The nature of the lithium enrichment in the most Li-rich giant star

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About 1% of giant stars1 have anomalously high Li abundances (\(A_\text{Li}\)) in their atmospheres, conflicting directly with the prediction of standard stellar evolution models2. This finding makes the production and evolution of Li in the Universe intriguing, not only in the sense of Big Bang nucleosynthesis3,4 or the interstellar medium5, but also for the evolution of stars. Decades of effort have been put into explaining why such extreme objects exist6–8, yet the origins of Li-rich giants are still being debated. Here, we report the discovery of the most Li-rich giant known to date, with a very high \(A_\text{Li}\) of 4.51. This rare phenomenon was observed coincidentally with another short-term event: the star is experiencing its luminosity bump on the red giant branch. Such a high \(A_\text{Li}\) indicates that the star might be at the very beginning of its Li-rich phase, which provides a great opportunity to investigate the origin and evolution of Li in the Galaxy. A detailed nuclear simulation is presented with up-to-date reaction rates to recreate the Li enrichment process in this star. Our results provide tight constraints on both observational and theoretical points of view, suggesting that low-mass giants can internally produce Li to a very high level through \(\beta\)-ray conversion during the red giant phase.

Lithium is too fragile to survive in deeper layers of a stellar atmosphere due to the high temperature. Thus, the first dredge up (FDU) process can sharply dilute the surface Li abundance (\(A_\text{Li}\)) in red giants. This explains why the first discovery4 of an Li-rich giant evoked great interest in exploring and understanding the Li-rich objects. However, only about 150 Li-rich giants have been found4,9–11 in the past three decades, and \(\sim 20\) of them were found to be super Li-rich with \(A_\text{Li}\) higher than 3.3. Considering the non-local thermodynamic equilibrium (NLTE) corrections, three stars12–14 were found to be at a level of \(A_\text{Li}\) \(> 4.0\). Such rare objects could provide a great opportunity to reveal the nature of the phenomenon of Li richness because high \(A_\text{Li}\) cannot be maintained for a long time due to frequent convection activity. Taking advantage of the powerful ability for spectral collection with the Large Sky Area Multi-Object Fiber Spectroscopy Telescope (LAMOST), we have obtained a large sample of Li-rich candidates by measuring the equivalent width of the Li i line at \(\lambda = 6707.8\) Å. One of our candidates, TYC 429-2097-1, has a super strong \(A_\text{Li}\) line (see Fig. 1a). We then made a follow-up high-resolution observation with the 2.4 m Automated Planet Finder telescope (APF) located at Lick Observatory on 23 June 2015. The spectrum covers a wavelength range of 374–970 nm with a resolution power of \(\sim 80,000\). The total integration time was 1.5 h and was divided into three single exposures (30 min each) for better subtraction of cosmic rays. The spectrum of TYC 429-2097-1 obtained from APF is presented in Fig. 1b, where the spectrum of HD 48381 is also plotted with a vertical shift of +0.3 as a comparison. HD 48381 is a star selected from the Gaia-ESO survey DR2, which has very similar stellar parameters to TYC 429-2097-1. We used the spectroscopic method to derive the stellar parameters (see the Methods for details). We present the final derived parameters of TYC 429-2097-1 and the estimated errors in Table 1. The \(A_\text{Li,NLTE}\) values for \(6,707.8, 6,103.6\) and \(8,126.3\) Å are \(4.42 \pm 0.09, 4.51 \pm 0.09\) and \(4.60 \pm 0.08\), respectively. The averaged \(A_\text{Li,NLTE} = 4.51 \pm 0.09\). Compared with previous studies, TYC 429-2097-1 has the highest \(A_\text{Li}\) among all Li-rich giants ever discovered (see Fig. 2). The \(A_\text{Li}\) in TYC 429-2097-1 is about 1,000 times higher than the widely used Li-rich ‘standard’ of \(A_\text{Li} = 1.5\) (lower purple dashed line in Fig. 2), despite it having been suggested that this ‘standard’ is luminosity dependent15. It is also about 15 times higher than meteoritic \(A_\text{Li}\) (upper purple dashed line in Fig. 2), which is thought to be the initial \(A_\text{Li}\) for newly formed young stars.

