Andreas Kaufer

Garik Isrealian

https://doi.org/10.1017/S1743921310004254 Published online by Cambridge University Press

Light Elements in the Universe
Proceedings IAU Symposium No. 268, 2009
C. Charbonnel, M. Tosi, F. Primas & C. Chiappini, eds.
© International Astronomical Union 2010
doi:10.1017/S1743921310004254

Lithium in stars with exoplanets

Garik Israelian

Instituto de Astrofisica de Canarias,
Calle Via Lactea s/n, E38200, La Laguna, Tenerife, Canary Islands, Spain
email: gil@iac.es

Abstract. Our recent study of solar-type stars from the HARPS GTO sample provides highly accurate information with regard to Lithium abundances in stars with and without detected planets (Israelian *et al.* 2009) . When the Li abundances of planet bearing stars are compared with the "single" stars, we find an excess of Li depletion in planet hosts with effective temperatures in the range 5700-5850 K. We also found that small amounts of Li have survived in the atmospheres of some planet-host solar analogs. Enhanced Li depletion in planet host stars puts constraints on mixing processes responsible for this phenomenon. We show that neither age nor metallicity are responsible for this observational fact.

Keywords. Stars: abundances, late-type, planetary systems

1. Introduction

The enhanced depletion of lithium in the Sun discovered more than 60 years ago remains the epitome of the Li puzzle. The base of the surface convective layer of the Sun is not hot enough for nuclear reactions to destroy Li, and yet the surface Li abundance is about 140 times less than the initial protosolar abundance which is the meteoritic value (Anders & Grevesse 1989). A large dispersion in Li abundance observed in solar-type stars of the same age, mass and metallicity is inconsistent with classical models of stellar evolution (DAntona & Mazzitelli 1994) and has reinforced the idea that the presence of planets may be responsible for this effect (King *et al.* 1997, Gonzalez & Laws 2000, Israelian *et al.* 2004).

King *et al.* (1997) were first to propose that the low Li abundances of the Sun and 16 Cyg B with respect to 16 Cyg A may be related to the presence of a planetary companion. Many studies have attempted to separate the effects of planets on Li abundance. Gonzalez & Laws (2000) corrected Li abundances in planet hosts for linear trends with age, metallicity, and $T_{\rm eff}$, and concluded that planet hosts contain less Li than field stars. This result was debated by Ryan (2000) who proposed that these differences were not significant. Many authors have revisited this topic since then (Israelian *et al.* 2004, Chen & Zhao 2006, Luck & Heiter 2006, Takeda *et al.* 2007, Gonzalez 2008) and all of them, except Luck & Heiter (2006) have concluded that stars with planets tend to have smaller Li abundance. However, stellar samples used in these studies were not homogeneous. It was possible that the planet host stars are Li poor because they are more metal rich. Moreover, neither of these authors could provide a homogeneous comparison sample of "single" stars without detected giant planets. These tasks have been undertaken by our group (Israelian *et al.* 2009) who recently has demonstrated that, indeed, stars with giant exoplanets contain less Li than "single" stars without (so far) detected planets in the HARPS GTO sample.

https://doi.org/10.1017/S1743921310004254 Published online by Cambridge University Press

