Tracking the Evolution of Lithium in Giants Using Asteroseismology: Super-Li-rich Stars Are Almost Exclusively Young Red-clump Stars

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Abstract

We report novel observational evidence on the evolutionary status of lithium-rich giant stars by combining asteroseismic and lithium abundance data. Comparing observations and models of the asteroseismic gravity-mode period spacing $\Delta \Pi_1$, we find that super-Li-rich giants (SLRs, $A(\text{Li}) > 3.2$ dex) are almost exclusively young red-clump (RC) stars. Depending on the exact phase of evolution, which requires more data to refine, SLR stars are either (i) less than $\sim$2 Myr or (ii) less than $\sim$40 Myr past the main core helium flash (CHeF). Our observations set a strong upper limit for the time of the inferred Li-enrichment phase of $<40$ Myr post-CHeF, lending support to the idea that lithium is produced around the time of the CHeF. In contrast, the more evolved RC stars ($>40$ Myr post-CHeF) generally have low lithium abundances ($A(\text{Li}) < 1.0$ dex). Between the young, super-Li-rich phase, and the mostly old, Li-poor RC phase, there is an average reduction of lithium by about 3 orders of magnitude. This Li destruction may occur rapidly. We find the situation to be less clear with stars having Li abundances between the two extremes of super-Li-rich and Li-poor. This group, the “Li-rich” stars ($3.2 > A(\text{Li}) > 1.0$ dex), shows a wide range of evolutionary states.

Unified Astronomy Thesaurus concepts: Stellar abundances (1577); Asteroseismology (73); Stellar interiors (1606); Low mass stars (2050)

1. Introduction

The origin of strong lithium abundance excess in red giants —“Li-rich giants”—has been a long-standing problem ever since its discovery about four decades ago (Wallstein & Sneden 1982). In the last few years significant progress has been made thanks primarily to large data sets of ground-based spectroscopic surveys such as LAMOST (Cui et al. 2012) and GALAH (De Silva et al. 2015), and the space-based Gaia astrometric (Gaia Collaboration et al. 2016, 2018) and Kepler time-resolved photometric surveys (Borucki et al. 2010). Studies using data from these surveys have now confirmed the early suspicions (e.g., Kumar et al. 2011; Silva Aguirre et al. 2014) that Li-rich giants are predominantly in the He-core burning phase of stellar evolution, also known as the red clump (RC; Bharat Kumar et al. 2018; Smiljanic et al. 2018; Casey et al. 2019; Deepak & Reddy 2019; Singh et al. 2019). This new development has significantly narrowed the search for finding the origin of the lithium enhancement.

It is also well established that Li is almost totally destroyed during the phase of evolution just preceding the RC, the red giant branch (RGB; Lind et al. 2009; Kumar et al. 2020), reaching values as low as $A(\text{Li}) \sim -1.0$ dex. In contrast, the average Li abundance on the RC is $A(\text{Li}) = +0.7$ dex (Kumar et al. 2020), implying that there must be a lithium production phase between the late RGB and RC. Since that study two theoretical models have been put forward for Li production. The first is by Morii et al. (2021) whose model produces Li at the RGB tip, before the onset of He-flash, via the inclusion of the neutrino magnetic moment. The second proposed model produces Li during the main CHeF, by assuming some ad hoc mixing during the extremely energetic flash (Schwab 2020). Both the models explain the observations, with average RC $A(\text{Li})$ of $+0.7$ dex; however, they do not attempt to explain the (super-)Li-rich giants. That said, variation in the parameters of the Schwab (2020) model can indeed produce the very high Li abundances required (see their Figure 4), although the author notes that these high Li abundances are quickly depleted in their model. The current study attempts to better isolate the location of the Li production site as stars transition from the RGB tip to the RC phase. We also aim to explore Li evolution along the RC.

We do this by using observations of the asteroseismic parameter $\Delta \Pi_1$, the asymptotic gravity-mode period spacing of dipole modes (Unno et al. 1989; Mosser et al. 2012a, 2014; Vrard et al. 2016), which has been shown to clearly vary with evolution in stellar models of the RC phase (Bildsten et al. 2012; Bossini et al. 2015; Constantino et al. 2015). We combine $\Delta \Pi_1$ with newly discovered Li abundances as well as Li abundances from the literature.