Although Li-rich giants were reported at various stages, such as red giant branch (RGB) and core helium-burning phases16, the Li-rich phase is likely to be a short-term event. An extremely Li-rich giant (possibly newly enriched) with rigorous investigation on its evolutionary stage would definitely be important. The location of the star was derived by the maximum likelihood method using the observed parameters (in this case, the effective temperature (\(T_\text{eff}\)), surface gravity (\(\log[\text{g}]\)) and [Fe/H] derived from the spectroscopic method) and a grid of evolutionary models computed with the modules for experiments in stellar astrophysics (MESA) code (see the Methods for details). The derived luminosity and mass are \(\log[L/L_\odot] = 1.95\) and \(M = 1.43 M_\odot\), respectively. We used the parallax of Gaia DR1 (ref. 19) to test the reliability of the information derived from the maximum likelihood method independently. The luminosity obtained from Gaia data leads to a very similar result of \(\log[L/L_\odot] = 2.00\). The mass was tested in the sense that if the mass is well determined, the surface gravity from Gaia parallax will show good consistency with the spectroscopic \(\log[\text{g}]\) of 2.25. As expected, the final result is \(\log[\text{g}] = 2.23\). Thus, we consider that the results derived from the maximum likelihood method are reliable, allowing us to robustly locate this star on the Hertzsprung–Russell diagram, along with the corresponding MESA tracks (see Supplementary Fig. 1). The star is probably occupying the region of
the RGB bump—a stage in which the $\mu$-barrier is destroyed and the enhanced extra mixing might be ongoing inside the star. In addition, we also estimated the $^{12}\text{C}/^{13}\text{C}$ ratio as it has been suggested that the extra mixing will cause a decrease of $^{12}\text{C}/^{13}\text{C}$ to the range of 10–20. We found that the $^{12}\text{C}/^{13}\text{C}$ ratio in this star is $12.0 \pm 3.0$, which is well within the predicted range. All the results obtained above are shown in Table 1.

It has long been suggested that the Li enrichment could be due to contaminations by external sources in the environment, such as engulfment of a substellar componen\textsuperscript{20} (for example, giant planets or brown dwarfs) and accretion from an Li-rich companion or diffuse medium. Yet the contribution from external sources is not infinite, since the contributor itself has a limited amount of Li, typically not higher than 3.3. A simulation on engulfment of a Jovian planet suggested that a typical upper limit for enrichment this way is ~2.2 (ref. 21). Our star has a much higher $A_{\text{Li}}$ than any of these values, so it is very unlikely that the overabundant Li comes from the direct contribution of external sources.

In contrast, the internal production of Li is based on the Cameron– Fowler mechanism\textsuperscript{22}. The production of $^7\text{Be}$ takes place where the temperature is too high to preserve the newly synthesized $^7\text{Li}$; hence, $^7\text{Be}$ must be transported quickly to the cooler region to form Li. This scenario would potentially require the low-mass giants to evolve to the RGB bump, where the mean molecular weight discontinuity (or $\mu$-barrier—a mass gradient caused by the FDU) is erased. Meanwhile, it would need the presence of deep, enhanced extra mixing to increase the depth and efficiency of the convective circulation, which in turn alters the $^{12}\text{C}/^{13}\text{C}$ to a lower level than that.
after the FDU. The observational features on both the evolutionary stage and the $^{12}$C/$^{13}$C ratio of our star coincide with these predictions remarkably well, but the limitation of self-production still remains unknown in the sense that none of the quantitative calculations with a nuclear reaction network has been presented to obtain such a high amount of Li before. To test this speculation, we have built such a simulation with a series of parameters. Using the RGB stellar structure as the input for the extra mixing calculation, with the updated nuclear reaction rates and the asymmetric parameters of the extra mixing model, we found that $A_{\text{Li}}$ in the envelope can exceed 4.0 for the processed material when the mass circulation has finished. Our extra mixing calculation with parameters of $M = 5.2 \times 10^{-4} M_\odot \, \text{yr}^{-1}$, $\Delta = 0.15$, $f_d = 0.9$ and $f_u = 0.1$ yields $A_{\text{Li}} = 4.506$, where $M$ is the rate of mass transport, $\Delta$ is $\log [T_{\text{eff}}] - \log [T_{\text{eff}}^0]$, where $T_{\text{eff}}$ is the temperature at which the energy released from the hydrogen-burning shell reaches its maximum and $T_{\text{eff}}^0$ is the maximum temperature sampled by the circulating material, and $f_d$ and $f_u$ are the fractional areas of the 'pipes' occupied by the mass flows moving downward and upward, respectively, and their values satisfy $f_d + f_u = 1$. This reproduces the observed $A_{\text{Li}}$ for TYC 429-2097-1 well. Repeating the same calculation with the alternative set of nuclear reaction rates from the JINA database yields a similar $A_{\text{Li}}$ of 4.515. In contrast, assuming this star had never experienced any extra mixing, the $A_{\text{Li}}$ would be constant at the initial value of $A_{\text{Li}} = 1.16$, because the temperature in the envelope is too low to ignite both the production and destruction reactions of $^7$Li. The abundances of $^3$He, $^7$Li and $^7$Be as functions of the processing time for the mass circulation are shown in Fig. 3.

