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# Lithium abundances for 1000 PTPS stars

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**Abstract.** Within the PennStateToruń Planet Search we monitor a sample of ~1000 stars at various stages of evolution with the Hobby-Eberly Telescope. The main goal of the project is a search for low-mass companions with the radial velocity measurements technique, an in-depth study of planetary systems evolution and detailed analysis of evolution-induced star-planet interactions. So far, we have identified about 200 planetary candidates and about100 new multiple stars. We present here a $^7$Li abundance analysis for all observed stars which resulted in detection of 18 Li–overabundant giants, including the super Li–rich star with A(Li)=4.59 (where A(Li)=$\log n_{Li}/n_H$ + 12). We present preliminary results of our A(Li) investigations. Global behavior of lithium abundances for stars in our sample reflects lithium abundance evolution from the Main Sequence to the Red Giant Branch. We also report a few newly discovered lithium overabundant giants showing periodic changes in radial velocities. For one of them the observed lithium enrichment might possibly be explained by a recent planet engulfment episode.

**Key words.** Stars: abundances – Stars: evolution

## 1. Introduction

Lithium is a very intriguing element. While built into the stars it may be easily destroyed at temperatures of only 2.5 mln K, what makes it a very sensitive indicator of processes in stellar interiors. Hence, investigation of lithium abundances requires understanding of various mechanisms occurring during stellar evolution, particularly those responsible for lithium production (overabundant giants) and destruction (lithium–poor dwarfs). Moreover, lithium abundance is sometimes related with planet occurrence – there is an ongoing discussion on possible connection between Li–depletion and hosting planets by dwarfs (see Ghezzi et al. 2010 and references therein). It has been also postulated that engulfment of close-in planets might be responsible for Li–enrichment in giants (Siess & Livio 1999; Villaver & Livio 2009). We therefore pay much attention to Lithium within the ongoing PennState-Toruń Planet Search (PTPS) with the Hobby Eberly-Telescope.

The richness of the PTPS sample in stars at various stages of stellar evolution allows for lithium abundance evolution discussion in relation to evolutionary status of stars. As the sample comes from a precise radial velocity survey we may discuss lithium abundances in the context of stellar binarity or low–mass companions as well. Here we present preliminary results of the A(Li) investigation of the complete PTPS sample. A more detailed study will be presented elsewhere (Adamów 2012).

## 2. Target selection and observations

The sample we are monitoring since early 2004 is composed of four groups of stars at various stages of stellar evolution. The first one, ~ 348 stars (originally SIM-EPIcS[1] reference candidates, selected as presumably RGC stars basing on their existing photometry and reduced proper motions Gelino et al. 2005; Law et al. 2006) constitute the so-called RGC subsample of the PTPS and falls in the "clump giant" region of the HR-diagram (Jimenez et al. 1998), which contains stars of various masses over a range of evolutionary stages. The second group comprises ~ 250 sub-giants, which have recently left the MS and are located ~1.5 mag above it. The third one is composed of about 200 regular giants while the last, fourth one contains ~ 200 dwarfs of spectral type F–M. The total PTPS sample is composed of field solar– and intermediate–mass stars.

Generally, all our targets, a total of >1000 GK-giants, sub-giants and dwarfs brighter than ~ 11 mag, occupy the area in the HR-diagram, which is approximately defined by the MS, the instability strip, and the coronal dividing line (a narrow strip in the HR-diagram marking the transition between stars with steady hot coronae and those with cool chromospheric winds, Linsky & Haisch 1979). Our sample is composed of much fainter stars than included in most of other RGC surveys (Famaey et al. 2005; Mishenina et al. 2006; Hekker & Meléndez 2007; Takeda et al. 2008; Valentini & Munari 2010) and can be compared to the sample of Bizyaev et al. (2006, 2010). Due to adopted observing strategy, optimized for the HET, stars are randomly distributed over thy northern sky. A more in–depth description of the PTPS sample will be presented in Niedzielski (2012).