2. Sample Selection

We extracted a sample of 6955 low-mass ($M < 2 M_\odot$) giants that are classified as RC stars based on Kepler asteroseismic data (Yu et al. 2018). We then searched the literature for $\Delta \Pi_1$ values (Mosser et al. 2012a, 2014; Vrard et al. 2016) and Li abundances (Takeda & Tajitsu 2017; Bharat Kumar et al. 2018; Singh et al. 2019; Yan et al. 2021). We found 37 stars with $A(\text{Li})$ and $\Delta \Pi_1$, and we measured $\Delta \Pi_1$ in 10 more (Section 3.2), giving a total of 47 RC stars with both parameters.

We also searched for Kepler field stars in the recently released catalog of medium-resolution (MRS, $R \approx 7500$) spectroscopic data of the LAMOST7 survey (Liu et al. 2020), finding 577 RC stars.

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9 http://dr6.lamost.org/
stars. We were able to measure Li in 22 of these stars (Section 3.1). Of these, we found ΔΠ for 6 of them in the literature (Mosser et al. 2012a, 2014; Vrard et al. 2016) and were able to measure ΔΠ for a further 6 of them (Section 3.2), giving an extra 12 stars with both parameters.

Combining this sample with the literature sample, we have a total of 59 RC stars with certain evolutionary phase and accurate Li abundances, all from the Kepler field. Luminosities were derived using the Gaia distances (Gaia Collaboration et al. 2018) and the bolometric correction from Torres (2010). We discuss possible biases in our sample in the Appendix. We found no bias in our sample that could alter our conclusions. The final sample is shown in Figure 1.

3. Results

3.1. LAMOST-MRS Lithium Abundances

Li abundances were derived by matching the synthetic spectra with the observed Li line at 6707.78 Å in the medium-resolution LAMOST spectra. We used the 2013 version of the local thermal equilibrium (LTE) radiative transfer code MOOG (Sneden 1973), in combination with the Kurucz ATLAS atmospheric models (Castelli & Kurucz 2003). Atmospheric parameters (T eff, log g, [Fe/H]) were taken from the Yu et al. (2018) catalog. Our line list, with atomic and molecular data, was compiled using the Linemake code.\footnote{https://github.com/vmplacco/linemake} Figure 2 shows a comparison of synthetic spectra with the observed spectra of a few representative stars. The estimated uncertainty in Li abundance is the quadratic sum of uncertainties in atmospheric parameters for each individual star (see Table 1). Li abundances were corrected for non-LTE effects using the ΔNLTE values provided by Lind et al. (2009).

We estimated the lower detectability limit in equivalent width (EW) for our data using the Cayrel (1988) formulation for uncertainties in EW for a range of signal-to-noise ratio (S/N) = 55–150. To err on the conservative side, we adopted a lower limit of 3 × δEW = (10.6–28.2) mÅ, which translates to lower limit abundances in the range +0.7 to +1.1 dex, depending on stellar parameters (Figure 2). This criterion resulted in 22 RC stars for which we could reliably derive Li abundances, for 12 of which we have ΔΠ (Table 1).

3.2. Asymptotic Gravity-mode Period Spacing ΔΠ1

Of the 59 RC giants in our sample, ΔΠ1 values for 43 are available in the literature (Mosser et al. 2012a, 2014; Vrard et al. 2016). For the other 16 we derived it ourselves. We downloaded the time series data from the Kepler archive and converted them to the frequency domain using the Lightkurve package\footnote{https://github.com/NASA/Lightkurve} (Lightkurve Collaboration et al. 2018). Details of our method of ΔΠ1 estimation are given in Mosser et al. (2014) and Vrard et al. (2016). We were able to derive asymptotic values (Table 1) for 16 RC giants that have sufficient S/N in their power density spectra.

