The nature of the Li enrichment in the most Li-rich giant star (postprint)

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Abstract

About 1% of giants have anomalously high Li abundances in their atmospheres, conflicting directly with the prediction of the standard stellar evolution models. This finding makes the production and evolution of Li in the Universe intriguing, not only in the sense of Big Bang nucleosynthesis or the interstellar medium, but also for the evolution of stars. Decades of efforts have been put into explaining why such extreme objects exist, yet the origins of Lirich giants are still being debated. Here we report the discovery of the most Li-rich giant known to date, with a very high Li abundance 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 Li abundance 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 7Be transportation during the red giant phase.

Full Text

Preamble

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About 1% of giants have anomalously high Li abundances in their atmospheres, conflicting directly with the predictions of standard stellar evolution models. This finding makes the production and evolution of Li in the Universe intriguing, not only in the sense of Big Bang nucleosynthesis and the interstellar medium, but also for the evolution of stars. Decades of effort have been put into explaining why such extreme objects exist, 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 Li abundance 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 Li abundance 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 from both observational and theoretical points of view, suggesting that low-mass giants can internally produce Li to a very high level through ^{7}Be transportation 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 in red giants. This explains why the first discovery of a Li-rich giant evoked great interest in exploring and understanding Li-rich objects. However, only about 150 Li-rich giants have been found in the past three decades, and 20 of them were found to be super Li-rich with Li abundances higher than 3.3. Considering the NLTE corrections, three stars were found to be at a level of A(Li) > 4.0. Such rare objects could provide a great opportunity to reveal the nature of the phenomenon of Li-richness because high Li abundance cannot be maintained for a long time due to frequent convection activity.

Taking advantage of the powerful spectral collection capability of 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 Li absorption line (see Fig. 1 [Figure 1: see original paper], panel a). We then made a follow-up high-resolution observation with the 2.4-m Automated Planet Finder Telescope (APF) located at Lick Observatory on June 23, 2015. The spectrum covers a wavelength range of 374 nm–970 nm with a resolution of 80,000. The total integration time was 1.5 hours and was divided into three single exposures (30 minutes each) for better subtraction of cosmic rays. The spectrum of TYC 429-2097-1 obtained from APF is presented in Fig. 1, panels (b) and (e), 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' section for details). The final derived parameters of TYC 429-2097-1 and the estimated errors are presented in Table 1 . The NLTE Li abundances for 6707.8 Å, 6103.6 Å, and 8126.3 Å are 4.42$±0.09, 4.51±0.09, *and*4.60±$0.08, respectively. The averaged Li abundance is A(Li) = 4.51 ± 0.09. Compared to previous studies, TYC 429-2097-1 has the highest Li abundance among all Li-rich giants ever discovered (see Fig. 2 [Figure 2: see original paper]). The Li abundance in TYC 429-2097-1 is about 1,000 times as high as the widely-used Li-rich 'standard' of A(Li)=1.5 (the lower purple dashed line in Fig. 2), despite this 'standard' being suggested to be luminosity-dependent. It is also about 15 times as high as the meteoritic Li abundance (the upper purple dashed line in Fig. 2), which is thought to be the initial Li abundance for newly-formed young stars.

Although Li-rich giants have been reported at various stages, such as the RGB and core He-burning phases, the Li-rich phase is likely to be a short-term event. An extremely Li-rich giant (possibly newly enriched) with rigorous investigation of its evolutionary stage would be definitely important. The location of the star was derived by the maximum likelihood method using the observed parameters (in this case, T ff, log g, and [Fe/H] derived from the spectroscopic method) and a grid of evolutionary models computed with the MESA code (see the 'Methods' section for details). The derived luminosity and mass are log(L/L)=1.95 and M =1.43 M , respectively. We used the parallax from Gaia DR1 to independently test the reliability of the information derived from the maximum likelihood method. The luminosity obtained from Gaia data leads to a very similar result of log(L_{Gaia}/L)=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 g of 2.25. As expected, the final result is log g_{Gaia} = 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 (H-R diagram) along with the corresponding MESA tracks (see Supplementary Figure 1). The star is likely occupying the region of the RGB-bump, a stage in which the µ-barrier is destroyed and enhanced 'extra-mixing' might be ongoing inside the star.