PTPS is conducted with the 9.2m Hobby-Eberly Telescope (HET, Ramsey et al. 1998) operated in the queue scheduled mode (Shetrone et al. 2007) and equipped with the High Resolution Spectrograph (Tull 1998), which is used in the R=60 000 resolution mode with a $I_2$ gas cell and it is fed with a 2 arcsec fiber. Details of our survey (observing strategy, motivation, and data analysis) have been presented in details elsewhere (Niedzielski et al. 2007; Niedzielski & Wolszczan 2008).

The spectra consist of 46 echelle orders recorded on the "blue" CCD chip (407 – 592 nm) and 24 orders on the "red" one (602 – 784 nm). The signal to noise ratio was typically better than 200 – 250 per resolution element at 590 nm. The "blue" spectra are used for precise radial velocity determinations with the gas–cell. For detailed spectroscopic analysis both "red" spectra, unaffected by the $I_2$ lines and "blue" template (obtained with no gas-cell inserted into the optical path) are used.

In the Li abundance analysis only one order of the red spectra containing the $^7$Li 6708 Å line was used. Since the HET/HRS flat-field spectra are occasionally contaminated with a spectral feature near the $^7$Li line which, depending on actual RV of a star, may mimic the Li line and influence the abundance analysis all used flat field spectra were checked and those affected by this feature were omitted to avoid the contamination. The uncontaminated flat-field images were selected and used, from either the same or nearest night. When using flat filed frames distant in time to the original ones, we cross-correlated and shifted the adopted extracted flat fields to avoid possible shifts of spectrum on the CCD matrix, what could result in introducing additional noise to spectra.

## 3. Data analysis

### 3.1. Data reduction

The CCD data reduction was performed using standard IRAF/Python tasks and scripts de-

[1] Space Interferometry Mission (SIM) key project: Extra-solar Planet Interferometric Survey (EPIcS) `http://sim.jpl.nasa.gov`

veloped for PTPS. Basic data reduction (debiasing, flat-fielding) was performed with standard IRAF tasks. Aperture finding, tracing and extraction was done with a Python script based on REDUCE (Piskunov & Valenti 2002) which is being continuously optimized for HET/HRS spectra. Finally the spectra were wavelength calibrated with standard IRAF tasks using the Th-Ar calibration lamp identification from HET Technical Document No. 300 ("The HET HRS Th–Ar and Echelle Tilt Atlas" by Jeff Mader and Matthew Shetrone). Fitting continuum and order joining was done with another Python script operating at central order parts allowing for minimum overlapping.

### *3.2. Stellar parameters*

The basic photometric data for the sample stars come from 2MASS Point Source catalogue (Cutri et al. 2003) and Tycho–2 catalogue (Høg & Murdin 2000) compiled by Gelino et al. (2005). For several stars missing data were gathered from Kharchenko & Roeser (2009). Using the existing archive photometric data we estimated the interstellar extinction from Schlegel et al. (1998), which is based on observations of interstellar gas and dust distribution in the Galaxy. Obtained values were scaled with distance in the manner described by Ammons et al. (2006). Effective temperatures were calculated from empirical calibration for 6 colors of Ramírez & Meléndez (2005) assuming metallicity in the range (-0.5,0.5) for all stars.

The initial sample of stars was divided into two groups: giants and dwarfs. Two different methods were used for that: reduced proper motions – $RPM = K + 5.0 \log\mu < 1$ for giants (Gelino et al. 2005) and empirical V vs. J,K,H relations for giants and dwarfs (Bilir et al. 2006).

For objects with unknown or unreliable Hipparcos parallaxes we initially assumed $M_{\rm V}$ from Straizys & Kuriliene (1981) empirical calibration and estimated luminosities on that basis. We calculated intrinsic color index $(B - V)_0$, rough estimates of $\log g$ and bolometric corrections $BC_{\rm V}$ for our stars from Straizys & Kuriliene (1981) empirical calibration. Stellar masses $M/M_\odot$, radii $R/R_\odot$ and estimates of ages were obtained by comparing the position of stars in the [log $L/L_\odot$, log $g$, log $T_{\rm eff}$] space with the theoretical evolutionary tracks of Girardi et al. (2000) and Salasnich et al. (2000). We used existing tracks corresponding to sollar metallicity $[Y = 0.273, Z = 0.019]$. To derive $M/M_\odot$ for every star the maximum-likelihood function defined as:

$$\chi^2 = \sum_{i=1}^{n} \left( \frac{q_i^{obs} - q_i^{mod}}{\sigma_i} \right)^2 , \qquad (1)$$

where $q_i^{obs}$, $q_i^{mod}$ and $\sigma_i$ denote observed and modeled parameters and their uncertainties respectively, was minimized over the model parameter space. In our case the number of parameters $n$ was set to 3 as $\log L/L_\odot$, $\log g$ and $\log T_{eff}$ were used.

