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Abundance Anomalies in Red Giants

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Abstract. The stellar theory is well developed to explain most of the inner workings of stars; however, researchers occasionally come across things that won't comply with the general understanding. The two such phenomena are anomalously very high lithium and extremely low carbon abundances in red giants. Both problems were identified more than four decades ago, but still, there is no consensus on their origin. I will briefly describe the problem and the recent studies in understanding the origin of these rare groups of stars.

1 Introduction:

Element Li with atomic number z = 3 is one of the three elements known to have primordial origin along with H and He. The state-of-art big bang nucleosynthesis (BBN) models and the latest observational data of baryon density predict A (Li) = 2.7~dex, a factor of four more than what is thought to be the primordial A(Li) from the observations of metal-poor stars. This is known in the literature as the "cosmic lithium problem". It is yet to be understood whether the BBN value is overestimated or the low observed value is due to stellar phenomena such as diffusion, which uniformly depleted Li in metal-poor stars. On the other hand, the current value as measured in young stars or in the interstellar medium is A(Li) ≈ 3.3~dex, a factor of six more than the BBN or about ten more than the observed value of A(Li)= 2.20~dex (Spite et al. 1982). Irrespective of what one takes as primordial lithium, either BBN or the observed value, A(Li) has increased significantly since the BBN.

One of the key issues is understanding the sources of A(Li) for its enrichment from the BBN to the present epoch. Some of the proposals include cosmic ray spallation, in which high-energy particles bombard heavier elements like C and O in the ISM, creating lighter elements like Li (Reeves 1970). Stars are generally understood to be A(Li) sinks rather than producers. However, it is long known that the evolved asymptotic giants (AGB) show high lithium, mostly in more massive (>3.5M⊙) stars, due to the Cameron- Fowler (CF) mechanism in which ^{3}He and ^{4}He fuse together to form ^{7}Be which will be converted to ^{7}Li by electron capture. However, this requires certain conditions like transporting ^{7}Be to cooler regions before it gets converted back to He atoms and transporting the converted ^{7}Li to the upper layers before it captures the proton and turns into two ^{4}He nuclei. It seems such conditions exist only in more massive O-rich AGB stars in which Li gets produced by hot bottom burning (HBB). None of these sources seems to account for the present-day A(Li) satisfactorily. The discovery of a large amount of A(Li) in the early 1980s in a low-mass red giant puzzled both the observers and theoreticians. Since low-mass stars account for close to 70% of dust in the ISM, understanding the high A(Li) origin has larger implications for Li evolution in the Galaxy and the stellar mixing process.

On the other hand, a small group of giants, historically known as weak g-band stars (wGbs), have significantly lower carbon abundances than theoretical models predict. The problem was identified in the early part of the 20th century (Canon & Pickering 1912) and later with intermittent studies. The last significant survey was by Bidelmann & MacConnel (1973), which discovered 34 wGb stars. Later, the high-resolution studies revealed that these are extremely carbon-deficient giants (CDGs) (Parthasarathy et al. 1984). Here, onwards, we refer to wGb stars as CDGs.

Here, we provide a brief account of the current status and progress made to understand the origin of both Li and C anomalies in red giants.

2 Lithium in Anomaly in stars:

Stars, after exhausting the hydrogen at the core, evolve off the main sequence and enter the red giant branch (RGB). During the RGB evolution, the hydrogen burning (HB) in a shell surrounding the He-core powers the stars. Stars on RGB undergo deep convection, mixing the processed material in the HB shell with the upper photospheres. The mixing is known as 1st dredge-up. As a result of 1st dredge-up, one would expect a significant decrease in lithium abundance, a marginal decrease in carbon and an increase in nitrogen abundance. Also, one would expect a significant reduction in the carbon isotopic ratio, $^{12}C/^{13}C$ (Iben 1967). For example, post 1st dredge-up, the main sequence A(Li) (=log N(Li)/N(H) + 12; where N is the number density of Li and H per unit volume) is expected to be reduced by a factor of 30-60; similarly, the value of $^{12}C/^{13}C$ from about 90 on the main sequence to 15 to 30. In general, observations and theoretical models are in harmony with regard to the chemical composition of stars on RGB.