3.3. A(Li) versus ΔΠ1: Evolution of Li along the RC

In Figure 3 we display A(Li) versus ΔΠ1 for the RC stars. We divide the sample into three groups depending on their Li abundance:

1. Li-normal (LN); A(Li) < 1.0 dex
2. Li-rich (LR); 1.0 < A(Li) < 3.2 dex
3. Super-Li-rich (SLR); A(Li) > 3.2 dex

The A(Li) = 1.0 dex delineation is based on the Kumar et al. (2020) study’s distribution on the RC (peaked at +0.7 dex), while the A(Li) = 3.2 dex delineation is based on the interstellar medium

\[ \Delta \Pi_1 \]
Table 1

RC Sample of 22 Stars (Out of Total 59) for Which A(Li) and/or ΔΠ₁ Are Measured in This Work (See Section 2 for Details)

| KIC  | V₁  | Tₑff  | log g | [Fe/H] | log(L/L₀) | A(Li)_{LTE} | M(₉ dissolve) | ΔΠ₁  |
|------|-----|-------|-------|--------|-----------|-------------|--------------|-------|
| 5079095 | 12.56 | 4769 ± 139 | 2.38 ± 0.01 | 0.03 ± 0.30 | 1.54 ± 0.04 | 2.66 ± 0.21 | 0.92 ± 0.09 | 298 ± 20 |
| 6593240 | 11.11 | 4808 ± 80 | 2.41 ± 0.01 | 0.0 ± 0.15 | 1.57 ± 0.03 | 2.74 ± 0.15 | 0.83 ± 0.09 | 277 ± 20 |
| 7020392 | 12.40 | 4893 ± 100 | 2.39 ± 0.01 | −0.25 ± 0.15 | 1.83 ± 0.04 | 1.45 ± 0.16 | 0.97 ± 0.12 | 299 ± 20 |
| 7595155 | 12.12 | 4601 ± 100 | 2.36 ± 0.01 | 0.30 ± 0.30 | 1.74 ± 0.03 | 1.23 ± 0.20 | 0.86 ± 0.08 | 291 ± 17 |
| 7612438 | 12.88 | 4921 ± 80 | 2.54 ± 0.01 | 0.07 ± 0.15 | 1.96 ± 0.08 | 1.86 ± 0.15 | 1.87 ± 0.10 | 279 ± 32 |
| 7954197 | 10.90 | 4814 ± 139 | 2.42 ± 0.01 | 0.12 ± 0.30 | 1.62 ± 0.03 | 1.32 ± 0.20 | 1.23 ± 0.12 | 269 ± 2 |
| 8363443 | 10.88 | 4606 ± 80 | 2.41 ± 0.01 | 0.38 ± 0.15 | 1.81 ± 0.03 | 3.55 ± 0.12 | 1.33 ± 0.09 | 248 ± 2 |
| 6819916 | 12.90 | 5117 ± 160 | 2.44 ± 0.01 | −0.05 ± 0.30 | 1.71 ± 0.06 | 2.71 ± 0.25 | 1.11 ± 0.11 | 300 ± 3 |
| 8879518 | 11.22 | 4863 ± 80 | 2.57 ± 0.01 | 0.14 ± 0.15 | 1.73 ± 0.03 | 3.51 ± 0.12 | 1.76 ± 0.13 | 268 ± 3 |
| 9048308 | 12.28 | 4733 ± 80 | 2.49 ± 0.01 | 0.06 ± 0.15 | 1.72 ± 0.04 | 2.59 ± 0.12 | 1.36 ± 0.09 | 329 ± 4 |
| 9907856 | 12.45 | 4855 ± 80 | 2.41 ± 0.01 | −0.17 ± 0.15 | 1.73 ± 0.01 | 2.56 ± 0.13 | 1.16 ± 0.25 | 328 ± 3 |
| 1129153 | 12.09 | 4830 ± 100 | 2.37 ± 0.03 | −0.37 ± 0.15 | 1.63 ± 0.08 | 1.45 ± 0.16 | 1.12 ± 0.21 | 228 ± 11 |