The resulting run of the $\chi^2$ over model parameters was found to be typically relatively flat, therefore the final stellar mass was calculated as a mean value over extended area of $\chi^2 \leq 3\,\chi^2_{min}$. That procedure resulted in consistent stellar masses determination and realistic estimates of uncertainties.

For 348 stars from Red Giant Clump basic atmospheric parameters as well as masses, radi and ages were determined by Zielinski et al. (2012) with the method of Takeda et al. (2005a,b). As shown in Zielinski et al. (2012) our estimates of stellar parameters and the values obtained as a result of detailed spectroscopic analysis are in reasonable agreement and allow for preliminary considerations.

### *3.3. Li abundance determianation*

Spectral analysis was performed with Spectroscopy Made Easy package (SME, Valenti & Piskunov 1996), which is based on SYNTH program by Piskunov (1992). SME assumes LTE and parallel geometry plane, but ignores magnetic field, molecular lines and mass loss. Synthetic spectrum synthesis is based on Kurucz's models of stellar atmospheres. In SME analysis, observational spectrum is considered as a model constraint. As an input SME requires a set of lines

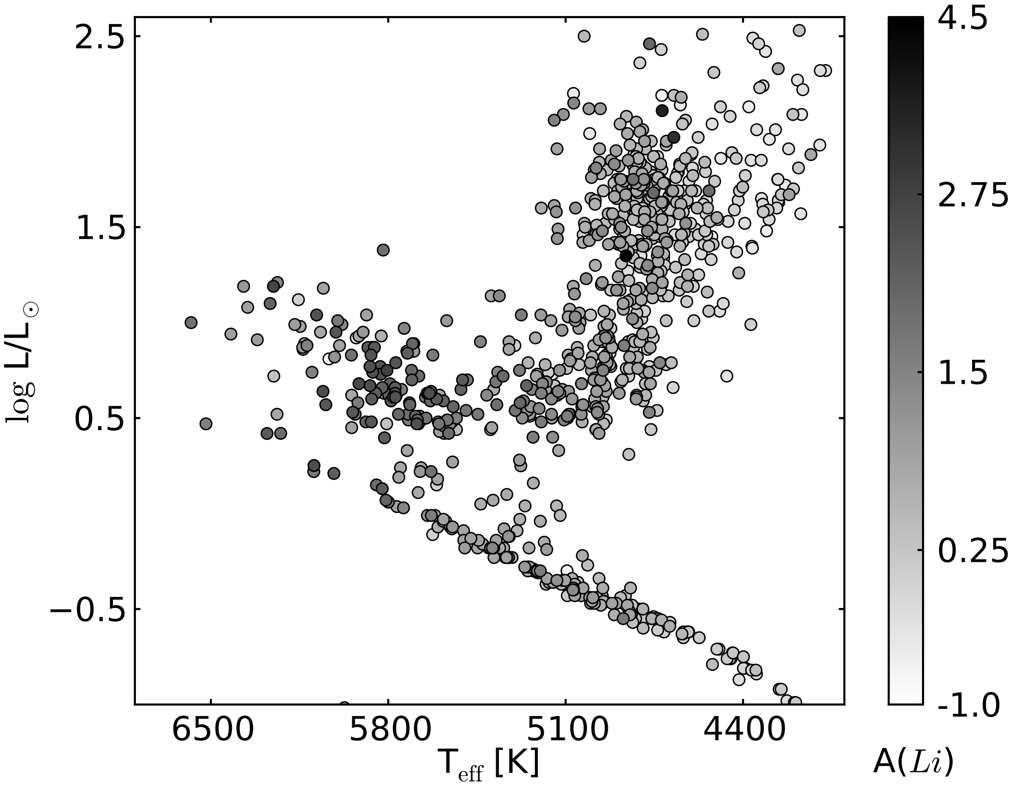


**Fig. 1.** The HR diagram for all PTPS stars. Lithium abundance is gray-scale coded (panel on the right).

from Vienna Atomic Line Database (VALD, Kupka et al. 1999) identified in the spectrum, stellar data (including radial velocity) and the instrumental profile. Although SME requires M/H ratio rather than Fe/H, we used Fe/H as the closest approximation of metallicity. We used SME in the 6695–6725 Å range and fitted $^7$Li line at 6708Å as well as several lines of Al, Ti, Si and Ca, rotation velocity and macroturbulence velocity together. In first attempt only templates spectra (with no $I_2$ gas cell inserted) were used for the analysis. However, $I_2$ spectrum affects the spectrum up to 6600 Å only, so it does not influence $^7$Li line region. Hence, in the final analysis it was also possible to use the "red" spectra obtained with the gas–cell inserted what allowed for A(Li) uncertainty estimates (rms).