During the extra mixing process, $^3$He is converted to $^7$Be via the reaction of $^3$He($^3$He, $^3$He)$^7$Be, and then $^7$Be is quickly converted to $^7$Li via the reaction of $^7$Be(e$^-$, $\gamma$)$^7$Li. To achieve such a high level of $A_{\text{Li}}$, abundant $^3$He is required. The initial surface $^3$He is computed from the MESA model, which is $Y(^3\text{He}) = 4.038 \times 10^{-4}$. Figure 3 shows the decrease of $^3$He as a function of time for extra mixing processing. A total amount of $Y(^3\text{He})/H = 1.477 \times 10^{-4}$ is burned off during this circulation, and the produced $Y(^7\text{Li})/H = 3.206 \times 10^{-4}$. This is because another reaction, $^3$He($^3$He, $^3$He)$^7$Be, dominates over the reaction $^3$He($^3$He, $^3$He)$^7$Be, thus consuming the majority of $^3$He. The strong competition from the $^3$He($^3$He, $^3$He)$^7$Be reaction prevents more $^3$He from converting to $^7$Li. Testing with different sets of extra mixing parameters shows that the maximum of $A_{\text{Li}}$ from our network calculation is 5.07. The $^3$He supply may eventually run out and cannot be renewed by the giant, in which case the surface $A_{\text{Li}}$ is likely to decrease, even if the internal conditions remain the same. In contrast, if the internal conditions do change, the surface $A_{\text{Li}}$ may also decline due to the destruction by convective activities in stars. Either way, the super Li-rich phase may disappear after a short period of time. In our calculation, the asymmetric mass circulation described by a large ratio of $f_d/f_u$ is a key factor for achieving super-high Li enrichment. This large $f_d/f_u$ ratio indicates that the upward flow is moving much faster (since its 'pipe' is thinner) than the downward flow, while the mass is conservative in the extra mixing process.

### Table 1 | Key information for TYC 429-2097-1

| Property | Value |
|----------|-------|
| Name     | TYC 429-2097-1 |
| $T_{\text{eff}}$ (K) | 4,696 ± 80 |
| log$[\text{Fe}/H]$ | 2.25 ± 0.10 |
| $[\xi]$ (km s$^{-1}$) | $-0.36 \pm 0.06$ |
| $A_{\text{Li},\text{NLTE}}$ | 4.51 ± 0.09 |
| Gaia parallax $\pi$ (milli-arcsec) | 0.73 ± 0.24 |
| Mass ($M_\odot$) | 1.43 ± 0.055 |
| log$L/L_\odot$ | 1.95 ± 0.25 |
| log$L_{\text{rad}}/L_\odot$ | 2.00 ± 0.06 |
| log$[\text{g}_{\odot}]$ | 2.23 ± 0.16 |
| $^{12}\text{C}/^{13}\text{C}$ | 12.0 ± 3.0 |
| $v \sin i$ (km s$^{-1}$) | 11.3 ± 1.5 |
| $[\alpha/\text{Fe}]$ | 0.19 ± 0.04 |

### Fig. 2 | Distribution of Li-rich giants

Left, distribution in the $T_{\text{eff}}$-Li/H plane. Right, distribution in the $T_{\text{eff}}$-$A_{\text{Li}}$ plane. TYC 429-2097-1 is indicated by a red star. The key shows which studies the other data have been taken from$^{[2,5,13,17,55-57]}$. All $A_{\text{Li}}$ values adopted here are based on NLTE calculations. If the original study did not perform NLTE abundance analysis, we applied the NLTE corrections interpolated from Lind’s grid to the original LTE abundances. The horizontal dashed lines in purple indicate $A_{\text{Li}} = 1.5$ and $A_{\text{Li}} = 3.3$, respectively. The dotted blue line shows the upper limit of Li enriched by engulfment of a giant planet.$^{[51]}$

