Spectroscopic study of two new super Li rich red clump K giants

Raghubar Singh$^1$⋆, Bacham E. Reddy$^1$ and Yerra Bharat Kumar$^{2,3}$

$^1$Indian Institute of Astrophysics, Koramangala, Bangalore, 560064, India
$^2$ Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
$^3$ LAMOST Fellow

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

In this paper, we report the discovery of two new super Li-rich K giants: HD 24960 and TYC 1751-1713-1. Based on high resolution ($R \approx 60,000$) spectroscopy, we have derived Li abundance of $A(\text{Li}) \approx 4.0$ dex for both stars. Other elemental abundances are normal of typical K giants. Low ratios of $[\text{C}/\text{N}] \leq -0.25$ and $^{12}\text{C}/^{13}\text{C} \leq 10$ suggest that the stars are in upper RGB phase. Further, based on Gaia astrometry and secondary calibrations using Kepler asteroseismic and LAMOST spectroscopic data, we argue that both stars belong to red clump (RC) phase with core He-burning. Results add to half a dozen already known red clump Li-rich K giants, and support the growing evidence that the origin of Li excess in RC giants seems to be associated with either He-flash at the tip of the red giant branch (RGB) or recent planet/ brown dwarf merger events closer to the RGB tip.

Key words: stars:low mass – stars: red giants – stars: red clump – stars: Li-rich – stars: atmospheres – stars: interiors

1 INTRODUCTION

Standard stellar models (Iben 1967a,b) predict significant changes, as a result of 1st dredge-up on red giant branch (RGB), to photospheric abundances of some key isotopes of RGB stars: decrease in Li, $^{12}\text{C}$ and increase in $^{13}\text{C}$ and $^{14}\text{N}$ (Charbonnel 2005). Models predict ratio of $^{12}\text{C}/^{13}\text{C}$ in the range of 20 to 25 (Charbonnel 1994) from their main sequence value of about 89 (Asplund et al. 2009). Similarly, Li is predicted to be a factor of about 30-70 less in RGB stars after the 1st dredge-up compared to their progenitors on the main sequence (Iben 1967a, Lagarde et al. 2012). However, standard models do not predict further changes to abundances beyond the 1st dredge-up (Iben 1967a).

In general, 1st dredge-up predictions agree well with the observations of RGB stars below the luminosity bump. However, giants at or above the bump, contrary to the standard predictions, show significantly changed abundances from the 1st dredge-up (Lind et al. 2009b, Kirby et al. 2016). The changes are in the same direction as 1st dredge-up but much severe. For example $^{12}\text{C}/^{13}\text{C}$ drops to less than 10 in most cases, and in some cases as low as its equilibrium value of 3 to 4 (Gilroy 1989, Gilroy & Brown 1991). Similarly, observed Li abundance in upper RGB stars is significantly low with typical value of $A(\text{Li}) \leq 0.5$ dex (e.g. Brown et al. 1989) which is about three magnitudes less than the initial maximum main-sequence value of $A(\text{Li})\sim 3.2$ dex (Lambert & Reddy 2004). The rapid decrease of carbon isotopes post-1st dredge-up is attributed to some kind of extra-mixing during stellar evolution through luminosity bump (Denissenkov & VandenBerg 2003). It is not known what exactly causes extra-mixing. However, there are a number of possible mechanisms such as thermohaline mixing (Eggleton et al. 2006), magneto-thermohaline mixing (Denissenkov et al. 2009), rotationally induced mixing (Denissenkov & Herwig 2004) etc. The general understanding is that it happens at the luminosity bump at which H-burning shell advances upward causing the removal of chemical composition discontinuity (Christensen-Dalsgaard 2015), a barrier to mixing, left behind by the 1st dredge-up. The removal of discontinuity in the abundance profile revives the mixing with the outer convective envelope resulting further reduction in the values of $^{12}\text{C}/^{13}\text{C}$ and Li abundance.

Against these general observational trend and theoretical predictions, a small group of low mass RGB stars show large amounts of Li, $A(\text{Li}) \geq 1.5$ dex (e.g Kumar et al. 2011). In some giants enhancements are 2 to 4 orders of magnitude above the expected values, exceeding the initial maximum main sequence or ISM values of $A(\text{Li}) = 3.2$ dex (Knauth et al. 2003), which are known as super Li-rich giants (e.g.

⋆ E-mail: raghubar.singh@iiap.res.in

© 2018 The Authors
Kumar et al. 2011). Presently, there are close to 200 Li-rich K giants of which about 2 dozen are super Li-rich (e.g. Casey et al. 2016; Smiljanic et al. 2018).