### *3.4. Radial velocities*

RVs were measured using the standard $I_2$ cell calibration technique (Butler et al. 1996). A template spectrum was constructed from a high-resolution Fourier Transform Spectrometer (FTS) $I_2$ spectrum and a high signal-to-noise stellar spectrum exposed without the $I_2$ cell. Doppler shifts were derived from least-square fits of template spectra to stellar spectra with the imprinted $I_2$ absorption lines (see Nowak 2012 for detailed description of the code). Typical RV uncertainty of 4-7 ms$^{-1}$ was sufficient to use the Stumpff (1980) algorithm to refer the measured RVs to the Solar System barycenter.

## 4. Results

### *4.1. General remarks*

Chemical composition is one of the basic indicators of stellar evolution. As a star evolves towards red giant branch, lithium abundance drops due to changes in convection zone and increasing stellar radius. Lithium depletion stops when the star reaches red giant branch. At that moment, observed A(Li) level is already expected to be very low.

Figure 1 presents A(Li) for all stars from the PTPS sample. One can easily identify several general properties of lithium abundance in stars of various masses and at various evolutionary stages: gradual lithium depletion for aging stars, the so-called *classical lithium problem* (all dwarfs on Main Sequence are lithium depleted with respect to theoretical level of A(Li)~3.0 for solar–like, MS star), lithium enrichment for giants (see next subsection), or relations between A(Li) and stellar parameters for the Main Sequence stars.

Younger, more massive and thus hotter Main Sequence stars tend to be more Li–rich, which is in agreement with results of other investigations (Chen et al. 2001). Recent studies (i.e. Gonzalez et al. 2009, Lebzelter et al. 2012) suggest that A(Li) – $T_{eff}$ relation can be also established for giants. Figure 2 presents a general A(Li) vs. $T_{eff}$ relation for all PTPS stars. General increase of A(Li) with effective temperature of stars is evident. A large scatter at effective temperatures lower than ~ 5250 K is a composed effect of a real physical process that might stem from ongoing evolutionary changes in stellar interiors, affecting $T_{eff}$ and A(Li) in different rates and the specific definition of our sample. These two effects have to be sorted-out before any conclusions concerning A(Li) – $T_{eff}$ relation for giants can be drawn.

In Figure 3 the relation between A(Li) and surface gravity – another parameter changing during stellar evolution, is presented. The spread in lithium abundances for dwarf is significant – one can see stars with lithium depletions varying by four orders of magnitude. There is a small group among them with A(Li) similar to expected meteoritic level of ~ 3. Small number of objects in this subsample is

