J. Astrophys. Astr. (2020) 41:49
https://doi.org/10.1007/s12036-020-09660-9

Evolution of lithium in low-mass giants: an observational perspective

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MS received 10 September 2020; accepted 2 November 2020; published online 18 December 2020

Abstract. The overabundance of lithium in low-mass red giants has been a topic of interest for over four decades. Low-mass stars are expected to destroy lithium gradually throughout their lifetimes. Against this expectation, about 1% of red giants in the Galaxy show anomalously large Li which, in the literature, are known as lithium-rich giants. The advent of large-scale stellar surveys (*LAMOST*, *GALAH*, *Kepler*, *Gaia*) coupled with high-resolution spectra enabled to find important clues about Li enhancement origin in red giants. These new studies suggest Li enhancement is mostly associated with the red clump region, post-He-flash. Here, we will describe our recent results along with current updates in the field.

Keywords. Late-type stars—stellar evolution—abundances-lithium.

1. Introduction

Lithium (Li) is one of the three elements, apart from Hydrogen and Helium, and the only element among solids known to have produced at the beginning of the universe in the Big Bang nucleosynthesis (BBN). The current best value for Li abundance of BBN, based on critical parameters like baryon-to-photon-ratio measured by WMAP, is A(Li) = 2.7 dex (Cyburt *et al.* 2016). This is considered as primordial value for Li abundance, which is in disagreement with the long observed value of primordial lithium in metal-poor dwarfs, A(Li) = 2.2 dex, known as Spite-Plateau (Spite & Spite 1982a). The difference between the two is significant, by an order of magnitude. Since the Spite-Plateau breaks down at the extreme metal-poor end ([Fe/H] $<-$ 2.8 dex), and the good agreement between the observed primordial H & He and BBN predictions suggests the discrepancy may be to do with the slow depletion of Li abundance over a star's lifetime via diffusion or other processes rather than BBN (e.g. Richard *et al.* 2005; Korn *et al.* 2006; Fu *et al.* 2015).

Irrespective of which value we adapt for the primordial abundance, observations show significant enrichment in Li abundance in the Galaxy since the Big Bang. The present value of Li observed in interstellar clouds or meteorites (Lodders 2003) is A(Li) = 3.28 dex, which is a factor of 4 more than the BBN prediction. Possible sources for Li enrichment (e.g., Matteucci 2010) are cosmic ray spallation, novae, supernovae, and nucleosynthesis in evolved stars. Fresh Li is known to be produced in intermediate-mass Asymptotic Giant Branch (AGB) stars via hot-bottom burning (McKellar 1940; Smith & Lambert 1989; Sackmann & Boothroyd 1992). However, Li production in low mass red giants is not predicted by stellar evolutionary models (e.g. Iben 1967).

Stars, in general, are considered as Li sinks. Li seems to get depleted in stars through their evolution from the pre-main-sequence phase (e.g. Fu *et al.* 2015) to the main sequence (MS). For example, the solar value of A(Li) = 1.02 (Asplund *et al.* 2009) is a factor of more than 100 less than the ISM value. Once stars evolve off the MS, they undergo convection via

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This article is part of the Topical Collection: Chemical Elements in the Universe: Origin and Evolution.

first dredge-up on RGB in which bi-products of H-shell burning mixed with the outer envelope altering the chemical composition of photospheres of red giants. According to standard stellar models (Iben 1967), A(Li) is among the significantly affected elements by the first dredge-up, and the others are carbon, nitrogen and $^{12}C/^{13}C$ ratio. Models predict a decrease in A(Li) in the post first dredge-up giants by a factor of 40–60, depending on mass and metallicity, from its MS value. Thus, an upper limit for Li normal giants is set at A(Li) = 1.5 dex. In general, predicted limits agree well with the observations (e.g. Brown *et al*. 1989; Kumar *et al*. 2011). In fact, observations show much less A(Li) values than the predictions (e.g. Brown *et al*. 1989; Lind *et al*. 2009b). Very low A(Li) may be due to non-standard extra mixing in giants at or during the luminosity bump (e.g. Lagarde *et al*. 2012).