In spite of finding a large number of Li-rich stars on RGB, there is no consensus on the origin of Li excess. One of the principal reasons for the continued debate may probably be due to lack of precise stellar evolutionary phase of Li-rich stars on RGB. Though Li-rich stars were reported to be across RGB starting from sub-giant phase (e.g. Martell & Shetrone 2013; Li et al. 2018) to all the way to red clump with He-core burning phase (e.g. Silva Aguirre et al. 2014; Bharat Kumar et al. 2018), majority of them are known to be concentrated in a narrow luminosity range of 1.4 \( \leq \log(L/L_\odot) \leq 2.0 \) overlapping with the luminosity bump region as well as the red clump region (Charbonnel & Balachandran 2000, Kumar et al. 2011). Since bump is associated with stellar internal changes many studies explored to explain the anomalous Li enhancement during the bump as a consequence of extra-mixing (e.g. Palacios et al. 2001).

However, the recent discovery of Li-rich K giants (e.g. Silva Aguirre et al. 2014; Bharat Kumar et al. 2018; Smiljanic et al. 2018) which are in Kepler or CoRoT field, and determining their evolutionary phase as red clump with He-core burning based on asteroseismic analysis (Bedding et al. 2011) shifted the focus of Li enhancement to the He-flash or post He-flash phase. Precise determination of stellar evolutionary phase of Li-rich stars on RGB has significant consequences as Li enhancement scenarios vary with evolutionary phase.

We report here high resolution spectroscopic analysis of two new super Li-rich K giants: HD 24960 and TYC 1751-1713-1 for which no prior spectroscopic analysis of elemental abundances is reported. Results in this paper will add to half a dozen known Li-rich K giants of red clump.

2 OBSERVATIONS

LAMOST\(^1\) low resolution (R=1800) spectra of the two stars in this study have been screened out from the spectra of much larger sample of K giants which have been scanned for finding new Li-rich K giants. Sample LAMOST spectra of two stars showing Li line at 6707 Å are shown in Fig 1 (top panels). Line at 6707 Å is quite strong and characteristic of unusual Li abundance (Bharat Kumar et al. 2018). Subsequently, the two candidate Li-rich K giants have been observed with 2.0-m Himalayan Chandra Telescope (HCT) equipped with the high resolution spectrograph or HESP (Hanle Echelle Spectrograph). Single spectrum of 10 minutes exposure for HD 24960 (\( m_v = 8.00 \)) and three spectra of 30 minutes exposure each for TYC 1751-1713-1 (\( m_v = 9.42 \)) are obtained. Spectra have good signal-to-noise ratio of SNR > 100.

Standard reduction procedure such as bias, flat field corrections, and extraction of one dimensional spectra of flux versus pixel has been followed using Image Reduction Analysis Facility (IRAF) tools. For identification and removal of atmospheric lines, we observed HD 5394, a bright hot star of spectral type BIV with very high rotational velocity of 

\( \text{vsini} = 265 \text{ Kms}^{-1} \) during the same night. Stellar spectra are wavelength calibrated using Th-Ar arc calibration spectra obtained immediately after each star’s observation. Finally spectra were continuum fitted for the measurement of equivalent widths (EWs). Cross correlation of stellar spectra with a template spectrum yields radial velocity (\( R_v \)) of \(-36.1 \text{ km s}^{-1} \) and \(5.06 \text{ km s}^{-1} \) for HD 24960 and TYC 1751-1713-1, respectively. Sample spectra of two stars in the regions of Li line at 6707 Å are shown in Figure 1 (bottom panels).

2.1 Analysis and Results

Abundances have been obtained for 24 chemical elements. For each element a number of representative lines of moderately strong, free of known blends and having reliable atomic data were identified based on a typical K giant, Arcturus

\(^1\) http://dr3.lamost.org/
(α-Boo) spectral atlas (Hinkle et al. 2000). Line strengths i.e. equivalent widths (EWs) are measured from continuum-normalized spectra using IRAF tools. Depending on line strengths and possible blends such as Hyper fine structure (HFS), abundances are derived either by matching observed spectra with the synthetic spectra or matching individual line EWs with the predicted EWs in case of clean lines with free of blends. For the analysis, we used LTE stellar atmospheric models from Kurucz (Castelli & Kurucz 2004), and the recently updated radiative transfer code MOOG 2013 version (Sneden 1973).