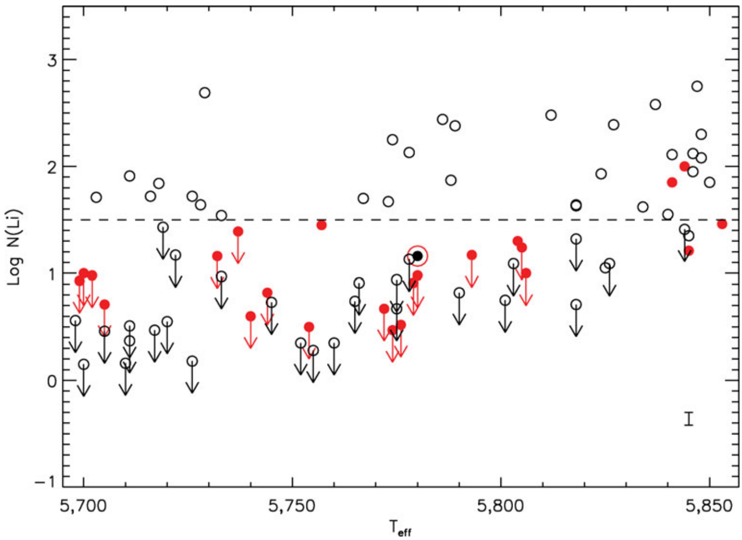

Figure 1. Lithium abundance against effective temperature in solar-analogue stars with and without detected planets. The planet-hosts are red filled circles. The minimum detectable Li abundance varies among the stars used in this study because their spectra have different signal–to-noise ratios. The straight line log N(Li) = 1.5 matches the upper envelope of the lower limits corresponding to a minimum S/N = 200 in a typical solar twin. We employ this line as a cut-off for selecting Li-depleted stars in our sample. The mean statistical errors (1?) for the log N(Li) and T_{eff} averaged over all stars are 0.06 dex and 30 K, respectively (Sousa *et al.* 2008). Errors in log N(Li) include uncertainties in T_{eff} and equivalent width measurements.

2. New analysis

To establish a definitive relation between the presence of planets and enhanced Li depletion in solar-type stars requires high quality observations and unbiased abundance analysis of Li for a large sample of stars with and without planets. We obtained Li abundances from high resolution, high S/N spectra for a sample of 451 stars in the HARPS high precision radial velocity survey (precision better than 1 m/s; Mayor *et al.* 2003) spanning the effective temperature range between 4900 and 6500 K. These are unevolved, slowly rotating non-active stars from a CORALIE catalogue (Mayor *et al.* 2003). Of these 451 stars, 70 are reported to host planets and the rest (often we call them single stars) have no detection so far. Our abundance analysis, which followed standard prescriptions for stellar models, spectral synthesis code and stellar parameter determination (Sousa *et al.* 2008), confirm a peculiar behavior of Li in the effective temperature range 5600-5900 K. To put this in a more solid statistical basis these two samples in the T_{eff} window 5600-5900 K were extended by adding 16 and 13 planet host and "single" stars, respectively, with Li abundances from our previous work where the same spectral synthesis tools have been employed (Israelian *et al.* 2004). It is remarkable that the immense majority of planet host stars have severely depleted lithium while in the comparison sample large fraction partially inhibited depletion. The Li abundance of 20 % of stars with exoplanets in the temperature range 5600-5900 K has log N(Li)$\geqslant$1.5 while for the 116 comparison stars the Li abundance shows a rather large dispersion with some 43 % of the stars displaying Li abundances log N(Li)$>$ 1.5. This result becomes more obvious in solar analog stars where some 50 % of 60 single stars in narrow window of $T_{sun}\pm$80 K appear with Log N(Li)$\geqslant$1.5 while only one planet host, out of 24, has log N(Li) $\geqslant$1.5 (Fig 1). Lithium survival at T_{eff} $>$ 5850 K is explained by the fact

https://doi.org/10.1017/S1743921310004254 Published online by Cambridge University Press

that the convective layers of stars more massive than the Sun are shallow and too far to reach the Li-burning layers. On the other hand, lower mass stars with $T_{eff} < 5700$ K have deeper convective layers and destroy Li more efficiently. We note that subgiants were not included in this study because they undergo dramatic changes in their internal structure that alters surface abundance of Li. The Li over-depletion in planet bearing main sequence stars is a generic feature over $T_{\rm eff}$ restricted range from 5700 to 5850 K. Let us now investigate if Li abundance in solar analog stars is determined by their age and/or metallicity.

3. Ages, metallicity, and rotation

3.1. *Metallicities*

Most of the planet-host stars discovered to date are metal-rich (Santos, Israelian & Mayor 2004). The metallicity excess could result from either the accretion of planets/planetesimals on to the star or the protostellar molecular cloud. This metallicity excess is also present in the solar analogue planet-bearing stars (see Fig. 2c). It is very important to investigate if a high metallicity is responsible for enhanced Li depletion in these stars. 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 the base of the convective zone are oxygen and iron (Piau & Turck-Chièze 2002). Our data (Fig 2c) show that the fraction of single stars with log N(Li) >1.5 is 50% at [Fe/H]<0 and [Fe/H] > 0. This suggests that the Li depletion mechanism does not depend on the metallicity in the range 0.5 < [Fe/H] < +0.5. Apart from this, we have investigated the dependence of log N(Li) on [O/Fe] (Piau & Turck-Chièze 2002) for planet-host stars, using oxygen abundances in planet-host stars from the literature (Ecuvillon *et al.* 2006), and again found no correlation. We conclude that the metallicity or [O/Fe] ratio is not responsible for an enhanced Li depletion in metal-rich planet-host stars.