Sample from literature for which ΔΠ₁ values are derived in this study

| KIC  | V₁  | Tₑff  | log g | [Fe/H] | log(L/L₀) | A(Li)_{LTE} | M(₉ dissolve) | ΔΠ₁  |
|------|-----|-------|-------|--------|-----------|-------------|--------------|-------|
| 3751167 | 13.74 | 4914 ± 80 | 2.33 ± 0.03 | −0.76 ± 0.15 | 1.86 ± 0.06 | 4.0 ± 0.35 | 0.95 ± 0.22 | 260 ± 13 |
| 7131376 | 13.99 | 4833 ± 152 | 2.45 ± 0.01 | 0.04 ± 0.30 | 1.52 ± 0.06 | 3.80 ± 0.35 | 1.25 ± 0.11 | 250 ± 8 |
| 7899597 | 13.61 | 4757 ± 80 | 2.40 ± 0.03 | −0.10 ± 0.15 | 1.77 ± 0.05 | 3.39 ± 0.06 | 1.28 ± 0.23 | 264 ± 18 |
| 8869656 | 9.34 | 4915 ± 137 | 2.40 ± 0.01 | −0.13 ± 0.30 | 1.68 ± 0.02 | 3.61 ± 0.09 | 1.21 ± 0.13 | 235 ± 13 |
| 9667064 | 13.35 | 4802 ± 80 | 2.38 ± 0.03 | 0.04 ± 0.15 | 1.86 ± 0.06 | 4.0 ± 0.35 | 1.40 ± 0.20 | 260 ± 16 |
| 9833651 | 12.52 | 4730 ± 80 | 2.49 ± 0.01 | 0.14 ± 0.15 | 1.66 ± 0.04 | 3.40 ± 0.09 | 1.50 ± 0.13 | 266 ± 3 |
| 11615224 | 11.15 | 4888 ± 100 | 2.38 ± 0.01 | −0.03 ± 0.15 | 1.89 ± 0.05 | 2.84 ± 0.02 | 0.85 ± 0.10 | 257 ± 2 |
| 11658789 | 13.35 | 5226 ± 155 | 2.42 ± 0.02 | −0.52 ± 0.30 | 1.69 ± 0.03 | 3.90 ± 0.35 | 0.87 ± 0.14 | 256 ± 2 |
| 11805390 | 9.78 | 4950 ± 80 | 2.58 ± 0.01 | −0.06 ± 0.15 | 1.65 ± 0.03 | 2.24 ± 0.10 | 1.34 ± 0.10 | 249 ± 2 |
| 12784683 | 11.46 | 4983 ± 145 | 2.37 ± 0.02 | −0.30 ± 0.30 | 1.68 ± 0.02 | 2.79 ± 0.08 | 1.16 ± 0.18 | 282 ± 18 |

Note. Masses were derived using the relation given in Kjeldsen & Bedding (1995).

* https://simbad.u-strasbg.fr/simbad/sim-fbasic

References. (1) This work; (2) Vrard et al. (2016); (3) Singh et al. (2019); (4) Yan et al. (2021).

value (Knauth et al. 2003). Our key result emerges from Figure 3—the great majority (12/15 = 80%) of the SLR stars have ΔΠ₁ peaked at low values (mean = 257 ± 23 s). We note that two of the three outliers in the SLR group have masses 2σ from the mean mass of our RC sample (∼1.8 Mₑ, where the sample mean mass is 1.2 ± 0.3 Mₑ). Without these outliers¹⁰ the average remains the same, at 255 s, but the dispersion is halved (σ = 10 s), as expected from the histogram. In contrast, the Li-normal stars all have higher ΔΠ₁, ranging from 280 s up to ∼330 s. Their mean is 306 ± 14 s, much higher than the SLR group.

The Li-rich stars (Figure 3) show more complex behavior. They have a very broad distribution of ΔΠ₁ values rather than forming a coherent group. We now discuss the implications of the ΔΠ₁−A(Li) observations in relation to stellar evolution.

4. Discussion

4.1. Observations versus Stellar Evolution

Low-mass giants (≤2 Mₑ) develop electron-degenerate cores while ascending the RGB. Initiation of an off-center helium flash in the degenerate core terminates the RGB evolution (Schwarzschild & Härm 1962; Demarque & Mengel 1971; Sweigart 1994). The first/main He-flash is very short-lived, lasting about 1000 yr. After the main flash a series of progressively weaker flashes ensues (Figure 4; also see Thomas 1967; Cassisi et al. 2003; Bildsten et al. 2012;