A small group of red giants confront the general understanding of Li destruction and show Li abundance as high as A(Li) > 4 dex, which is about a factor of more than 1000 higher than the theoretical predictions and average observed values of A(Li) of giants on the upper RGB. Since the discovery by Wallerstein and Sneden (1982) of the first Li-rich giant (LRG), no viable solution has been found for the origin of high Li in giants, which remained a puzzle till now.

2.1 **Large Spectroscopic Surveys:** After the first discovery of LRG, the large high-resolution spectroscopic survey by Lambert (1989) revealed that LRGs are quite rare, about 1 in 100. Until the year 2000, only a handful of LRGs were discovered. Of which only a couple of them are super Li-rich giants (SLRGs) with A(Li) ≥ 3.2~dex, and most of them overlap a region known as the luminosity bump (LB) on RGB (Charbonnel and Balachandran, 2000). Because of this, they have suggested that extra-mixing takes place at the LB phase due to the H-burning shell moving outwards, resulting in the high Li produced in the star quickly. Also, there were other proposals like external influences like a merger of planets or brown dwarfs (ref). The merger of planets, which preserves the original A(Li) from their natal clouds, like Earth, enhance the star's photospheric

A(Li) but requires many more planets like Earth's mergers to match with the observed A(Li).

Some of the studies in early 2000 also revealed that giants with high A(Li) with infrared excess indicate mergers as such events result in mass loss (Reddy et al.2002). To understand the origin and constrain models, a large spectroscopic survey was undertaken (see Kumar et al. 2011). This was a first-of-its-kind large survey involving 2000 red giants with solar metallicity spanning from the start of 1st dredge-up to the upper RGB using low - resolution spectra (see Fig~1). They devised a way of measuring A(Li) using line ratios of lines at 6707A and the nearby CaI line at 6710A. Since both Ca and Li lines are zero-volt lines, they are basically insensitive to Teff, and the ratio estimates A(Li) in the star for given metallicity. This study resulted from more than 15 new LRGs and four SLRGs doubling their existing count.

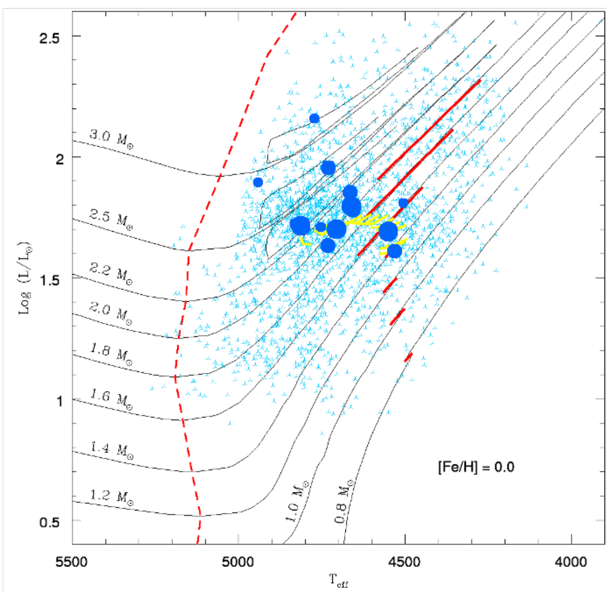

Fig. 1. *A sample of 2000 giants is shown in a plot of luminosity and Teff. The dashed red line and solid lines represent the approximate beginning of the 1st dredge-up and the phase of luminosity bump evolution, respectively.*