### Fig. 3 | Calculated surface abundances and mass fractions of $^3$He, $^7$Be and $^7$Li as functions of the processing time for the mass circulation

The left-hand y-axis indicates the mass fractions in logarithmic scale, whereas the right-hand y-axis indicates the logarithmic abundances. The initial time is set to zero when the sample material at the base of the envelope starts the mass circulation. The vertical solid line indicates the boundary between the downward and upward motion of the processed material. The yield of $^7$Be reaches its maximum by the end of the downward motion at $t = 423$ yr, after which $^7$Li begins to dominate during the upward motion of the sample material for 47 yr.
The cause of the extra mixing has not been well understood, and rotationally induced mixing is often attempted. Indeed, TYC 429-2097-1 is a slightly rapid rotator with a projective velocity of 11.3 km s\(^{-1}\), which is about 10 times faster than that of normal giants. The spinning up of an RGB star is either caused by the tidal synchronization effects in a close binary system or the engulfment of a massive planet\(^{20}\). We calculated the radial velocities based on the two independent observations through LAMOST and APF (with an interval of ten months), and found no significant radial velocity change at a level of a few kilometres per second, which is the typical uncertainty for radial velocities derived from LAMOST spectra. Thus, it is very unlikely that a star has a stellar companion that is massive and close enough to spin up via tidal synchronization. In contrast, one would expect some associated features that are detectable if a massive planet was engulfed and digested. For example, it was found that there might be a large probability of Li-rich giants exhibiting excess in the infrared flux, yet we found no sign of infrared excess (see Supplementary Fig. 2). In addition, if the matter exchange did happen at a certain time, there should be some fluctuations in the abundance pattern. However, TYC 429-2097-1's \(^{12}\)C/\(^{13}\)C is at a typical level for its stage, and its \(^{12}\)Fe abundance is also quite normal among the giants with similar [Fe/H]. Given all these facts, we speculate that in our case, the enhanced extra mixing might neither be caused by the presence of a massive planet (if there were any) nor a close stellar companion. There are other assumptions often approximated as the internal cause of enhanced extra mixing: that is, thermohaline instabilities and magnetic buoyancy. The thermohaline convection driven by the \(^{3}\)He/\(^{4}\)He reaction, which produces a local depression in the mean molecular weight, can cause enhanced extra mixing inside the star. The magnetic buoyancy mechanism in the presence of a magnetic dynamo would permit the buoyancy of magnetized material near the hydrogen-burning shell, thus inducing the formation of matter circulation in RGB stars\(^{2}\). We speculate that the magnetic buoyancy and thermohaline instabilities might play roles together during the mass circulation, in which the former may lead to very fast upward circulation and the latter drive downward circulation at a much slower speed.

Although the A\(_{\text{eff}}\) measured in this star is very high, it is still well within the upper limit that the theoretical model could reach. It is also important to note that the RGB bump is not the only stage for inhabitation of Li-rich giants; many Li-rich giants have been reported in various stages in previous studies, including those in the core helium-burning phase, which is very close to the RGB bump region on the Hertzprung–Russell diagram. Although our data do not support this as the most likely mechanism, if our star occupies this stage, an alternative scenario will be needed for our interpretation such a high A\(_{\text{eff}}\).

### Methods

**Data reduction.** We followed the standard procedure for data reduction with an Interactive Data Language (IDL) package, which was originally designed for the fibre optics Cassegrain échelle spectrophotometer\(^{15}\). The instrumental response and background scatter light were considered during the reduction, and cosmic rays and bad pixels were removed carefully. The resulting spectrum has a signal-to-noise ratio of ~160 at 6,707.8 Å.