In addition, we also estimated the ^{12}C/^{13}C ratio as it has been suggested that extra mixing will cause a decrease of ^{12}C/^{13}C to the range of 10–20. We found that the ^{12}C/^{13}C ratio in this star is 12.0 ± 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 Li enrichment could be due to contaminations by external sources in the environment, such as the engulfment of a substellar component (e.g., giant planets or brown dwarfs) and the accretion from a 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 by this mechanism is 2.2. Our star has a much higher Li abundance than any of those values, thus it is very unlikely that the overabundant Li comes from the direct contribution of external sources.

The internal production of Li, on the other hand, is based on the Cameron-Fowler mechanism (CF mechanism). The production of ^{7}Be takes place where the temperature is too high to preserve the newly synthesized ^{7}Li, hence ^{7}Be must be transported quickly to a cooler region to form Li. This scenario would potentially require low-mass giants to evolve to the RGB-bump, where the mean molecular weight discontinuity (or µ-barrier, a mass gradient caused by FDU) is erased. Meanwhile, it would need the presence of deep, enhanced 'extra mixing' (EM) to increase the depth and efficiency of convective circulation, which in turn alters the ^{12}C/^{13}C ratio to a lower level than that after FDU. The observational features on both the evolutionary stage and ^{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 made such simulations with a series of parameters. By using the RGB stellar structure as the input for the EM calculation, with updated nuclear reaction rates and the asymmetric parameters of the EM model, we found that A(Li) in the envelope can exceed 4.0 for the processed material when the mass circulation finishes.

Our EM calculation with parameters of M = 52, Δ=0.15, f_d=0.1 (see the 'Methods' section for details) yields A(Li)=4.506, where M is the rate of mass transport in units of 10^{-6} M yr^{-1}, Δ is log T_H − log T_p, where T_H is the temperature at which the energy released from the H-burning shell reaches maximum and T_p 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 Li abundance 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 abundance of A(Li)=4.515. As 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 conserved in the EM process.

The cause of the EM has not been well understood, and rotationally induced mixing is often attempted. Indeed, TYC 429-2097-1 is a slightly rapid rotator with a projected velocity of 11.3 km s^{-1}, which is about ten times faster than that for normal giants. The spinning up of an RGB star is either caused by tidal synchronization effects in a close binary system or the engulfment of a massive planet. We calculated the radial velocities based on the two independent observations through LAMOST and APF (with an interval of 10 months), and found no significant radial velocity change at a level of a few kilometers per second, which is the typical uncertainty for the RV derived from LAMOST spectra. Thus it is very unlikely that the star has a stellar companion which is massive and close enough to spin up via tidal synchronization. On the other hand, 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 for Li-rich giants exhibiting excess in the infrared (IR) flux, yet we found no sign of IR excess (see Supplementary Figure 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 α-abundance is also quite normal among 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, i.e., thermohaline instabilities and magnetic buoyancy. The thermohaline convection driven by the $^{3}He(^{3}He,2p)^{4}He$ 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 H-burning shell, thus inducing the form of matter circulation in RGB stars. We speculate that 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 Li abundance measured in this star is super 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 by previous work, including the core He-burning phase, which is very close to the RGB-bump region on the H-R diagram. Although it is not preferred by our data, if our star occupies this stage, a new scenario will be in urgent need for interpreting such high Li abundance.

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Methods

Data Reduction

We followed the standard procedure for data reduction with an Interactive Data Language (IDL) package, which was originally designed for the FOCES spectrograph. 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 6707.8 Å.

Deriving the Stellar Parameters

We first combined three iron line lists and calibrated 213 lines out of 257 with the solar spectrum. Then we eliminated those seriously blended or poorly recognized lines seen in the spectrum of TYC 429-2097-1, as well as lines that are too strong (>120 mÅ) or too weak (<20 mÅ). Finally, 57 Fe I and 12 Fe II lines are used as the parameter indicators. The effective temperature (T ff) is derived from the excitation equilibrium of Fe I lines with excitation energy (E c) greater than 2.0 eV. The surface gravity (log g) is approached by equalizing the two sets of Fe abundances obtained from Fe I and Fe II lines, respectively. Statistically, the Fe abundance derived from each individual Fe I line and the equivalent width (EW) from the same Fe I line will be mutually independent if the micro-turbulence velocity ( ) is correctly set. Using this approach, we can obtain , and then the metallicity ([Fe/H]) can be settled simultaneously if all the mentioned constraints are achieved. All the Fe abundances are derived from NLTE analysis with the MARCS atmospheric models since it has been suggested that Fe I lines suffer a non-negligible NLTE effect. The procedure of this approach is much 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 end up with a self-consistent solution. Supplementary Figure 3 shows the derived Fe abundances from individual lines as functions of their EWs (upper panel) and E c (lower panel). Based on the experience of our previous work using similar spectroscopic methods, the errors for T ff, log g, [Fe/H] and are estimated to be $±$80 K, $±$0.10 dex, $±$0.06 dex and $±0.10*kms*^{-1}$, respectively.

