., stars with planets in the temperature range around the solar temperature (solar analogues) have significantly lower lithium abundances when compared with "single" stars (for which no planets were detected so far). The uniformity of the HARPS sample (composed mainly of old inactive stars) allowed Israelian et al. to exclude effects like stellar rotation, stellar activity, or chemical abundances as the cause for the observed difference.

In this paper we use stellar evolution models to explore the possibility that stellar age and mass could be responsible for the observed difference. In Sect. 2 we present the procedure used for the determination of precise and uniform masses and ages for our sample. In Sect. 3 we explore possible correlations between these two parameters and the lithium abundances. We conclude in Sect. 4.

2. Masses and ages

The stellar age and mass was determined by means of comparison between stellar evolutionary models and observations. Individual values of the stellar luminosity, effective temperature, and metallicity for the solar analogues in our sample (Israelian et al. 2009) were taken from the uniform study of (Sousa et al. 2008). These were used for a comparison with stellar models computed with the CESAM code version 3 (Morel 1997), running in the Coimbra Observatory. The details on the physics of these models can be found in Fernandes & Santos (2004) with one exception: the equation of state EFF is used

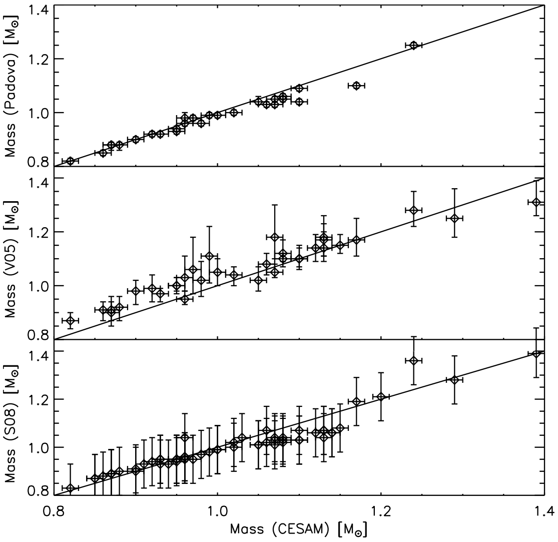

Fig. 1. Comparison between masses determined in this work using CESAM with the ones presented in Sousa et al. (2008) (*bottom*), Valenti & Fischer (2005) (*middle*) and determined using the Padova models (*top*). The filled lines represent the identity line.

(Eggleton et al. 1973), an analytical equation of state suitable for FGK stars. With these input physics the solar model fits the observed luminosity and effective temperature for the common accepted solar age of 4.6 Gyr (Dziembowski et al. 1999), as better as 10^{-4}, considering a mixing length parameter of convection $\alpha = 1.65$, the helium abundance $Y = 0.2675$, and the metal abundance $Z = 0.0173$. With these values, and assuming the primordial helium equal to 0.25 (e.g. Peimbert et al. 2009), the helium abundance to metallicity ratio is $\Delta Y/\Delta Z = 1.53$. The mass and age resolution for the models used in this procedure are 0.01 $M_{\odot}$ and a maximum time step of 200 Myr respectively.

For each star with a metal abundance fixed to the observed metallicity value (according to Sousa et al. 2008), we computed several models for different ages and masses to fit the observed luminosity and effective temperature. We assumed for those models the solar mixing length parameter, a null overshooting parameter ($\alpha_{\rm ov}$) for stars with masses lower than 1.1 $M_{\odot}$, and $\alpha_{\rm ov} = 0.2$ for higher mass stars (e.g. Claret 2007).

The stellar mass and age are estimated as follows: for each stellar evolutionary model we compute the functional

$$\chi^2(M,t) = \left(\frac{\log L_{\rm obs} - \log L_{\rm mod}}{\sigma_L}\right)^2 + \left(\frac{\log T_{\rm eff,obs} - \log T_{\rm eff,mod}}{\sigma_{T_{\rm eff}}}\right)^2$$

where the subscripts *obs* and *mod* refer to the observed values and theoretical (model) values respectively (e.g. Lastennet & Valls-Gabaud 2002). The σ values are taken from Sousa et al. (2008). The solution is obtained by minimizing the above function. For each star the final mass and age is obtained when the prediction of the theoretical stellar model is inside the observational error bar, i.e., $\chi^2(M,t) < 2$.