Interestingly, all the new LRGs also lie close to the LB, which also overlaps with the red clump region. However, none were found before or after the LB region, suggesting that a merger scenario for high A(Li) is unlikely. There is no reason to believe that mergers can happen only during the LB phase. The Kumar et al. (2011) study also made a hypothesis that probably the He-flash at the tip of RGB may be causing the high A(Li) since LRGs also occupy the red clump phase, which is immediately after the He-flash. The large survey by Deepak & Reddy (2019), about 50,000 giants from the GALAH spectroscopic survey, enabled them to identify clumping of giants, one at LB and one at red clump. It turned out that most of the LRG giants discovered belonged to the red clump and a few only to the LB, confirming He-flash holds the key for Li enhancement origin in red giants. Following this, another study based on the GALAH

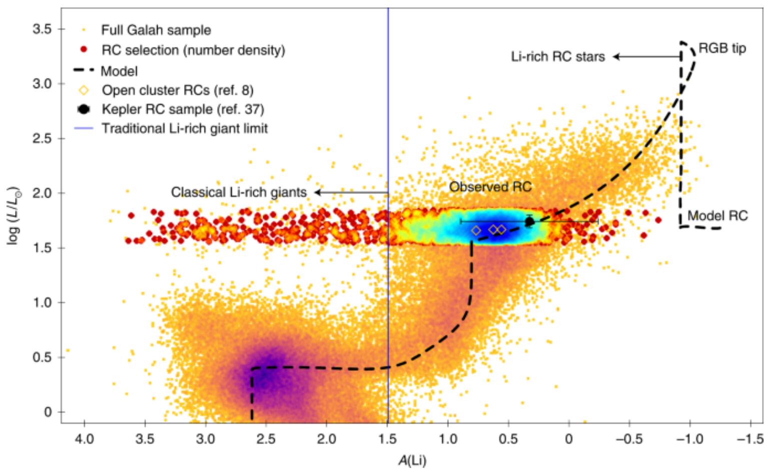

Fig. 2. The sample of 107,776 stars in L- A(Li) shows the evolution of A(Li) along the RGB. The dashed line is the theoretical prediction constricted using MESA stellar models. The horizontal band of stars is the LRGs belonging to RC. The figure is reproduced from Kumar et al. (2020).

The survey revealed that LRGs are common among red clump giants, and the average A(Li) of red clump giants is close to 40 times more than their counterparts on the upper RGB. The study also demonstrated that Li only gets destroyed while ascending the RGB, reaching Li abundance as low as A(Li)= -1.0~dex (see Fig~2).

2.2 Origin of Li anomaly and astroseismology: One of the main reasons for not being able to understand the origin of high Li among giants is the lack of clarity of the LRG evolutionary phase. In particular, separating RC giants from those ascending the RGB as their regions in the Hertzsprung - Russell (HR) diagram overlap. The Kepler asteroseismic data played a key role in separating RGB giants with inert He-core and those RC giants with He-core burning, post-He-flash. The two characteristic parameters are the average period spacing of gravity or g-mode oscillations associated with the central core and the frequency separation between the pressure or p-mode oscillations associated with the upper convective envelope ($\boldsymbol{\delta\nu}$) (Bedding et al. 2011). The first systematic survey for SLRs among 12500 giants that are common in the Kepler photometric and LAMOST spectroscopic fields resulted from 24 SLR giants, and surprisingly, all of them were found to be RC giants with $\boldsymbol{\Delta P} \geq \mathbf{150\ sec}\ \boldsymbol{and}\ \boldsymbol{\delta\nu} \leq \mathbf{8}\ \boldsymbol{\mu\ Hertz}$ reinforcing the idea that Li most probably enriched during the He-flash (Singh et al. 2019). Further evidence came by establishing the correlation between A(Li) and values of cap delta p, a proxy to the evolution of a degenerate core into a convective core (Singh et al. 2021). In that, A(Li) starts decreasing with the increase, i.e. high A(Li) or young RC giants mostly have low $\boldsymbol{\Delta p}$ and normal Li or older RC giants with high $\boldsymbol{\Delta p}$. This study demonstrated rapid depletion of A(Li) in RC giants and set upper limit of 2 Million years within which Li-enhancement occurred. The study by Mallick et al. (2023) showed the lack of LRGs among high-mass giants and their occurrence only among low-mass giants (M $\leq$ 2 solar masses), suggesting Li enhancement happens during the He-flash since the He-flash is known to occur only in low-mass giants.