Determination of the Elemental Abundances

For all the species discussed in this paper, we use the spectrum synthesis method to derive their abundances. The theoretical profiles of the corresponding lines are calculated based on the MARCS model. An interactive IDL code Spectrum Investigation Utility (SIU) was applied to calculate the synthetic line profiles. The coupled radiative transfer and statistical equilibrium equations for the NLTE calculation were solved following the efficient method with a revised DETAIL program based on the accelerated lambda iteration; we refer readers to Mashonkina et al. (2011) for a more detailed description of this method. The resulting departure files are transferred into SIU for NLTE line synthesis. The solar iron abundance of log = 7.5 was assumed in our work.

In the abundance analysis of Li, the resonance line at 6707.8 Å, the subordinate line at 6103.6 Å, and the line at 8126.3 Å were used to derive the Li abundance. Although the line at 8126.3 Å is blended with two telluric lines, it shows a similar result to those derived from the resonance and subordinate lines. The final Li abundance is determined by averaging the results from these three lines. It has been noted by many previous studies that the NLTE corrections are important for strong lines. In general, the NLTE correction for Li is not large for 'Li-normal' stars; however, it will significantly increase for Li-rich objects, especially for the strong resonance line at 6707.8 Å. In very extreme cases (such as ours), the local thermodynamic equilibrium (LTE) theoretical profile of 6707.8 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 in Shi et al. 2007. The carbon abundances were derived from the C I line at 5086 Å and the C_2 line at 5135 Å. The nitrogen lines were either blended or too weak in our spectrum, so we turned to the CN band near 8003.5 Å to estimate the N abundance by fixing C to the value we just derived. Then the carbon isotopic ratio was determined by adjusting the contributions from ^{12}C and ^{13}C until we obtained the best fit to the observed CN band profile. The determination of α-abundance (Mg, Si, and Ca) with NLTE analysis was based on a series of previous studies. The final α-abundance was obtained by averaging the abundances obtained from those elements. We also derived abundances of several other elements, which can be found in Supplementary Table 1.

The error of the Li abundance was estimated by changing the stellar parameters (namely T ff, log g, and [Fe/H]) within their error ranges and calculating the corresponding variations in the abundance. The result of this test is presented in Supplementary Table 2 . It is clear that the Li abundance is more sensitive to the variation of T ff than to that of log g or [Fe/H]. A change of 80 K in T ff will result in a variation of 0.09 dex for the Li abundance. Thus, we adopted the variation caused by the error of the effective temperature as the uncertainty for each Li I line, which is $±$0.09, $±$0.09, and $±$0.08 for the lines at 6707.8 Å, 6103.6 Å, and 8126.3 Å, respectively. The error of the final Li abundance is obtained by calculating the standard deviation of abundances derived from the three lines. For the other elements, if more than three lines are used for the abundance determination, we calculate their standard deviation and compare it to the error caused by the uncertainties of the stellar parameters, and the larger one was adopted as the final error. For a few species such as the ^{12}C/^{13}C ratio that were not suitable for the above analysis, we estimated their errors by giving the upper and lower limits of the best-fit to the profile.

Maximum Likelihood Method and Evolutionary Stage

The likelihood function is expressed following Basu et al., which is defined as:

$$L = LP_{obs1}LP_{obs2}LP_{obs3}\cdots,$$

where P b is the observed parameter (e.g., T ff) and LP b = $(1/\sqrt{}(2\pi\sigma^2))$ exp[-(P b - P d)$^2/(2\sigma^2)$]. The normalized probability of each model p is expressed as:

$$p_i = L_i/(\sum_{i=1}^{N_m} L_i),$$

where L is the likelihood function of the ith model and N is the total number of models. The probability is integrated from the boundary constrained by 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.