In Table 1 we present the derived values for mass and age in our sample. The typical (relative) errors bars of our estimations are 0.01 $M_{\odot}$ in mass and 0.5 Gyr and 1.0 Gyr, respectively, for ages lower and higher than 5 Gyr. This level of precision is possible because of the very small (relative) errors in the stellar parameters derived for the solar analogues in Sousa et al. (2008). We note however that we are not taking into account variations in parameters like the mixing length and helium abundance. Changes in these parameters could lead to errors in the stellar masses and ages (e.g. Fernandes & Santos 2004).

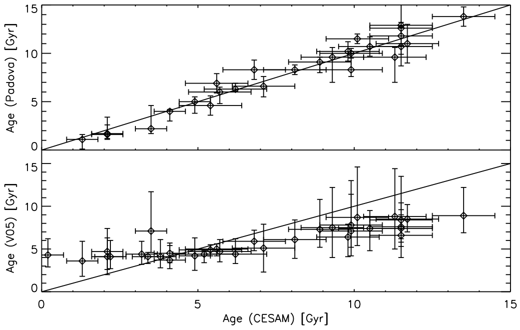

Fig. 2. Same as Fig. 1, but for ages.

In order to check our methodology, we applied the stellar evolutionary models from the Padova group, computed with the web interface dealing with stellar isochrones and their derivatives (`http://stev.oapd.inaf.it/cgi-bin/cmd`) to the stars of our sample. Taking into account that the Padova models are constrained to metal abundance lower than $Z < 0.03$, we have arbitrarily chosen a subsample of 27 stars to cover the range of mass and age of the stars in the paper. In Figs. 1 and 2 we show the comparison between masses and ages respectively, using the CESAM and Padova models. In addition we also include a comparison to the values published in Sousa et al. (2008) and Valenti & Fischer (2005) (with this latter we have 41 stars in common). A very good agreement exists between all sets of values, except for the ages of Valenti & Fischer (2005) which seem to be constrained to values closer to the Sun age. The reason for this is not clear; this discussion is out of the scope of the present paper. However, if the age span of the stars in our sample were smaller (taking the values from Valenti & Fischer), it would strengthen the results discussed below.

3. Lithium vs. age

Table 1 shows the values of mass and age derived for the stars in this work and their lithium abundances (Israelian et al. 2009). The sample studied here corresponds to the majority of solar analogues studied in Israelian et al. (2009). However, here we only considered those belonging to the HARPS sample (~60). For these stars we have the best uniform stellar parameters (Sousa et al. 2008), assuring the total consistency of our results. Four stars in the sample were also excluded since no reliable masses and ages could be derived (HD 28701, HD 78558, HD 96423, HD 143114).

The top panel in Fig. 3 shows the lithium abundance plotted against the effective temperature for the stars presented in Table 1. This result is almost indistinguishable from Fig. 1 in Israelian et al. (2009). There is a general tendency for lower temperature stars to present on average lower lithium abundances, an expected result (see e.g. Pinsonneault et al. 1990; Sestito & Randich 2005). It is also evident that the stars that host planets are distributed in the lower region of the plot, while the stars with no evidence for planetary companions are spread over the entire diagram.

In the middle plot of Fig. 3 we present the lithium abundance as a function of the derived stellar age. As expected, the bulk of the stars are old. The HARPS sample was chosen to avoid active (younger) stars due to the higher difficulty in searching for planets in these objects (e.g. Santos et al. 2000). Interestingly a few younger objects are seen in the left part of this panel

Table 1. New mass and age values together with published values for lithium abundance (<represents upper limit), [Fe/H] and $T_{\rm eff}$.