3.2. *Chromospheric ages and rotation*

It is often stated that the lithium abundance of solar-type main sequence stars decreases progressively with age (Sestito & Randich 2005). If that were the case, we should expect a correlation between lithium and stellar age indicators. Chromospheric activity is a reliable age indicator for solar-type stars from young ages to about 1 Gyr (Pace *et al.* 2009), or perhaps even to the age of the Sun (Wright *et al.* 2004). Abundances of Li versus chromospheric activity indices, $R_{\rm HK}$, for the solar analogue stars with and without detected planets are shown in Fig. 2a. We find no correlation between Li and the activity index and conclude that the solar analogue stars with and without planets considered in this work have similar ages. This conclusion is valid as long as the chromospheric activity index $R_{\rm HK}$ can be used as an age indicator. It means our stars are older than 1 Gyr (Pace *et al.* 2009) or perhaps as old as 4.5 Gyr (Wright *et al.* 2004).

It is known (Cutispoto *et al.* 2003) that chromospheric activity correlates with stellar rotation (vsini). If the planet hosts were older than the comparison sample, their rotational velocities would be smaller than in the comparison sample. This is not observed either (Fig 2b), adding support to our conclusion that the ages of planet hosts and “single” stars in our sample exceed 1 Gyr.

We have compiled previously published isochrone ages for Li-rich (log N(Li) > 1.9) stars shown in Fig 1. One may think that these main sequence solar analogue stars are young since their atmospheres contain a lot of Lithium. However, the average isochrone ages of our planet-hosts and “single” stars are found in the window 5 to 9 Gyr (Holmberg

https://doi.org/10.1017/S1743921310004254 Published online by Cambridge University Press