The grid of evolutionary models for calculating the likelihood are generated from MESA code. The grid covers a wide range of mass from 0.6–3.0 M with a 0.02 M interval on mass and a 0.005 interval on metallicity (Z). The evolution tracks are constructed from the pre-main sequence to the asymptotic giant branch (AGB) phase. For generating the grid, the initial parameter setup was mostly the same as described in Paxton et al. except for the solar chemical abundance (Z/X) . We adopted (Z/X) = 0.0229 because a calibrated solar model with this mixture fits the internal structures from helioseismology slightly better than the others. The MESA -T inversion tables are based on an updated version of Rogers & Nayfonov tables extended the opacity for the solar composition to the low-temperature case in 2015, and we adopted their results in our computation. The stellar metallicity was transferred into 'metal' abundance Z , from which the hydrogen and helium abundances (X and Y) were calculated.

To obtain the luminosity and log g_{Gaia} from the parallax, we first calculated the bolometric magnitude for the absolute V magnitude by M_{bol} = V_{mag} + BC + 5 log π + 5 - A_V (in this equation, π is used in the unit of arcsec), where the bolometric correction BC was computed following Alonso et al. and A_V was estimated by the Galactic extinction map presented by Schlafly & Finkbeiner (2011) (all values that were needed for the calculation are presented in Supplementary Table). We calculated the luminosity using the relation M_{bol} - M_{bol} = -2.5 log(L_{Gaia}/L), where M_{bol} = 4.74 mag. Finally, the log g_{Gaia} was determined following the fundamental relation log g = log g + log(M/M) + 0.4(M_{bol} - M_{bol}) - 4 log(T ff/T ff), where log g = 4.44, M = 1.36 M , T ff = 5777 K, and M_{bol} = 4.74 mag. The errors were given via the uncertainty transfer formula assuming that the errors were contributed by the uncertainty of the Gaia parallax.

Parametric Calculation of Internal Li-enriching

During the RGB stage of a low-mass star, we introduced the 'extra-mixing' or the 'circulation process' after the H-burning shell has erased the chemical discontinuity left behind by FDU, signatured by the bump of the luminosity function in RGB. We followed the parameterization of Nollett et al. to perform the parametric calculations using M, T_p, f_d and f_u as free parameters.

The basic assumptions are described as follows. The EM is a process of meridional circulation in the radiative zone of low-mass red giant stars; the path of mass flow looks like a 'conveyor belt' . A parcel of material with the initial abundance composition Y_E(0) at the base of the convective envelope circulates downward through the radiative zone structure and finally returns to the envelope with newly processed abundance composition Y_P(i). The velocity of the sampled material can be expressed as dr/dt = M / (f $4\pi r^2$), where f is equal to f_d (or f_u) for the downward (or upward) circulation, and the density is a function of radius r, governed by the stellar structure. The stellar structure, M and Δ specify as functions of time, the conditions of temperature T and density where the material passes through.

The computing code integrates the network of reactions of the hydrogen burning chain by following the circulation trajectory. The nuclear reaction rates adopted are from NACRE except for two rates: the updated rate of ^{7}Be(p, γ)^{8}B is from Du et al. 2015 and the rate of ^{7}Be(e,)^{7}Li from the JINA database. The convective overturn-time of the envelope is set to 1 yr, which is a good approximation in the sense that the mixing between the processed material and the convective envelope is instantaneous. The abundance of the i-th nucleus changes in the envelope during the transport due to nucleosynthesis and material replacement, and this corresponds to integrating dY_E/dt = (M/M_E)(Y_P - Y_E(0)), where M_E is the mass of convective envelope. In order to obtain the RGB stellar structure, including in particular the initial abundance composition in the envelope and the distributions of temperature and density in the radiative zone, we calculated the stellar evolution model for M = 1.36 M by the MESA code. The initial abundance of ^{7}Li in the sample material at the base of the envelope is 1.024×10^{-11} (A(Li)=1.86) obtained from the present stellar evolutionary model calculation, and the ^{7}Li abundance may increase to a level of A(Li) exceeding 4 in the processed material when the mass circulation finishes.

During the downward mass circulation, the abundance of ^{7}Be increases quickly because the construction reaction ^{3}He(^{4}He, γ)^{7}Be wins against the destruction reaction ^{7}Be(p, γ)^{8}B, and the maximum yield of ^{7}Be is around the turning point of the mass circulation, where the temperature reaches the highest value T_p. In contrast, the production change of ^{7}Li behaves rather dramatically during the downward mass circulation due to the complex competition between the production reaction ^{7}Be(e$^-$,)^{7}Li and the destruction reactions ^{7}Li(p, γ)^{8}Be and ^{7}Li(p, α)^{4}He. The abundance of ^{7}Li drops suddenly at about 200 yrs of the processing time as the rates of destruction reactions increase quickly with increasing temperature, and the ^{7}Li abundance keeps very low during the downward mass circulation although it increases slightly after about 230 yrs due to the decay of fast-growing abundant ^{7}Be. In contrast, the abundance of ^{7}Li increases sharply during the upward mass circulation due to the fast decreasing of the destruction reaction rates of ^{7}Li as the temperature decreases quickly. The processed Li abundance finally reaches a super-high level of A(Li)=4.506. The abundance of ^{7}Li in the envelope contains the contributions of the mass circulation and mass replacement processes, and the total processing time can be estimated as M_E/M, which is about 2.1×10^4 yrs by using the average value of the envelope mass for this RGB star.