**Deriving the stellar parameters.** First, we combined three iron line lists\(^{26\text{-}28}\) and calibrated 213 lines out of 257 with the solar spectrum\(^{29}\). Then, we eliminated those severely blended or poorly recognized lines seen from the spectrum of TYC 429-2097-1, as well as the lines that were too strong (>120 mÅ) or too weak (<20 mÅ). Finally, 57 Fe i and 12 Fe ii lines were used as the parameter indicators. The final A\(_{\text{eff}}\) was derived from the excitation equilibrium of Fe i lines with an excitation energy (E\(_{\text{exc}}\)) greater than 2.0 eV\(^{30}\). The \(\log[g]\) value was determined by equalizing the two sets of iron abundances obtained from the Fe i and Fe ii lines, respectively. Statistically, the iron abundance derived from each individual Fe i line and the equivalent width from the same Fe i line will be mutually independent if the micro-turbulence velocity (\(\xi\)) is correctly set. Using this trick, we can obtain \(\xi\), and then the metallicity ([Fe/H]) can be settled simultaneously if all the mentioned constraints are achieved. All the iron abundances are derived from NLTE analysis with the MARCS atmospheric models\(^{31}\) since it has been suggested that Fe i lines suffer a non-negligible NLTE effect.\(^{32}\) The procedure of this approach is much more like an iteration. We started with the results from the LAMOST pipeline as the initial input, and then by calculating MARCS models and adjusting the stellar parameters step by step, we finally ended up with a self-consistent solution. Supplementary Fig. 3 shows the derived iron abundances from individual lines as functions of their equivalent widths (top panel) and E\(_{\text{exc}}\) (bottom panel). Based on the experience of our previous work using the similar spectroscopic method, the errors for \(\log[g]\), [Fe/H] and \(\xi\) are estimated to be ±0.08 K, ±0.10 dex, ±0.06 dex and ±0.10 km s\(^{-1}\), respectively.

**Determination of the elemental abundances.** We used the spectrum synthesis method to derive the abundances of all the species discussed in this paper. The theoretical profiles of the corresponding lines were calculated based on the MARCS I.1.0 code and the Synthetic Spectral LibraIy (SLOI) was applied to calculate the synthetic line profiles. The coupled radiative transfer and statistical equilibrium equations for the NLTE calculation were solved based on the accelerated lambda iteration method. We refer readers to Mashonkina et al.\(^{14}\) for a more detailed description of this method\(^\text{-}2\). The resulting departure files were transferred into SIU for NLTE line synthesis. The solar abundance of log\([\text{Fe/H}]\) = 7.5 was assumed in our work.

In the abundance analysis of Li, the resonance line at 6,707.8 Å, the subresonate line at 6,103.6 Å and the line at 8,126.3 Å\(^{30\text{-}32}\) were used to derive \(A_{\text{Li}}\). Although the line at 8,126.3 Å is blended with two telluric lines, it shows a similar result to those derived from the resonance and subordinate lines. The final \(A_{\text{Li}}\), was determined by averaging the results from these three lines. Many previous studies note that NLTE corrections are important for strong lines. In general, the NLTE correction for Li is not large for the ‘Li-normal’ stars; however, it will significantly increase for Li-rich objects, especially for the strong resonance line at 6,707.8 Å. In very extreme cases (such as ours), the local thermodynamic equilibrium (LTE) theoretical profile of 6,707.8 Å could be saturated at the core. Therefore, the NLTE effects were taken into consideration in our abundance analysis for Li. For the NLTE analysis, we applied the same atomic model and line data as those presented by Shi et al.\(^{33}\).

The carbon abundances were derived from the C i line at 5,086 Å and the line at 8,126.3 Å\(^{32}\) were used to derive \(A_{\text{C}}\). We estimated their errors by giving the upper and lower limit of the best fit to the profile. The variation caused by the error of the effective temperature as the uncertainty for \(T_{\text{eff}}\) is 

\[
T_{\text{eff}} \pm 1 \, \text{K} \quad \text{or} \quad \log\[g] \pm 0.10 \, \text{dex} \quad \text{or} \quad \text{[Fe/H]} \pm 0.06 \, \text{dex}
\]

The variation caused by the effective temperature as the uncertainty for \(T_{\text{eff}}\) is 

\[
T_{\text{eff}} \pm 1 \, \text{K} \quad \text{or} \quad \log\[g] \pm 0.10 \, \text{dex} \quad \text{or} \quad \text{[Fe/H]} \pm 0.06 \, \text{dex}
\]

The maximum likelihood method and evolutionary stage. The likelihood function is expressed following Basu et al.\(^{38}\), which is defined as:

\[
L = L_{\text{obs}} L_{\text{obs}} L_{\text{obs}} \cdots \cdot \cdot \cdot
\]

where \(L_{\text{obs}}\) is the observed parameter (for example, \(T_{\text{eff}}\)) and

\[
L_{\text{obs}} = \frac{1}{\sqrt{2\pi \sigma_{\text{obs}}}} \exp \left(-\frac{(P_{\text{obs}} - P_{\text{model}})^2}{2\sigma_{\text{obs}}^2} \right)
\]