2. Lithium-rich giants

Against the expectations and general trends of observations, a small number of red giants found to have A(Li) $>$ 1.5 dex. These are known as Li-rich giants. The origin of these giants is still not understood, and has remained a puzzle ever since their first discovery in the 1980s (Wallerstein & Sneden 1982). Since then, a few more Li-rich giants were found, but their number is relatively small. Systematic surveys suggest Li-rich giants are just about one in hundred in the Galaxy (Brown *et al*. 1989; Gonzalez *et al*. 2009; Kumar *et al*. 2011; Monaco *et al*. 2011; Ruchti *et al*. 2011; Deepak & Readdy 2019; Gao *et al*. 2019). The rarity of Li-rich stars suggests Li enrichment on the RGB is a transient phenomenon.

One of the key obstacles in the understanding of Li enhancement origin is the lack of knowledge about the exact evolutionary phase of Li-rich giants on RGB. It is because key evolutionary phases on RGB have little or no separation from with each other in the L-T_{eff} plane of the HR diagram. As a result, it is challenging to separate stars of one phase from another unambiguously. For example, stars on luminosity bump ascending RGB for the first time and stars in red clump region, post-He flash, share common space in L-T_{eff} plane or with a small separation of 0.2–0.3 dex in luminosity, and 50–300K in T_{eff} (Girardi 2016). This problem is very severe among field giants of population I, which is one of the main reasons why studies based on only photometry or spectroscopy could not conclude about the location of Li-rich giants on RGB. In many cases, studies reported Li-rich giants all across RGB leading to various hypotheses like planet engulfment (Siess & Livio 1999; Denissenkov & Herwig 2004; Aguilera-Gómez *et al*. 2016) and *in situ* nucleosynthesis (e.g. Palacios *et al*. 2001, 2006; Denissenkov 2012; Yan *et al*. 2018).

With the advent of the Hipparcos mission (van Leeuwen 2007), it became possible to measure relatively accurate luminosities for a large number of stars. Many studies conducted to determine Li origin in low- mass red giants but the issue became complicated as studies claimed Li-rich giants all across the RGB including the red clump (below luminosity bump: Carlberg *et al*. (2015); Casey *et al*. (2016); Martell and Shetrone (2013); RGB bump: Charbonnel and Balachandran (2000); Kumar and Reddy (2009); Yan *et al*. (2018); upper RGB: Monaco *et al*. (2011)). Kumar *et al*. (2011) performed a systematic, unbiased study of 2000 giants selected from Hipparcos data combining with low-resolution spectra obtained using 2-m class VBT and HCT telescopes. They showed that Li-giants confine to a narrow luminosity range of $\log(L/L_{\odot})$ = 1.5–2.0 dex (Figure 1). Though the study could not distinguish stars of RC and RGB, they did suggest that Li enhancement is probably associated with red clump, and He-flash at the RGB tip may be the source.

2.1 *Era of large-scale surveys*

In the last few years, data from many large-scale surveys became available, which we put to use to understand the problem of Li-rich giants. The Kepler Space Mission provides time-resolved photometry of several stars in selected sky fields (Mathur *et al*. 2017) which is used for the asteroseismic analysis of stars, including red giants. The characteristic average frequency separation ($\Delta\nu$) of mixed modes of pressure and gravity and average period spacing (Δp) between the modes of red giants of inert-He core and core He-burning (Bedding *et al*. 2011) enabled to separate red clump giants from those of ascending RGB for the first time. Spectroscopic surveys like LAMOST (Cui *et al*. 2012) and GALAH (De Silva *et al*. 2015, Buder *et al*. 2018) made available low- (R $\approx$ 1800–7500) and high-resolution (R $\approx$ 28000) spectra for a large sample of stars. These surveys, combined with Gaia astrometry (Gaia Collaboration *et al*. 2018), are used to decipher the Li-problem in red giants.