The Projected Rotational Velocity

Following the assumption of Bruntt et al., the external broadening of the line profile was assumed to be contributed from stellar rotation, instrumental broadening, and macro-turbulence. The projected rotational velocity (v sin i) was derived using five isolated iron lines at 6151 Å, 6229 Å, 6380 Å, 6703 Å, and 6810 Å. The instrumental broadening was calculated from fitting the emission lines of the arc lamp with a Gaussian profile. The macro-turbulence velocity was estimated using the relation of Hekker et al., which is a function of T ff and log g. Then we calculated a set of theoretical spectra broadened with different rotational velocities, and v sin i was determined by finding the best fit to the observed iron line profiles.

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Supplementary Information

Supplementary Table 1. Other information of TYC 429-2097-1

Property	Value
Position (J2000)	17:53:46.07 +06:42:41.20
V (mag)	11.27 (UCAC4)
Gaia parallax π (milli-arcsec)	0.73 ± 0.24
M (M)	1.43 +0.55 -0.54
log(L/L)	1.95 +0.25 -0.19
log(L_{Gaia}/L)	2.00 ± 0.06
log g_{Gaia}	2.23 ± 0.16
^{12}C/^{13}C	12.0 ± 3.0
v sin i (km s^{-1})	11.3 ± 1.5
[α/Fe]	0.19 ± 0.04

Property	Value
[C/Fe]	-0.27
[N/Fe]	0.45 ± 0.10
[Mg/Fe]	0.23 ± 0.05
[Si/Fe]	0.19 ± 0.01
[Ca/Fe]	0.16 ± 0.06

Supplementary Table 2. The variation of Li abundance caused by the uncertainties of stellar parameters

Wavelength	ΔT ff (80 K)	Δlog g (0.10 dex)	Δ[Fe/H] (0.06 dex)
6103.6 Å	$±$0.09	$±$0.02	$±$0.01
6707.8 Å	$±$0.09	$±$0.02	$±$0.01
8126.3 Å	$±$0.08	$±$0.02	$±$0.01

Supplementary Figure 1. The evolutionary tracks computed from the MESA code for TYC 429-2097-1. The mass range of the tracks is from 1.0 M (bottom) to 1.8 M (top), with an interval of 0.2 M . The evolutionary stages for each track are indicated with different colors: black -SGB, dark blue -RGB, red -RGB-bump, and orange -RGB tip. The position of TYC 429-2097-1 is indicated with a black dot. The error bars indicate the uncertainties in T ff and log g, which are adopted to be $±$80 K and 0.10 dex from our stellar parameters determination method.

Supplementary Figure 2. The IR-excess diagram for TYC 429-2097-1. TYC 429-2097-1 is indicated with a red dot, while the other stars are from Rebull et al. 2015. The horizontal line at A(Li) = 1.5 shows the adopted division between Li-rich and normal stars, and the vertical line at [3.4] -[22] = 0 indicates the photospheric locus. The blue dots denote objects with strong IR excess, while the black dots represent stars with no significant IR excess.

Supplementary Figure 3. The determination of the stellar parameters. The figure shows the absolute NLTE abundance from lines of Fe I (red open circles) and Fe II (blue dots) in TYC 429-2097-1 as functions of their EWs (top panel) and E c (bottom panel). The slopes are indicated in the corresponding panel. The mean A(Fe) averaged from Fe I and Fe II lines is shown with a dash-dotted line in both panels. The final stellar parameters are denoted in the sequence of T ff (K), log g, [Fe/H], and (km s^{-1}) in the bottom panel.

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Author Contributions

H.-L.Y., J.-R.S. and G.Z. proposed and designed this 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.-S.C., E.-T.L., 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 observation. All the authors discussed the results and contributed to the writing of the manuscript.

Author Information

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