¹⁰ We do not remove these stars from the sample; this is only a test of the sensitivity of the dispersion, since with the outliers the distribution is non-Gaussian.
We note that the seismic masses are the current masses of the stars. The total RG mass loss was modeled using the Reiners (1975) formula ($\gamma = 0.3$). We used the standard MESA nuclear network (“basic.net”) and standard equation of state (see Paxton et al. 2019 for details), and $\alpha_{\text{MLT}} = 2.0$. Convective boundary locations were based on the Schwarzschild criterion, extended with exponential overshoot (Herwig et al. 1997). In Figure 4 we show a representative model that matches the mean mass of our sample, 1.2 $M_\odot$, and is of solar metallicity$^{12}$ (the mean [Fe/H] of our sample is $-0.14 \pm 0.26$ dex). As Bossini et al. (2017) showed, the very early RC $\Delta\Pi_1$ evolution is not dependent on mass; however, it has some dependence on metallicity. Comparing the dispersion of [Fe/H] in our sample (0.26 dex) with the models in Figure 3 of Bossini et al. (2017), we expect a variation of $\sim 5$ s in $\Delta\Pi_1$. This is approximately the same as our observational error bars (Figure 3). On the other hand, the late RC is particularly sensitive to the treatment of convective boundaries (e.g., Constantino et al. 2015; Bossini et al. 2015). To match the highest $\Delta\Pi_1$ values ($\sim 330$ s) we adopted an overshoot parameter $f_{\text{OS}} = 0.02$.

We display the model evolution of $\Delta\Pi_1$ versus time in the top panels of Figure 4. Overplotted are the 1σ intervals of $\Delta\Pi_1$ for the observations of the SLR and Li-normal groups (see Figure 3). It can be seen that the high values of $\Delta\Pi_1$ of the Li-normal stars are only available in the second half of the RC evolution (from $\sim 40$ Myr onward), or for extremely brief periods ($\sim 0.005$ Myr) during the early helium flashes, which are unlikely to be observed in such numbers. We thus identify the Li-normal stars as more evolved RC stars.

In contrast, the low $\Delta\Pi_1$ values of the SLR stars are only consistent with young RC stars ($\leq 40$ Myr in the 1.2 $M_\odot$ model). Interestingly we find there is very little overlap between the Li-normal and SLR populations. This may indicate a rapid Li-depletion event (but see Section 4.4).

4.2. Are SLR Stars He-flash Stars?

One of the main hypotheses for the Li-enrichment event is that it occurs during the main helium flash (Kumar et al. 2011; Mocák et al. 2011; Silva Aguirre et al. 2014; Kumar et al. 2020; Schwab 2020). Here we explore the possibility that our sample of SLR stars are currently experiencing the CHef, or are in the following subflashing phases.

In Figure 4 it can be seen that there is some degeneracy in $\Delta\Pi_1$ during the early phases of the RC evolution. This makes identifying the exact young RC phase that the SLR stars reside in more difficult.

The vertical portions of the $\Delta\Pi_1$ evolution are extremely short-lived, so it is very unlikely to find stars in these phases. Adding the extra dimension of $\Delta \nu$ (bottom panel of Figure 4), we see that the $\Delta \nu$ values of the model’s early subflashes are inconsistent with our sample. This is also true of the main CHef (not pictured), which has $\Delta \nu \sim 0.04$ $\mu$Hz. In addition, the main flash has $\Delta\Pi_1 = 700$ s, well outside our observed range. Thus, we can rule out our SLR stars being in the main core helium flash. The third subflash (SF3) has $\Delta\Pi_1 \sim 300$ s, well above the SLR average value of 257 s, so we rule this out also. We checked the variation of $\Delta\Pi_1$ during the subflashes in our small set of models and found only small deviations of $\sim 5$ s in our mass and metallicity range.$^{13}$ This variation is similar to our uncertainties on $\Delta\Pi_1$. Three possibilities remain, defined by the SLR $\Delta\Pi_1$ band:

1. The first $\sim 40$ Myr of RC evolution, “early RC” (ERC in Figure 4);

$^{12}$ Solar abundances were from Asplund et al. (2009).