Star(HD)	Mass($M_\odot$)	Age(Gy)	log[N(Li)]	[Fe/H]	$T_{\rm eff}$
planet hosts:					
16141	1.14	6.0	<1.00	0.16	5806
16417	1.20	5.2	1.85	0.13	5841
20782	0.95	9.9	<0.47	−0.06	5774
66428	1.07	5.7	<0.71	0.25	5705
92788	1.10	2.2	<0.82	0.27	5744
107148	1.13	3.2	<1.24	0.31	5805
114729	0.93	11.6	2.00	−0.28	5844
134987	1.08	6.2	<0.60	0.25	5740
160691	1.15	5.2	<0.98	0.30	5780
202206	1.13	<0.5	1.45	0.29	5757
204313	1.08	2.9	<0.52	0.18	5776
222582	0.98	8.9	<0.91	−0.01	5779
comparison stars:					
1461	1.06	4.9	<0.74	0.19	5765
2071	0.96	3.5	<1.43	−0.09	5719
4307	0.99	9.8	2.48	−0.23	5812
8406	0.96	3.3	1.72	−0.10	5726
11505	0.87	>14	<0.35	−0.22	5752
12387	0.85	> 14	<0.15	−0.24	5700
19467	0.90	13.5	<0.55	−0.14	5720
20619	0.87	9.9	1.71	−0.22	5703
21938	0.78	>14	<1.13	−0.47	5778
27063	1.06	<0.5	1.70	0.05	5767
28471	0.95	8.7	<0.73	−0.05	5745
32724	0.96	11.0	1.63	−0.17	5818
34449	1.03	<0.5	2.08	−0.09	5848
37962	0.87	11.3	1.84	−0.20	5718
38858	0.88	9.3	1.54	−0.22	5733
44420	1.13	2.2	<0.71	0.29	5818
44594	1.08	4.1	1.55	0.15	5840
star(HD)	mass($M_\odot$)	Age(Gy)	log[N(Li)]	[Fe/H]	$T_{\rm eff}$
45289	0.95	11.5	<0.47	−0.02	5717
76151	1.07	1.3	1.87	0.12	5788
78429	1.02	8.1	<0.35	0.09	5760
78538	1.02	1.3	2.44	−0.03	5786
78612	0.93	11.8	1.62	−0.24	5834
88084	0.94	7.9	<0.91	−0.10	5766
89454	1.07	<0.5	1.64	0.12	5728
92719	1.00	1.7	1.93	−0.10	5824
95521	0.95	4.1	1.67	−0.15	5773
96700	0.92	11.5	1.35	−0.18	5845
97998	0.82	10.1	1.72	−0.42	5716
108309	1.10	6.8	<0.94	0.12	5775
111031	1.12	3.8	<0.75	0.27	5801
114613	1.24	5.4	2.69	0.19	5729
114853	0.86	11.5	<0.46	−0.23	5705
115585	1.14	5.8	<0.51	0.35	5711
145809	0.97	10.5	2.13	−0.25	5778
146233	1.05	2.1	1.64	0.04	5818
154962	1.29	4.1	2.39	0.32	5827
183658	1.00	7.1	<1.09	0.03	5803
189567	0.85	13.9	<0.18	−0.24	5726
189625	1.10	2.1	2.12	0.18	5846
198075	0.96	1.5	1.95	−0.24	5846
208704	0.96	9.5	<1.09	−0.09	5826
210918	0.93	11.7	<0.28	−0.09	5755
211415	0.91	9.7	1.85	−0.21	5850
215456	1.05	8.5	2.38	−0.09	5789
220507	0.96	11.5	<0.56	0.01	5698
221420	1.39	3.4	2.75	0.33	5847
223171	1.17	5.6	2.11	0.12	5841
224393	0.90	2.1	2.25	−0.38	5774

(<2 Gyr), a region where no lithium-depleted star is seen. This suggests a lithium abundance dependence with age. Above an age of ~2 Gyr, however, we observe a wider dispersion in lithium for all stars in the plot, and no correlation is seen.

The middle plot of Fig. 2 also clearly shows that even though we have planet hosts stars in all the age interval, these are preferably located at lower lithium abundances. No particular age correlation is present. Age does not seem to explain the observed difference between the lithium abundances in the two samples.

Finally, we present in the bottom panel the lithium abundance as a function the derived stellar mass. As for the age, we can easily see that the dispersion of the lithium abundances has the same behaviour for the complete range of masses in the sample. No evidence is found that stellar mass could be responsible for the observed lithium offset between the two samples. We note that the two planet hosts with the highest lithium abundances show no particular age or mass tendency. Their high abundance is likely explained because they are among the highest temperature stars in our sample.

We have also verified if the relatively large range in metallicities for our stars together with the dispersion in ages and masses could not be hiding any trend. To do this, we selected only stars within the metallicity interval $0.1 < [{\rm Fe/H}] < 0.3$, where the largest overlap between stars with and without planets exists. From these we selected only those with masses between 1.05 and 1.15 $M_\odot$ (Fig. 4, upper panel, lithium as a function of stellar age), and with ages between 2 Gyr and 6 Gyr (Fig. 4, lower panel, lithium as a function of stellar mass). The plots of Fig. 4 do not show any hint of a mass or age-lithium correlation that could explain the observed difference between planet host and "single" stars.