2.1.1 Atmospheric parameters
Atmospheric parameters: $T_{\text{eff}}$, log $g$, microturbulence velocity ($\xi$) and [Fe/H] have been derived using a set of well defined Fe i and Fe ii lines taken from the compilation of Reddy et al. (2003) and Ramírez & Allende Prieto (2011). A total of 40 Fe i and 10 Fe ii lines with EWs less than about 110 mÅ are used. Standard iterative procedure is adapted for deriving $T_{\text{eff}}$, log $g$ and $\xi$. We chose $T_{\text{eff}}$ and $\xi$ of an atmospheric model for which Fe i lines’ abundances are independent of their corresponding lower excitation potential (LEP) and their EWs, respectively. In case of log $g$, models are varied until neutral average Fe i abundance is equal to that of singly ionized Fe i abundance. Derived parameters along with the uncertainties are given in Table 1. Uncertainties are estimated by using sensitivity of abundance trends to changes in small steps to respective parameters. We find no appreciable effect on lines’ abundance versus LEP relation for a change up to $\delta T_{\text{eff}} = \pm 70$ K for TYC 1751-1713-1 and 35 K for HD 24960. Thus, $\pm 70$ K and 35 K is taken as uncertainty in the determination of $T_{\text{eff}}$. Also, values of $T_{\text{eff}}$ and log $g$ derived using photometry combined with Gaia parallaxes (Gaia Collaboration et al. 2018). Photometry is taken from from 2MASS (Skrutskie et al. 2006) and Simbad. The de-reddened colors of (V-K)$_{\odot}$ and (J-K)$_{\odot}$ combined with empirical relations from González Hernández & Bonifacio (2009) yield an average $T_{\text{eff}}$ of 4870±60 K for TYC 1751-1713-1 and 4800±80 K for HD 24960. Reddening value of E(B-V) = 0.09 is taken from dust maps (Green et al. 2015) in the direction of stellar sources. Values of log $g$ are also derived using a relation;

$$\log g = \log g_{\odot} + \log \left( \frac{M}{M_{\odot}} \right) - \log \left( \frac{L}{L_{\odot}} \right) + 4 \times \log \left( \frac{T_{\text{eff}}}{T_{\odot}} \right)$$

Masses are estimated using stellar evolutionary tracks (Paxton et al. 2018) with corresponding stellar metallicity that pass through respective positions of Luminosity and $T_{\text{eff}}$ in the HR-diagram. Derived $T_{\text{eff}}$ and log $g$ values using astrometry and photometry along with spectroscopic values are given in Table 1. Values are in good agreement within the quoted uncertainties. We adopt values from spectroscopic analysis.

2.1.2 Abundances
Lithium: Li abundance has been derived from resonance

\[ \text{Table 1. Derived stellar parameters of program stars.} \]

|         | TYC 1751-1713-1 | HD 24960 |
|---------|----------------|----------|
| RA      | 01:21:41.845   | 03:59:27.632 |
| DEC     | +25:15:06.79   | +36:19:06.53 |
| V (mag) | 9.42           | 8.00      |
| HESP Spectra SNR | 110          | 120      |
| Parallax (mas) | 1.95±0.04    | 3.67±0.04 |
| log g(gms$^{-2}$) | 2.58±0.17     | 2.39±0.19 |
| log g(photometric) | 2.45±0.04   | 2.40±0.03 |
| Teff [K] | 4830±70        | 4835±35   |
| Teff(photometric) | 4870±60       | 4800±80   |
| $\xi$ (kms$^{-1}$) | 1.47±0.15   | 1.41±0.04 |
| [Fe/Fe] | −0.25±0.10     | −0.45±0.04 |
| vsini (kms$^{-1}$) | 4.40±0.8     | 6.0±1     |
| $V_{\text{r}}$ (kms$^{-1}$) | 3.60±0.10 | 4.0±0.20 |
| [C/Fe] | 0.06±0.20       | 0.21±0.09 |
| [N/Fe] | 0.37±0.16       | 0.94±0.18 |
| [O/Fe] | 0.11±0.17       | 0.33±0.12 |
| $^{12}$C/$^{13}$C | 10±1          | 10±2      |
| A(Li)$_{LTE,6703}$ Å | 3.86±0.13    | 3.82±0.07 |
| A(Li)$_{LTE,6708}$ Å | 3.97±0.13    | 3.94±0.07 |
| A(Li)$_{LTE,6718}$ Å | 4.15±0.15    | 4.21±0.10 |
| A(Li)$_{LTE,6730}$ Å | 4.05±0.15    | 4.06±0.10 |
| Age (Gyr) | 8.8            | 8.1       |
| Mass ($M_{\odot}$) | 1.3±0.05    | 1.2±0.05 |
| Sptype    | K2III         | K2III     |