$^{13}$ The number of SFs remain the same (five), but there are some small differences in timescales, dependent on mass and metallicity. The similarity is due to the He cores all being quite similar, which also gives rise to the RC itself.
2. The first \( \sim 0.3 \) Myr of evolution, which encompasses the “merged” subflash SF5, named “very early RC” (VERC: 1.6–1.9 Myr range in Figure 4);  
3. The final separated helium subflash, SF4, which has a lifetime of 0.04 Myr and \( \Delta \nu \) values within the range of our observations.

Large surveys give us statistical information on Li-rich giants that may also help in identifying the exact phase of SLR stars. Using the large samples of Kumar et al. (2020) and Singh et al. (2019) we have calculated the SLR fractions to be 0.3% and 0.5%, respectively. If we hypothesize that all stars go through an SLR phase, then we can estimate timescales of the SLR phase. The RC phase lasts for \( \sim 100 \) Myr, implying that the SLR phase would last around 0.3–0.5 Myr. The lifetime of SF4 is only 0.04 Myr, so this is inconsistent with the timescale estimated from the surveys. Put another way, we find too many SLR stars for the SF4 scenario, by a factor of \( \sim 10 \). Further, we estimated the probability of finding even one SF star in our sample and found an expectation of 0.02 stars. Given these various lines of evidence we conclude that our SLR stars are highly unlikely to be in a flashing phase.

### 4.3. How Young Are the SLR Stars?

To attempt to distinguish between the two remaining phases we turn to our series of models, to quantify the theoretical versus observational dispersion in \( \Delta \Pi_1 \) and \( \Delta \nu \). We found that the various stellar tracks covered the whole observed wide range of \( \Delta \nu \) for the SLR stars. Other uncertain model parameters, such as the convective mixing length \( \alpha_{\text{MLT}} \), would further increase the dispersion in \( \Delta \nu \) (Constantino et al. 2015; Bossini et al. 2017). Thus, we are unable to distinguish between the VERC and ERC scenarios using \( \Delta \nu \).

In contrast, as mentioned above, \( \Delta \Pi_1 \) does not vary much with mass in the early RC, as reported by Bossini et al. (2017). During the VERC phase (not reported by Bossini et al. 2017) we find a small dispersion in our set of models. The variation with mass is \( \sim \pm 5 \) s, and with metallicity \( \sim \pm 10 \) s, which is comparable to the observed dispersion of the SLR stars \( (\sigma = 23 \text{ s} \text{ or } \sigma = 10 \text{ s if outliers are ignored, see Section 3}) \). Thus, within the mass and metallicity variation of our sample, the ERC and VERC phases always present low \( \Delta \Pi_1 \) values, close to what we observe in the SLR stars. This reinforces the finding that these objects are all young, or very young, RC stars.

Unfortunately, due to the \( \Delta \nu \) and \( \Delta \Pi_1 \) degeneracy we can not distinguish between these two phases. We now briefly discuss the implications of both scenarios.

In the ERC case only a small proportion, \( \sim 1\% \), of stars would be super-Li-rich. This is a factor of 2–3 higher than the fraction found when taking into account all RC stars, consistent with the SLR stars being only found in the first \( \sim 40\% \) of the RC lifetime. In the VERC case \( \sim 100\% \) of low-mass stars would be SLR. That is, super-Li-richness would be a universal phase of low-mass stars. They would already be super-Li-rich as they start the RC, which would be consistent with the model of Schwab (2020), where the Li enrichment occurs during the main CHeF. A universal SLR phase would also resonate with the finding of Kumar et al. (2020), who report that all low-mass stars appear to go through a Li-enrichment phase, albeit to more moderate abundances—although this difference would be explained by our Li-normal group, which indicates that strong depletion occurs during the RC.

#### 4.4. The Li-rich group

The Li-rich group (Figure 3) is more difficult to interpret, since the \( \Delta \Pi_1 \) distribution is so broad. We speculate that these stars could be in a phase of evolution intermediate to the SLR and Li-normal stars, currently depleting Li on their way to the late RC. This aligns with their \( \Delta \Pi_1 \) distribution being peaked at 290 s, which is between that of the SLR group (257 s) and the Li-normal group (306 s). If the Li-rich stars are currently undergoing Li depletion then it suggests the Li depletion is a slower process. More information is needed to disentangle the evolutionary state(s) of this group.