4. Conclusions

We derived uniform values for the stellar ages and masses in a sample of solar analogue stars, for which Israelian et al. (2009) have found a clear difference in the lithium abundances correlated to the existence of planets. Our analysis has shown that age and mass cannot explain the lithium abundance differences. This strongly suggests that the observed differences are not related to stellar intrinsic properties. This result confirms the uniformity of the studied sample.

Our results are directly linked with Li observations in open clusters. A large high-quality database for Li in open clusters acquired in the last years has permitted us to draw a secure picture of the empirical behaviour and evolution of Li in solar analogue stars (Randich 2008; Randich et al. 2009; Sestito & Randich 2005). Numerous observations show that stars with the same age, temperature, and metallicity can be affected by different amounts of Li depletion. A dispersion in Li of at least a factor of 10 has been observed in the solar-age, solar metallicity clusters M 67 (Pasquini et al. 2008) and several other old, solar metallicity or metal rich clusters (Randich 2008; Randich et al. 2009). This spread strongly suggests that Li depletion must be affected by an additional parameter besides mass, age, and chemical composition. This parameter could be an initial angular momentum of the star affected by the formation and evolution of planets. Similar Li dispersion (or often cited as bi-modality) is also observed in solar type field stars (Favata et al. 1996; Galeev et al. 2004; Chen et al. 2001; Lambert & Reddy 2004). We think that the same mechanism is responsible for the large Li dispersion in the field and open cluster solar type stars. Figure 3 clearly supports this suggestion.

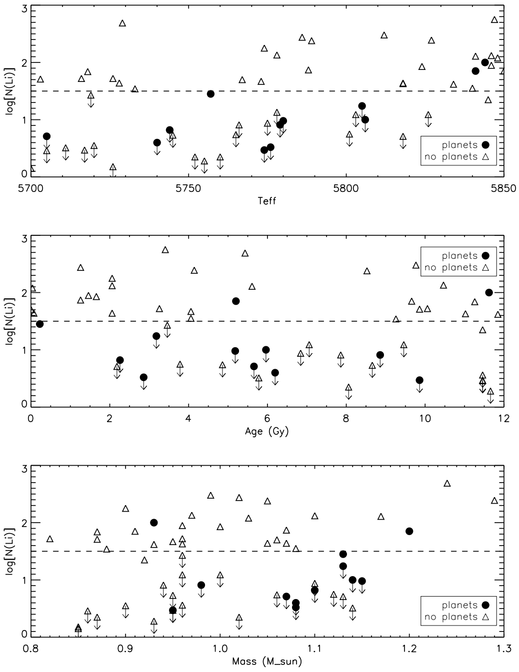

Fig. 3. Lithium abundances as a function of effective temperature (*top*), age (*middle*), and mass (*lower panel*). Filled circles denote stars with planets, while open triangles denote "single" stars. Arrows indicate upper limits.

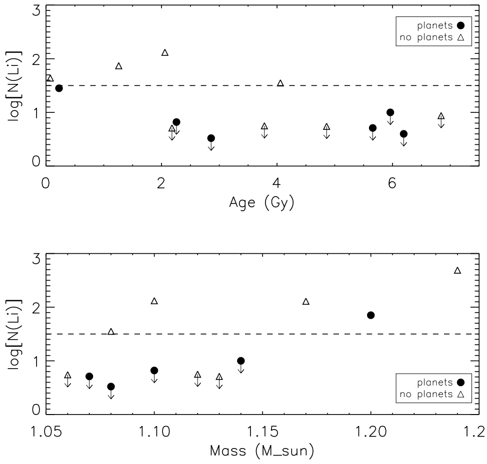

Fig. 4. Lithium abundances as a function of stellar mass (*top*) and age (*bottom*) in restricted subsamples of our stars.

No clear explanation has been found for the lithium abundance difference observed between stars with and without planets, though a few possibilities have been suggested. These include the star-planet interaction (Castro et al. 2009), the infall of planets into the star (leading to higher mixing – Theado et al., priv. comm.), or a difference in the rotational history of the star due to star-disc interaction. Massive proto-planetary discs capable of forming planets will likely help to break stellar rotation, thus changing the depletion rate of lithium (e.g. Charbonnel & Primas 2005; Cochran et al. 1997; Bouvier 2008; Pinsonneault 2010). Interestingly, the same mechanism could have been responsible for the low lithium abundance observed in our own Sun, itself a planet host stars, and can be used to explain the dispersion of lithium abundances observed in clusters of different ages (Sestito & Randich 2005).

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