The normalized probability of each model \(P\) is expressed as

\[
P = \frac{L}{\sum L_i}
\]

where \(L_i\) is the likelihood function of the ith model and \(N_i\) is the total number of models. The probability was calculated by fitting the observed probability with the 3σ error range of the observed parameters. Thus, the maximum value of the integrated probability is 0.5, and the best-fitted parameters are obtained from this probability (ref. \(\text{16}\)).
Projected rotational velocity. Following the assumption of Bruntt et al. 3, the external broadening of the line profile was assumed to be contributed to by the stellar rotation, instrumental broadening and macro-turbulence. The projected rotational velocity (\(v \sin i\)) was derived using 5 isolated iron lines at 6153, 6160, 6380, 6703 and 6810 Å. The instrumental broadening was calculated by fitting the emission lines of the arc lamp with a Gaussian profile. The macro-turbulence velocity was estimated using the relation of Hecker et al.53, which is a function of \(T_{\text{eff}}\) and \(\log [g]\). Then, we calculated a set of the theoretical spectra broadened with different rotational velocities, and \(v \sin i\) was determined by finding the best fit to the observed iron line profiles.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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References

1. Brown, J. A., Smeden, C., Lambert, D. L. & Duchovvsky, E. Jr A search for lithium-rich giant stars. Astrophys. J. Suppl. 71, 293–322 (1989).
2. Iben, I. Jr Stellar evolution. VI. Evolution from the main sequence to the red-giant branch for stars of mass 1 M\(_{\odot}\), 1.25 M\(_{\odot}\) and 1.5 M\(_{\odot}\). Astrophys. J. 147, 624 (1967).
3. Cyburt, R. H., Fields, B. D., Olive, K. A. & Yeh, T.-H. Big bang nucleosynthesis: present status. Rev. Mod. Phys. 88, 015004 (2016).
4. Spite, M. & Spite, F. Lithium abundance at the formation of the Galaxy. Nature 297, 483–485 (1982).
5. Tajitsu, A., Sadakane, K., Naito, H., Arai, A. & Aoki, W. Explosive lithium production in the classical nova V339 Del (Nova Delphini 2013). Nature 518, 381–384 (2015).
6. Zinn, W. & West, A. R. Metallicity of open clusters. Astrophys. J. 510, 217–231 (1999).
7. Demisenkov, P. A. & Herwig, F. Enhanced extra mixing in low-mass red giants: lithium production and thermal stability. Astrophys. J. 612, 1081–1091 (2004).
8. Charbonnel, C. & Lagarde, N. Thermohaline instability and rotation-induced mixing. I. Low- and intermediate-mass solar metallicity stars up to the end of the RGB. Astron. J. 135, 217–231 (2013).
9. Wallerstein, G. & Soden, C. A K giant with an unusually high abundance of lithium—HD 112127. Astrophys. J. 255, 577–584 (1982).
10. Monaco, L. et al. Lithium-rich giants in the Galactic thick disk. Astron. Astrophys. 529, A90 (2011).
11. Kirby, E. N., Fu, X., Grahakshartka, P. & Deng, L. Discovery of super-Li-rich red giants in dwarf spheroidal galaxies. Astrophys. J. 752, L16 (2012).
12. Martell, S. L. & Shetrone, M. D. Lithium-rich field giants in the Sloan Digital Sky Survey. Mon. Not. R. Astron. Soc. 430, 611–620 (2013).
13. Adamów, M., Niedzielski, A., Villaver, E., Wolczan, A. & Nowak, G. The Penn State-Torun Centre for Astronomy Planet Search stars. II. Lithium abundance analysis of the Red Giant Clump sample. Astron. Astrophys. 569, A55 (2014).
14. Casey, A. R. et al. The Gaia-ESO survey: revisiting the Li-rich giant problem. Mon. Not. R. Astron. Soc. 461, 3336–3352 (2016).
15. Balachandran, S. C., Fekel, F. C., Henry, G. W. & Uitenbroek, H. Two K giants with supermetallic lithium abundances: HDE 233517 and HD 9746. Astrophys. J. 542, 978–988 (2000).
16. Reddy, B. E. & Lambert, D. L. Three Li-rich K giants: IRAS 13227-6523, 13359-4153, and 17596-3952. Astron. J. 129, 2831–2835 (2005).
17. Kirby, E. N. et al. Lithium-rich giants in globular clusters. Astrophys. J. 819, 135 (2016).
18. Silva Aguirre, V. et al. Old puzzle, new insight: a lithium-rich giant quietly burning helium in its core. Astrophys. J. 784, L16 (2014).
19. Gaia Collaboration et al. Gaia data release 1. Summary of the astrometric, photometric, and survey properties. Astron. Astrophys. 595, A2 (2016).
20. Alexander, J. B. A possible source of lithium in the atmospheres of some red giants. Observatory 87, 238–240 (1967).
21. Aguilera-Gómez, C., Chanamé, J., Pinsonneault, M. H. & Carlberg, J. K. On lithium-rich red giants: engulfment on the giant branch of Trumpler 20. Astrophys. J. 833, L24 (2016).
22. Cameron, A. G. W. & Fowler, W. A. Lithium and the s-process in red-giant stars. Astrophys. J. 161, 1 (1971).
23. Cyburt, R. H. et al. The JINA Reaclib Database: its recent updates and impact on type-I X-ray bursts. Astrophys. J. Suppl. 189, 240–252 (2010).
24. Busso, M., Wasserburg, G. J., Nollett, K. M. & Calandra, A. Can extra mixing in RGB and AGB stars be attributed to magnetic mechanisms? Astrophys. J. 669, 802–810 (2007).
25. Pfeiffer, M. J., Frank, C., Baumuller, D., Fuhrmann, K. & Gehren, T. FOCES—a fibre optics Cassegrain échelle spectrograph. Astron. Astrophys. Suppl. 130, 381–393 (1998).
26. Takeda, Y., Sato, B., Kambe, E., Sadakane, K. & Ohkubo, M. Spectroscopic determination of stellar atmospheric parameters: application to mid-F through early-K dwarfs and subgiants. *Publ. Astron. Soc. Jpn.* 54, 1041–1056 (2002).