#### 5. Conclusion

By combining asteroseismic and spectroscopic measurements for a sample of giant stars we discovered a correlation between \( A(\text{Li}) \) and \( \Delta \Pi_1 \), whereby super-Li-rich stars are almost universally young RC stars, and Li-normal stars are predominately older RC stars.

The simplest explanation for this is that (i) there is a Li-enrichment phase before the start of the RC, either near the RGB tip or during the core flashing phase, and (ii) Li is depleted during the early phases of RC evolution. The exact time of the Li depletion, which could be in the very early phases of RC evolution \( (\sim 0.3\% \text{ of RC lifetime}) \) or later during the early RC (first \( \sim 40\% \) of RC evolution) is indistinguishable from our current data. If it occurs in the very early RC phase then it implies that all low-mass stars go through an SLR phase. If it occurs later then \( \sim 1\% \) go through an SLR phase. More data are required to separate these scenarios. Further, the relation between \( A(\text{Li}) \) and \( \Delta \Pi_1 \) will help to trace the transition of giants from the tip of RGB to RC phase where stars burn helium at the center quiescently.

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#### Appendix

### Possible Biases in Stellar Sample

Of our 59 RC giants 30 are taken from Takeda & Tajitsu (2017). This forms our low-Li sample of stars as their \( A(\text{Li}) \) are based on high-resolution spectra. The Takeda & Tajitsu (2017) sample, which only used brightness as a selection criterion, was itself taken from the original sample of Mosser et al. (2012a), who derived \( \Delta \Pi_1 \) for 95 RC stars that had long-cadence observations of the Kepler field.

At no stage did we select on the basis of \( \Delta \Pi_1 \). Our \( A(\text{Li}) \) values are however limited in a couple of cases. First, the abundances from the LAMOST medium-resolution spectra are
peak in GALAH. The bias to high Li can be seen in our sample, as can the unusual of our RC sample compared to the large GALAH sample the K20 sample has a systematic shift relative to the Takeda & Tajitsu (Figure 5. the Astrophysical Journal Letters, ΔΠ of our sample represents a very substantial fraction (larger samples. As discussed above, our sample has proportionally models and the Mosser et al. (SLR stars. We have stars. We see no reason why the detectability of mentioned, our sample contains 58% of all known Kepler problem with the models or the observations, or both. As we used the sample from Singh et al. (2019) whose Li measurements were restricted only to very strong Li lines due to low spectral resolution (LAMOST, R ~1800). This resulted in a bias toward SLR stars in their sample, which is mapped to our sample. By combining these samples biased to Li-rich stars with the low-Li sample of Takeda & Tajitsu (2017), we cover the whole range of ΔΠ1.

Super-Li-rich stars are central to our main result (Sections 3 and 4). The Kepler field is known to have 26 SLR stars in total (Singh et al. 2019; also Table 1); they are rare objects. Of these, we have 15 in our sample with ΔΠ1 measurements. As such our sample represents a very substantial fraction (58%) of all the known SLR stars in the Kepler field.

A possible bias against observing low ΔΠ1 values was reported by Constantino et al. (2015), based on comparisons between models and the Mosser et al. (2012b) sample. At low ΔΠ1 their models predict more stars than are observed. This could be a problem with the models or the observations, or both. As mentioned, our sample contains 58% of all known Kepler field SLR stars. We have ΔΠ1 for all of these stars, and our main result (Section 3) is that they are strongly peaked at low values. This shows that we, and others (see Section 2 for ΔΠ1 sources), have been able to measure low values of Π1 in the majority of these stars. We see no reason why the detectability of ΔΠ1 should depend on Li abundance.

In Figure 5 we provide histograms comparing the distributions of ΔΠ1 and A(Li) in our sample with large survey samples. Our sample covers the whole range of A(Li) and ΔΠ1 present in the larger samples. As discussed above, our sample has proportionally more (SL)R stars than an unbiased survey, which is seen clearly in Figure 5. The ΔΠ1 distribution, despite being independent of our sampling, has an unusual peak at low ΔΠ1 ~ 255 s—is this our main result, that SLR stars have predominately low ΔΠ1.

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Figure 5. The ΔΠ distribution, despite being independent of our sampling, has an unusual peak at low ΔΠ ~ 255 s—is this our main result, that SLR stars have predominately low ΔΠ1.