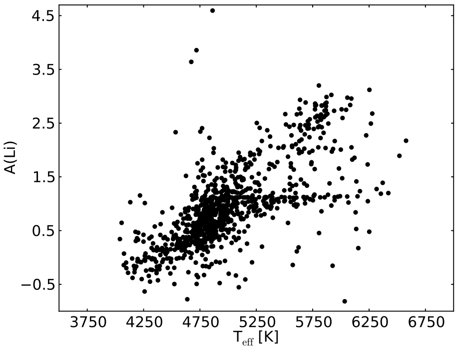


**Fig. 2.** Effective temperature vs. lithium abundance for all PTPS stars.

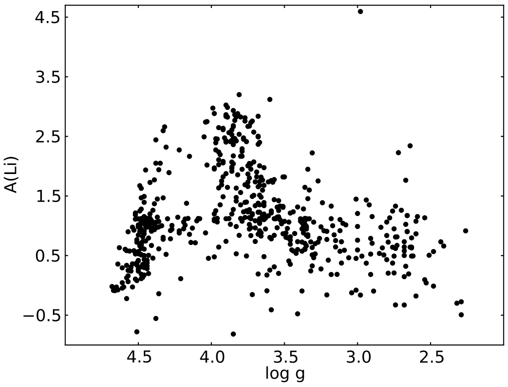


**Fig. 3.** $\log g$ vs. lithium abundance for all PTPS stars.

the effect of observational selection in PTPS. Dwarfs with A(Li) ~ 3 are typically placed in the Upper Main Sequence, a part of HR diagram which we avoid since stars located there, due to sparse and broad absorption lines in their spectra are unsuitable for high precision radial velocity planet search.

The transition to the red giant phase is associated with a strong lithium depletion due to the first dredge–up. In Fig. 3 this effect is clearly seen as an almost vertical drop of A(Li) for stars with $\log g$ = 3.5-4. Due to a large number of giants and sub-giants in the PTPS sample we can study this effect in detail.

For stars with $\log g$ <3.5 the relation between surface gravity and the lithium abundance seems to be flat. Vast majority of stars is indeed placed below below the theoretical

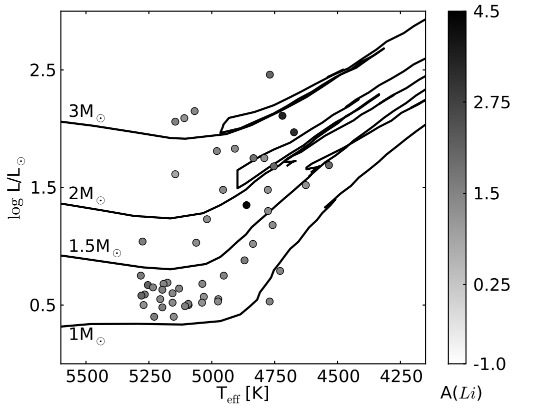


**Fig. 4.** The HR diagram for the A(Li)>1.5 giants. Evolutionary tracks with [Fe/H]=0 and different stellar masses help in identifying evolution phase. Stars in the left part of the diagram (with $T_{eff} \lesssim 5000$) are still undergoing dredge up dilution, hence they should not be considered as Li–rich giants.

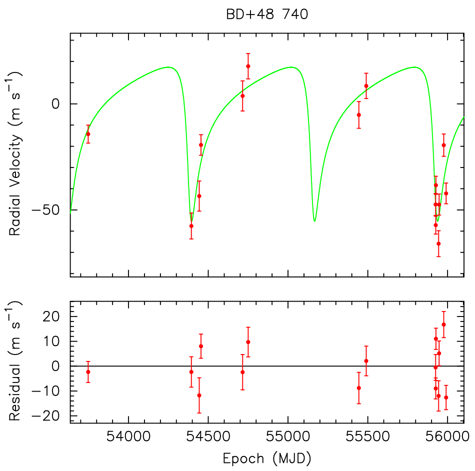


**Fig. 5.** Preliminary Keplerian fit to 15 epochs of radial velocity observations of PTPS 1015

A(Li)∼1.5 upper limit for giants after completing the first dredge up. There are, however, very intriguing exceptions.

### *4.2. Li overabundant giants*

Figure 4 shows the part of HR diagram where the most Li-reach giants are present. Not all of them may be considered as Li - overabundant. As it is clear from comparison of their position on the HRD with evolutionary tracks some of them appear to be before the first dredge–up still. However, there are 18 stars among red giant stars after the dredge-up with lithium abundance higher than 1.5 level in our sample. Only 5 of them do not show variations in radial velocities which could be interpreted as a presence of stellar or low mass companion (planet or brown dwarf), which makes them single, non-active stars (within the precision maintained within PTPS). 10 stars in the Li–rich giants sample are being monitored as probable planet hosts and the other three objects are binaries.