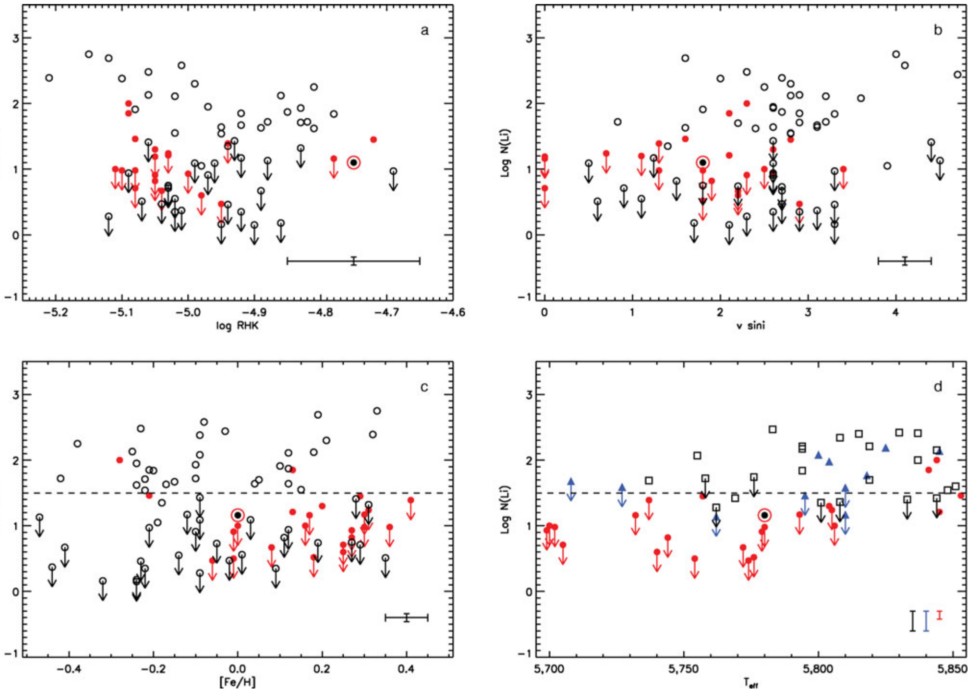

Figure 2. Panels (a) and (b). Lithium abundances in solar-analogue stars with and without detected planets versus chromospheric activity indices (log R_{HK}) and rotational velocity (vsini). R_{HK} values were taken from the literature (Wright *et al.* 2004, Saffe *et al.* 2005, Gray *et al.* 2006) while rotational velocities of the comparison sample stars and many planet hosts were measured from CORALIE and HARPS spectra using a cross correlation function (Santos *et al.* 2002). Typical 1σ uncertainties for log R_{HK} and vsini are 0.1 dex and 0.3 km/sec, respectively (Wright *et al.* 2004, Santos *et al.* 2002). Rotational velocities of several planet-hosts were taken from the literature (Valenti & Fischer 2005). Panel (c). Li abundances for the same stars versus metallicity. The latter was measured (Sousa *et al.* 2008) with a precision of 0.03 dex (1σ). Panel (d). Li abundances in planet hosts and stars of the open clusters M67 and NGC 6253. In this panel we plot Li abundances versus effective temperature in planet hosts (red filled circles), and stars of the open clusters M67 (blue triangles) and NGC 6253 (open squares). The data for M67 were taken from the literature. Li abundances in NGC 6253 have been derived from VLT/Giraffe spectra using standard methods (Randich *et al.*, in preparation). Typical 1σ error bars for cluster stars are 0.15 dex and 100 K for log N(Li) and T_{eff}, respectively.

et al. 2009). Nevertheless, stellar ages derived from isochrones cannot be used since they are very uncertain with the dispersion as large as 4 Gyr (Saffe *et al.* 2005).

3.3. *Lithium and ages in planet hosts and open clusters*

Observations of solar-type stars in the temperature range 5700-6100 K in open clusters (Sestito & Randich 2005, Randich 2008) show that the Li depletion continuously occurs from the Zero Age Main Sequence (ZAMS) up to ~1 Gyr, with a time scale of 1.4 Gyr. It becomes bimodal at >1 Gyr as the fraction of stars continue depleting Li at higher rate. Our Sun is perhaps the best representative of this group. The Li depletion completely stops for the majority of stars and all cluster average abundances converge to a plateau value close to the Spite plateau of Pop II stars (see Sestito & Randich 2005, Randich 2008, Randich, S. this proceedings).

https://doi.org/10.1017/S1743921310004254 Published online by Cambridge University Press

We have seen (Fig. 2) that the comparison with field stars leads to the conclusion that neither age nor metallicity is responsible for the excess Li depletion. This is reinforced by observations of Li in solar-type stars in old solar metallicity and/or metal-rich open clusters, which indeed show a wide dispersion of Li abundances with values ranging from log N(Li) = 2.5 down to 1.0 and lower (Sestito *et al.* 2007, Randich 2008, Pasquini *et al.* 2008). This is the case for M67 (age 3.5–4.8 Gyr and [Fe/H] = 0.06)(Pasquini *et al.* 2008) and NGC 6253 (age 3 Gyr and [Fe/H] = 0.35) (Yadav *et al.* 2008, Sestito *et al.* 2007), as is clearly seen in Fig 2d. These two clusters offer a homogeneous sample of solar analogues in terms of age and metallicity. Both high and low Li abundance solar analogues are present in these two clusters. The high Li abundance in a large fraction of old metal-rich stars in NGC 6253 and M67 supports our conclusion that high metallicity and/or age are not the main cause for the systematic low Li abundances in solar analogue planet-host stars. Two other clusters, Cr261 (age 6 Gyr and [Fe/H] = 0.13) and NGC 188 (age 8 Gyr and [Fe/H]$\sim$0) show significant Li dispersion (Sestito & Randich 2005, Randich 2008, Randich, S., this conference). Slow mixing models of solar-type stars predict Li abundances log N(Li)$\leqslant$1 and cannot explain a large fraction of Li-rich solar analogues in these clusters with log N(Li)$\sim$2.4. The analysis of several old open clusters observed with FLAMES confirm that the Li dispersion does not depend on age or metallicity. (S. Randich, this conference).

4. Conclusions

We propose that the low Li abundance of planet-host solar analogue stars is associated with the presence of planets. The presence of a planetary system may affect the angular momentum evolution of the star and the surface convective mixing, thereby causing enhanced lithium depletion. Planet migration could possibly trigger angular momentum transfer in the convective zone, leading to additional mixing below this zone. Theoretical models (Pinsonneault *et al.* 1989) show how magnetic braking scales with rotational velocity leading to turbulent diffusion mixing and enhanced lithium depletion. In this case we would expect severely Li-depleted stars to host planets with shorter orbital periods. On the other hand, long-lasting star–disc interaction during the pre-main sequence may cause planet-host stars to be slow rotators and develop a high degree of differential rotation between the radiative core and the convective envelope. This process may lead to enhanced lithium depletion too (Bouvier 2008).