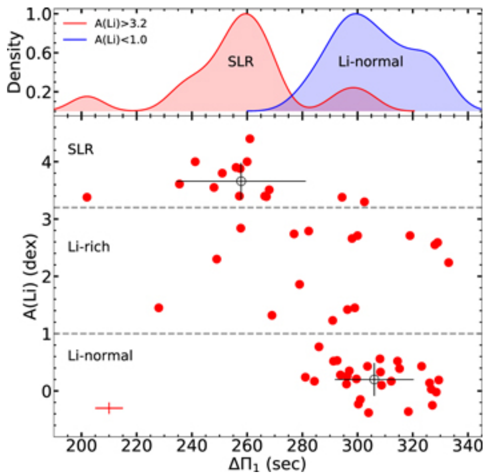

Fig. 3. ΔΠ1 maps the core transition from a degenerate to a fully convective core. Note Li-normal or old RC giants clumping around high g-mode period spacing values and high A(Li), younger RCs with low ΔΠ1 values. The figure is reproduced from Singh et al. (2021).

3. **Low carbon anomaly:** As mentioned in section 1.0, a rare class of giants known to be wGb stars, which later came to be known as carbon deficient giants (CDGs). The carbon abundance in CDGs is much less than theoretical predictions and also the bulk of observations of similar stars. After almost 50 years, Maben et al. (2023a) undertook a survey to find CDGs, as their numbers (about 34) have been stagnant since the last survey in the early 1970s. This study made use of a high-resolution spectroscopic survey of APOGEE, which catalogued spectra with R~22,500 and found more than 100 giants with medium to extreme carbon abundances (see Fig~3). Based on theoretical model predictions for similar metallicity of different mass giants, we set [C/Fe] ≤ -0.6 as the limit, below which giants

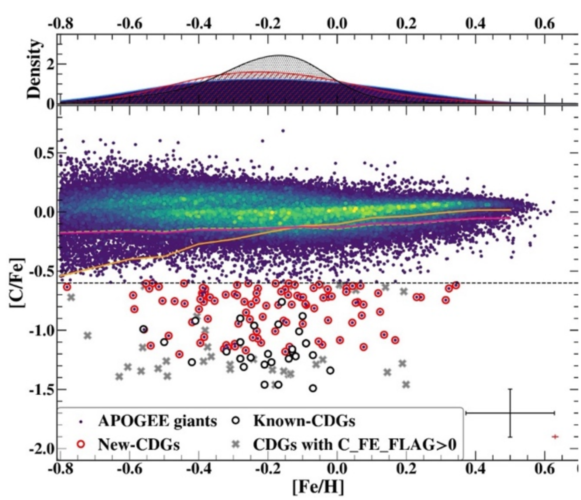

Fig. 4. *Carbon abundances versus metallicity, [Fe/H] of giants in the Galactic disk. The predicted [C/Fe] ratios from the standard models for initial masses are 1 M⊙ (orange solid line), 2 M⊙ (green dashed line), and 3 M⊙ (pink solid line) for giants close to the RGB tip. The horizontal dashed line at [C/Fe] = −0.6 dex denotes the cut we use to identify carbon-deficient stars.*

are considered CDGs. Their placement in the HR diagram suggests most of the giants belong to the RC, and many of them are low mass <2 solar mass giants. The follow-up study by the same group (Maben et al. 2023b) determined evolutionary phases and masses for 15 CDGs based on asteroseismic analysis. The two studies revealed that CDGs are mostly RC giants and are of low mass. They also suggested some kind of connection between LRGs and CDGs. These need to be probed further to understand CDG's origin, whether this is due to a very efficient CN nuclear reaction or some kind of external origin like mergers.

4. Conclusions: Significant observational progress has been made towards understanding the origin of the two well-known anomalies in stellar astrophysics, namely the high lithium and very low carbon anomalies. However, the physical mechanisms that create these anomalies in a small group of giants have yet to be understood.

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