27. Mashonkina, L., Gehren, T., Shi, J.-R., Korn, A. J. & Grupp, F. A non-LTE study of neutral and singly-ionized iron line spectra in 1D models of the Sun and selected late-type stars. *Astron. Astrophys.* 528, A87 (2011).

28. Carlberg, J. K., Cunha, K., Smith, V. V. & Majewski, S. R. Observable signatures of planet accretion in red giant stars. I. Rapid rotation and light element replenishment. *Astrophys. J.* 757, 109 (2012).

29. Kurucz, R. L., Furenlid, I., Braith, J. & Testerman, L. Solar flux atlas from 296 to 1300 nm. *National Solar Observatory Atlas*, 25–33 (National Solar Observatory, Sunspot, NM, 1984).

30. Sitnova, T. et al. Systematic non-LTE study of the ~2.6 < [Fe/H] < 0.2 F and G dwarfs in the solar neighborhood. I. Stellar temperature parameters. *Astron. Astrophys.* J. 808, 148 (2015).

31. Gustafsson, B. et al. A grid of MARCS model atmospheres for late-type stars. I. Methods and general properties. *Astron. Astrophys.* 486, 951–970 (2008).

32. Adamow, M. et al. Tracking advanced planetary systems (TAPAS) with HARPS-N II. Super Li-rich giant HD 107028. *Astron. Astrophys.* 581, A94 (2015).

33. Shi, J. R., Gehren, T., Zhang, H. W., Zeng, J. L. & Zhao, G. Lithium abundances in metal-poor stars. *Astron. Astrophys.* 465, 587–591 (2007).

34. Alexeeva, S. A. & Mashonkina, L. I. Carbon abundances of reference late-type stars from 1D analysis of atomic C I and molecular CH lines. *Mon. Not. R. Astron. Soc.* 453, 1619–1631 (2015).

35. Mashonkina, L. Astrophysical tests of atomic data important for the stellar Mg abundance determinations. *Astron. Astrophys.* 550, A28 (2013).

36. Zhang, J., Shi, J., Pan, K., Allende Prieto, C. & Liu, C. NLTE analysis of high-resolution H-band spectra. I. Neutral silicon. *Astrophys. J.* 833, 137 (2016).

37. Mashonkina, L., Korn, A. J. & Przybilla, N. A non-LTE study of neutral and singly-ionized calcium in late-type stars. *Astron. Astrophys.* 461, 261–275 (2007).