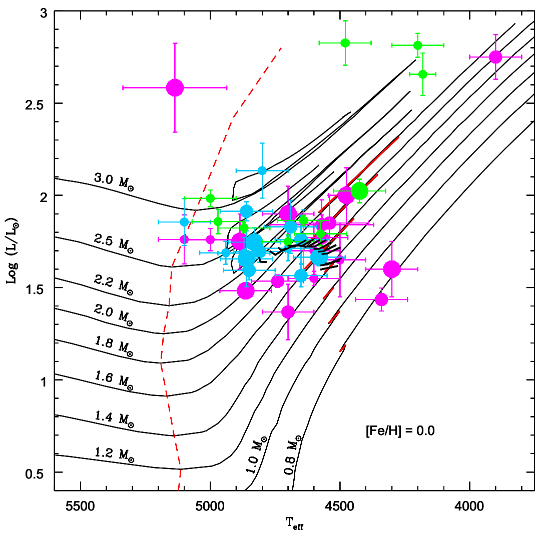

Figure 1. Results from (Kumar *et al.* 2011) survey are shown. Note all the low-mass (M $\leq$ 2M$_{\odot}$) Li-rich giants are in a narrow luminosity range. Blue symbols are Li-rich giants from our survey, green are from Brown *et al.* (1989), and magenta are from literature.

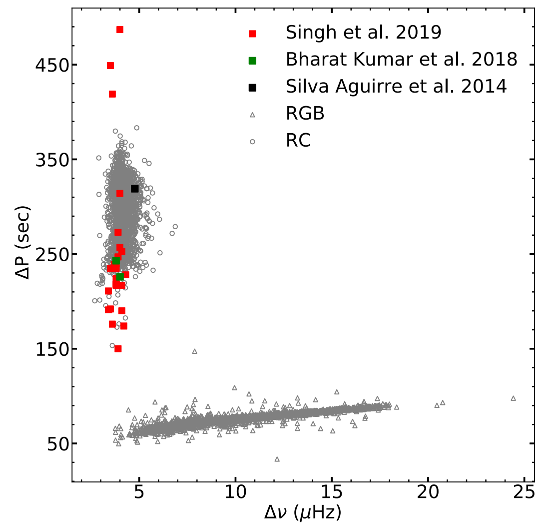

Figure 2. Li-rich giants in an asteroseismic diagram of Δp against $\Delta\nu$. Background grey symbols represent He-core burning giants (vertical clump with Δp >100) and RGB giants of inert He-core (horizontal clump along the x-axis) (Vrard *et al.* 2016). Our survey results represented by red and green symbols.

2.1.1 *Li-rich giants at Red clump phase* The first Li-rich giant, for which evolutionary phase of He-core burning directly determined by asteroseismic analysis, was discovered by Silva Aguirre *et al.* (2014) (Figure 1). This development is the key evidence for the hypothesis that Li-rich giants may be associated with red clump (Kumar *et al.* 2011). It prompted us to search for Li-rich giants among the Kepler field. Unfortunately, none of the known Li-rich giants were in the Kepler field, which may be due to restricted fields of Kepler mission. We initiated a new search for Li-rich giants among the LAMOST survey combined with the asteroseismic catalogue (Vrard *et al.* 2016) which yielded two common giants. Both the Li-rich giants found to have average period spacing Δp and mean frequency of p-mode ($\delta\nu$) compatible with giants being He-core burning stars at RC (Figure 2; Bharat Kumar *et al.* 2018). Li abundances of giants in the LAMOST survey were derived by applying the methodology developed for low-resolution spectra by Kumar *et al.* (2018). This discovery reinforced our earlier hypothesis that Li enhancement origin probably lies in the red clump. With the intuition that there may be a single source for Li production rather than multiple sources, we looked for common giants among the entire Kepler survey fields (including raw data) and LAMOST catalogues. Since LAMOST spectra were of low resolution, we restricted our analysis to only giants for which Li resonance line at 6707Å is strong, yielding A(Li) $\geq$ 3.2 dex. We got 24 of these super Li red giants, having [Fe/H] > -1.5, and all of them were found to be RC (Singh *et al.* 2019a; Figure 2). Another significant survey came from Deepak and Readdy (2019) who based on GALAH and Gaia astrometry separated clump giants from those of giants using density contours. Their results showed that most of the Li-rich giants indeed belong to the red clump. Similarly, Casey *et al.* (2019) found thousands of Li-rich giants from LAMOST survey and showed that the majority of them are associated with the red clump phase. Smiljanic *et al.* (2018) also found Li-rich red clump stars in the CoRoT field from GAIA-ESO high-resolution spectroscopy survey. We also have used secondary calibrations based on asteroseismic analysis and high-resolution spectra for a few Li-rich giants which were found to be red clump (see Singh *et al.* 2019b).