PTPS 1015 is a bright giant with $T_{eff}$=4534, $\log L/L_\odot$=1.68 ± 0.2 and A(Li)=2.33. The uncertainty in luminosity does not allow for unambiguous assignment of its evolutionary status. However taking into account precisely known effective temperature it can be placed close to the stable helium burning part of the evolutionary track of 1.5 $M_\odot$, solar metallicity star. 15 radial velocity measurements for this object, collected within PTPS between January 12, 2005 and March 5, 2012 revealed amplitude of ∼ 93 ms$^{-1}$. Solar-type oscillations (Kjeldsen & Bedding 1995) of ∼ 8 ms$^{-1}$ and average uncertainty in RV determinations of ∼ 6 ms$^{-1}$ added in quadratures are 10 times smaller than observed RV amplitude, hence RV variations of this stars cannot be explained only by stellar activity or photometric oscillations. The RV measurements were modeled in terms of the standard, six–parameters Keplerian orbits(Fig. 5), which showed that PTPS 1015 probably hosts a planetary companion in a highly eccentric orbit (e=0.7).

Such high eccentricity is not common among planet-hosting giants. Moreover, IRAS photometry shows evidences of weak IR excess, which in combination with high Li content and the unusual orbit of the planet found in observations of PTPS 1015 may suggest the recent engulfment of the hypothetical inner planet according to Siess & Livio (1999) scenario. Detailed discussion of the BD+48 740 case is presented in Adamów et al. (2012).

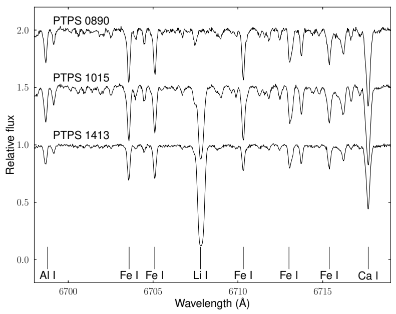


**Fig. 6.** The spectral region around $^7$Li line for PTPS 1413 – the most Li–rich star in PTPS sample, PTPS 1015 - probable planet host, and PTPS 0890 – a giant with A(Li)=0.23.

PTPS 1413 is a rare, extremely Li–rich object with A(Li)=4.59 – high above the meteoritic level. The star was observed within PTPS between January 20, 2006 and February 24, 2008. Six epochs of precise relative RV were gathered over 765 days which revealed RV amplitude of only 17 ms$^{-1}$. With the estimated amplitude of solar-type oscillations of $\sim$ 3 ms$^{-1}$ and estimated average RV uncertainty for this star of $\sim$ 6 ms$^{-1}$ the RV scatter is only 2.5 times larger than the expected observational uncertainties and therefore the star was rejected from further precise RV monitoring and a status of a single one was assigned for it. The nature of the process responsible for lithium enhancement that must have occurred in this object is unknown.

Spectra of PTPS 1015 and PTPS 1413 are presented in Fig. 6.

## 5. Conclusions

We presented preliminary analysis of $^7$Li abundances for a sample of $\sim$ 1000 PTPS stars. An important aspects of this work are (i) the large sample of stars at various evolutionary phases, (ii) homogenous set of data and (iii) analysis completed with one tool – SME package. The collection of lithium abundances in combination with an existing PTPS database of radial velocities is in position to give a new insight into possible lithium enhancement mechanisms for giants. We have detected 14 Li–rich giants being either stellar binaries or planet hosts candidates so far. For one of them, PTPS 1015, the observed Li–enhancement might possibly be explained with a planet engulfment episode. In addition to RV measurements, we determine basic atmospheric parameters ($T_{eff}$, $\log g$, $v_t$, $v_{mac}$, chemical composition), luminosities, masses, radii and rotational velocities for all stars in the sample. Therefore the data collected within PTPS represent also a great tool for verifying connection of lithium abundance with stellar parameters.

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