38. Basu, S., Chaplin, W. J. & Elsworth, Y. Determination of stellar radii from asteroseismic data. *Astrophys. J.* 710, 1596–1609 (2010).

39. Wu, Y.-Q. et al. Stellar parameters of main sequence turn-off star candidates observed with LAMOST and Kepler. *Res. Astron. Astrophys.* 17, 5 (2017).

40. Paxton, B. et al. Modules for experiments in stellar astrophysics (MESA). *Astron. Astrophys.* Suppl. 192, 3 (2011).

41. Grevesse, N. & Sauval, A. J. Standard solar composition. *Space Sci. Rev.* 85, 161–174 (1998).

42. Liu, S., Li, T. D., Li, L. H. & Yang, W. M. Solar models with revised abundance. *Astrophys. J.* 731, L42 (2011).

43. Asplund, M., Grevesse, N., Sauval, A. J. & Scott, P. The chemical composition of the Sun. *Annu. Rev. Astron. Astrophys.* 47, 481–522 (2009).

44. Rogers, F. J. & Nayfonov, A. Updated and expanded OPAL equation-of-state tables: implications for helioseismology. *Astrophys. J.* 576, 1064–1074 (2002).

45. Ferguson, J. W. et al. Low-temperature opacities. *Astrophys. J.* 623, 585–596 (2005).

46. Alonso, A., Arribas, S. & Martinez-Roger, C. The effective temperature scale of giant stars (F0-K5). II. Empirical calibration of Teff versus colours and [Fe/H]. *Astron. Astrophys. Suppl.* 140, 261–277 (1999).

47. Schaffler, E. F. & Finkbeiner, D. P. Measuring reddenning with Sloan Digital Sky Survey stellar spectra and recalibrating SFD. *Astrophys. J.* 737, 103 (2011).

48. Nollett, K. M., Busso, M. & Wasserburg, G. J. Cool bottom processes on the thermally pulsing asymptotic giant branch and the isotopic composition of circumstellar dust grains. *Astrophys. J.* 582, 1036–1058 (2003).

49. Angulo, C. et al. A compilation of charged-particle induced thermonuclear reaction rates. *Nucl. Phys. A* 656, 3–183 (1999).

50. Du, X. et al. Determination of astrophysical B(p, p)B reaction rates from the G+, Gli resonance. *Sci. China Phys. Mech. Astron.* 58, 062001 (2015).

51. Bruntt, H. et al. Accurate fundamental parameters for 23 bright solar-type stars. *Mon. Not. R. Astron. Soc.* 405, 1907 (2010).

52. Heckert, S. & Meléndez, J. Precise radial velocities of giant stars. III. Spectroscopic stellar parameters. *Astron. Astrophys.* 475, 1003 (2007).

53. Kumar, Y. B., Reddy, B. E. & Lambert, D. L. Origin of lithium enrichment in K giants. *Astrophys. J.* 730, L12 (2011).

54. De La Reza, R. & da Silva, L. Lithium abundances in strong lithium K giant stars: LTE and non-LTE analyses. *Astrophys. J.* 439, 917–927 (1995).

55. Kumar, Y. B. & Reddy, B. E. HD 77361: a new case of super Li-rich K giant with anomalous low12C/13C ratio. *Astrophys. J.* 703, L46–L50 (2009).

56. Ruchti, G. R. et al. Metal-poor lithium-rich giants in the Radial Velocity Experiment Survey. *Astrophys. J.* 743, 107 (2011).

57. Carlberg, J. K. et al. The puzzling Li-rich giant associated with NGC 6819. *Astrophys. J.* 802, 7 (2015).

58. Lind, K., Asplund, M. & Barklem, P. S. Departures from LTE for neutral Li in late-type stars. *Astron. Astrophys.* 503, 541–544 (2009).

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Author contributions

H.-L.Y., J.-R.S. and G.Z. proposed and designed the study; H.-L.Y. and J.-R.S. led the data analysis, with contributions from Y.-T.Z., Q.G., J.-B.Z. and Z.-M.Z. Y.-J.T., S.-Z., Z.-H.L., B.G. and W.-P.L. performed the nuclear calculations. S.-L.B. and Y.-Q.W. calculated the evolutionary models and tracks. H.-N.L. carried out the observations. All authors discussed the results and contributed to the writing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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