2.1.2 *Li-rich giants at Pre-RGB bump phase* Adding to the existing complexity, Li *et al.* (2018) discovered a dozen very metal-poor ([Fe/H] <-1.5) giants with abnormally high Li abundances for their evolutionary phase. The survey was conducted using the LAMOST low-resolution spectra. The potential Li-rich giants were observed with the Subaru 8.2-m telescope for high-resolution spectroscopic analysis. As shown in Figure 3, some of them show Li abundances as high as ISM value of

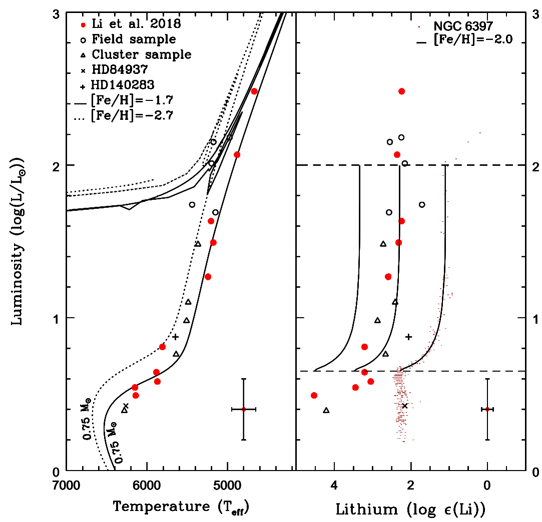

Figure 3. Results from Li *et al.* (2018) survey are shown. Note the Li-rich metal poor giants are in the wide range of luminosity across the HR diagram. Red symbols are Li-rich giants from our survey and black dots are from Lind *et al.* (2009b).

A(Li) =3.28 dex, certainly much higher than the Spite-Plateau value of A(Li) = 2.2 dex in metal-poor dwarfs. Unlike Li-rich giants of population I, as discussed above, they seem to have a wide range of luminosity ($\log(L/L_\odot) \approx 0.5$–2.5 dex) across the RGB. Also, a few of them appear to be still undergoing first dredge-up (stars just below the RGB bump represented by dashed horizontal line), meaning the observed values of A(Li) in these giants may be due to incomplete first dredge-up mixing. However, two of them have A(Li) > 4.0 dex, significantly higher than the maximum A(Li) with which these stars might have formed. A couple of Li-rich giants are also in the upper RGB phase, post luminosity bump. It is not clear whether population II giants have different mechanisms for producing Li. Indeed, one needs to study their evolutionary phase using asteroseismic data to make any suggestions regarding the origin of high Li among these metal-poor giants.

3. Summary

In our recent studies, we made significant progress in unraveling the long-standing problem of Li enhancement among low-mass red giants. This development became possible thanks to the availability of relevant large data sets from stellar surveys such as LAMOST, Gaia, GALAH and Kepler. These studies suggest that majority of the Li-rich giants, previously thought to be anywhere on RGB, mostly belong to red clump region in He-core burning phase. However, it is not clear whether all of them belong to red clump, post-He-flash, meaning Li enhancement is nothing do with the giants ascending RGB. In this direction, a systematic study for Li among red clump stars may give further insights, and help to constrain theoretical models for Li production mechanisms such as He-flash at the RGB tip or some mergers with central He-core giant on RGB. We are now embarking on a large-scale survey of Li-rich giants among red clump giants.

Acknowledgements

YBK thanks the organisers for providing the local hospitality and travel support to attend the meeting and present this work. YBK acknowledges NSFC funding through Grant No. 11850410437.

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