We know that all stars used in the HARPS GTO program are non-active, slow rotators. Thus, from the RV point of view they are all equally good planet-host candidates. It is impossible to explain why HARPS was unable to detect the relatively young planetary systems with ages between (for example) 1 and 3 Gyr. This fact alone suggests that planet-host and "single" stars in our sample come from groups with the same age distribution. Thus, our finding presented in Fig. 1 can be considered as an independent confirmation of the well-known Li puzzle discovered in open clusters (Randich 2008). We confirm that factors other than age, mass, and metallicity, such as angular momentum (which planets may alter), can affect stellar lithium abundance.

Studying young stars to identify the effect that planets have on their rotation is the next step to explain the correlation between lithium abundance and planets. Young stars and planets are more difficult to observe, but they reveal more than old stars do about how fast they rotated in their infancy. In the future, it may be possible to test the hypothesis that altering stars' rotation affects lithium depletion. Discovery of planets in open clusters will certainly help to understand the Li puzzle.

https://doi.org/10.1017/S1743921310004254 Published online by Cambridge University Press

References

Anders, E. & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
Bouvier, J. 2008, *A&A* (Letters), 489, 53
Chen, Y. Q. & Zhao, G. 2006, *AJ*, 131, 1861
Cutispoto, G., Tagliaferri, G., de Medeiros, J. R., Pastori, L., Pasquini, L. & Andersen, J. 2003, *A&A*, 397, 987
DAntona, F. & Mazzitelli, I. 1994, *ApJS*, 90, 467
Ecuvillon, A., Israelian, G., Santos, N. C., Shchukina, N. G., Mayor, M., & Rebolo, R. 2006, *A&A*, 445, 633
Gonzalez, G. 2008, *MNRAS*, 386, 928
Gonzalez, G. & Laws, C. 2000, *AJ*, 119, 390
Gray, R. O., Corbally, C. J., Garrison, R. F., McFadden, T., Bubar, E. J., McGahee, C. E., O'Donoghue, A. A., & Knox, E. R. 2006, *AJ*, 132, 161
Holmberg, J., Nordström, B., & Andersen, J. 2009, *A&A*, 501, 941
Israelian, G., Santos, N., Mayor, M., & Rebolo, R. 2004, *A&A*, 414, 601
Israelian, G., Delgado Mena, E., Santos, N., Sousa, S., Mayor, M., Udry, S., Dominguez Cerdena, C, Rebolo, R., & Randich, S. 2009, *Nature*, 462, 189
King, J. R., Deliyannis, C. P., Hiltgen, D. S., Stephen, A., Cunha, K., & Boesgaard, A. M. 1997, *AJ*, 113, 1871
Luck, E. & Heiter, U. 2006, 131, 3069
Mayor, M. *et al.* 2003, *Messenger*, 114, 20
Pace, G., Melendez, J., Pasquini, L., Carraro, G., Danziger, J., François, P., Matteucci, F., & Santos, N. C. 2009, *A&A* (Letters), 499, 9
Pasquini, L., Biazzo, K., Bonifacio, P., Randich, S., & Bedin, L. R. 2008, *A&A*, 489, 677
Piau, L. & Turck-Chièze, S. 2002, *A&A*, 566, 419
Pinsonneault, M., Kawaler, S. D., Sofia, S., & Demarque, P. 1989, *ApJ*, 338, 424
Randich, S. 2008, *Mem. Soc. Astr. It.*, 79, 516
Ryan, S. 2000, *MNRAS* (Letters), 316, 35
Saffe, C., Gomez, M., & Chavero, C. 2005, *A&A*, 443, 609
Santos, N. C., Mayor, M., Naef, D., Pepe, F., Queloz, D. *et al.* 2002, *A&A*, 392, 215
Santos, N. C., Israelian, G., & Mayor, M. 2004, *A&A*, 415, 1153
Sestito, P. & Randich, S. 2005, *A&A*, 442, 615
Sestito, P., Randich, S., & Bragaglia, A. 2007, *A&A*, 465, 185
Sousa, S. G., Santos, N. C., Mayor, M., Udry, S., Casagrande, L. *et al.* 2008, *A&A*, 487, 373
Takeda, Y., Kawanomoto, S., Honda, S., Ando, H., & Sakurai, T. 2007, *A&A*, 468, 663
Valenti, J. & Fischer, D. 2005, *ApJS*, 159, 141
Wright, J., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2004, *ApJS*, 152, 261
Yadav, R. K. S., Bedin, L. R., Piotto, G., Anderson, J., Cassisi, S. *et al.* 2008, *A&A*, 484, 609

https://doi.org/10.1017/S1743921310004254 Published online by Cambridge University Press