http://simbad.u-strasbg.fr/simbad/sim-fbasic
line at 6707.8 Å and a subordinate line at 6103.6 Å. In general, later transition is not seen unless stars have extremely large Li abundance. Abundance are derived using spectral synthesis to account for weak blends, and hyperfine structure (HFS) in case of resonance line at 6707 Å. For line synthesis, we adopted line list along with oscillator strengths from the compilation of Reddy et al. (2002) and HFS from Hobbs et al. (1999). Spectral synthesis of respective lines yields Li abundances of A(Li) = 4.15$^3$ and 3.86 dex for TYC 1751-1713-1 and A(Li) = 4.18 and 3.82 dex for HD 24960. Comparison of observed spectra with the predicted spectra for different Li abundances for both stars are shown in Fig 2. Both transitions are affected by non-LTE effects (Lind et al. 2009a) and the derived abundances are corrected using their recipe. The average non-LTE corrected abundances are: A(Li) = 4.0 dex for TYC 1751-1713-1 and 4.01 dex for HD 24960 (See Table 1).

$^3$A(Li) = log(N(Li)/N(H)

C, N, O & $^{12}$C/$^{13}$C: Abundance ratios of C/N and, in particular, isotopic ratios of $^{12}$C/$^{13}$C are key tracers of evolution on RGB. We have derived carbon abundance using three well defined atomic lines at 5052.15 Å, 5380.36 Å and 6587.62 Å with gf values taken from (Wiese et al. 1996). Atomic N lines in the spectra are quite weak as the stars are too cool and the N transitions in the visible spectra are of high voltage lines. For N abundance, we relied on a few selected CN lines in the region of 8000-8006 Å and with the derived C abundance as input. Basic line data of CN lines for spectral synthesis is taken from de Laverny & Gustafsson (1998). Oxygen abundances are based on two forbidden [OI] lines at 6300.30 Å and 6363.78 Å. In case of 6300.30 Å synthesis, we included line list with atomic data given in (Allende Prieto et al. 2001). Values for isotopic ratio $^{12}$C/$^{13}$C have been derived using a molecular line of $^{12}$C$^3$N at 8004.6 Å. Derived C, N, O and $^{12}$C/$^{13}$C ratios are given in Table 1.

Other Elements: In addition to key elements like Li, C, N and $^{12}$C/$^{13}$C, we have derived abundances of other elements to look for any possible trends with Li excess. Atomic data for most of the transitions are taken from the compilation of Reddy et al. (2003) and Ramírez & Allende Prieto (2011). The derived average abundances of elements from Li to Nd for which we could measure reliable EWs are tabulated in Table 2. Except the abundance of Li, other elemental abundances as defined by $[X/Fe] = [X/H]_{	ext{star}} - [Fe/H]_{	ext{star}}$ do not suggest any abnormality, and they are typical for stars on the RGB. Also, abundance patterns are typical of Galactic thin disk component to which both stars belong as per the kinematic measurements with probability of being thin disk by more than 95% (Reddy et al. 2006).

Uncertainties: Quoted errors in average abundances given in Table 1 & 2 are quadric sum of uncertainties in relative abundances due to estimated uncertainties in model parameters: $\Delta$Eff, $\Delta$log, $\Delta$[Fe/H] and $\Delta$[X/H]. Also included is the estimated uncertainty in measuring EWs ($\Delta$EW) which is a function of S/N ratio of spectra (Cayrel 1988). The individual uncertainties in each of these parameters are assumed to be independent, and the net error in each abundance is given by

$$X_{\text{error}} = \sqrt{\Delta\text{Eff}} f^2 + \Delta\text{log} g^2 + \Delta\text{log} v^2 + \Delta\text{[Fe/H]}^2 + \Delta\text{EW}^2$$

Obviously, abundances from neutral lines are more sensitive to $\Delta$Eff, ionized species (Fe II, Ba II etc.) to $\Delta$logg, and the abundances derived using stronger lines are more sensitive to $\Delta$[X/H]. Effect of $\Delta$[Fe/H] is very little or nil as abundances.

2.1.3 $v_{\text{sin}}i$ and infrared excess

Many studies speculated on the possible correlation between Li-excess, and $v_{\text{sin}}i$ and IR excess which can be one of the key evidences for planet/sub-dwarf merger scenarios (Carlberg et al. 2010).

In general, average stellar rotational velocities ($v_{\text{sin}}i$) for K giants are low, at about 2 Km s$^{-1}$, compared to their progenitors on the main sequence (de Medeiros et al. 1996). As stars evolve off to RGB their $v_{\text{sin}}i$ drops significantly due to angular momentum conservation. However, a few Li-rich giants do show higher $v_{\text{sin}}i$ values than the typically observed values prompting speculations of correlation between $v_{\text{sin}}i$ and Li-excess (Drake et al. 2002). In the case of two stars in this study, we have derived $v_{\text{sin}}i$ values using two neutral Fe I lines 6703.5 Å and 6705.1 Å. Observed spectral profiles are compared with the profiles predicted for given input atomic data, abundance, and instrumental broadening derived from Th-Ar calibration spectrum. By varying values of $v_{\text{sin}}i$ and macro turbulence($V_m$) simultaneously, we found best fits with minimum $\chi^2$ value for $v_{\text{sin}}i$ = 6±1 km s$^{-1}$ and $V_m$ = 4.0±0.2 km s$^{-1}$ for HD 24960, and 4.4±0.8 km s$^{-1}$ and $V_m$ = 3.6±0.1 km s$^{-1}$ for TYC 1751-1713-1. Values of $V_m$ and $v_{\text{sin}}i$ are given in Table 1.

For determining IR excess, we used spectral energy distribution (SED). The observed available fluxes in different bands are fitted with theoretical Kurucz atmospheric flux models (Castelli et al. 1997) for a set of derived atmospheric parameters. We used mid IR fluxes from AKARI (Ishihara et al. 2010) and WISE (Wright et al. 2010), and near IR fluxes from 2MASS (Skrutskie et al. 2006) survey. The data for optical bands (G, G$_{BP}$, G$_{RP}$) comes from Gaia survey (Gaia Collaboration et al. 2018). Near- and mid-IR fluxes of both stars are of very good quality as indicated by flags in respective catalogues. As shown in Figure 4 neither of the stars show evidence of IR excess at least in the near- and mid-IR regime. Stars may have excess in far IR due to cold dust for which we don’t have data because far IR fluxes of 24 $\mu$m, 60 $\mu$m and 100 $\mu$m given in IRAS catalogue (Moshir et al. 1990) are upper limits which are not considered in fitting SEDs. Lack of IR excess, at least in the near IR, suggests lack of mass loss activity either at present or in the recent past. This is further corroborated by the near symmetric $H_{\alpha}$ profiles (Mészáros et al. 2009) (see Figure 5) as asymmetric profiles are commonly used for stellar mass-loss.
Evolutionary phase of Li-rich stars is one of the key issues which is not unambiguously determined for most of the Li-rich RGB stars. The resolution of the issue is closely tied to the understanding of Li excess origin in K giants. Here, we used two different methods to determine stellar evolutionary phase. First one involves simply placing stars in the HR diagram of luminosity versus $T_{\text{eff}}$ plane and compare with theoretical evolutionary tracks. As shown in Figure 6 evolutionary tracks from MESA (Paxton et al. 2011, 2018) with corresponding metallicity suggest that stars are at the red clump region, post He-flash at the RGB tip. Errors in luminosity due to errors in parallaxes, and $T_{\text{eff}}$ are shown as vertical and horizontal bars. Parallaxes are taken from Gaia survey (Gaia Collaboration et al. 2018). Other source of error in determining star’s position in the HR-diagram is the metallicity. We plotted two tracks for each star for upper and lower limits of $[\text{Fe/H}]$ (tracks with broken lines). Tracks for given average metallicities of masses of $M = 1.26 \, M_\odot$ for HD 24960 and $1.3 \pm 0.05 \, M_\odot$ for TYC 1751-1713-1 best converge with stars positions in $\log(L/L_\odot)$ - $T_{\text{eff}}$ plane. Though the position appears to coincide well with the red clump region, given the very small gap between the clump and the bump for field stars of metallicities closer to the sun, it would be difficult to rule out the possibility of their location on the RGB either at or close to the luminosity bump in HR diagram. This is one of the main difficulties to separate stars of RC from that of the bump (Kumar et al. 2011).

Table 2. Summary of elemental abundances with estimated errors of the two program stars.

| Element | HD 24960 ($[\text{Fe/H}]=-0.45$) | TYC 1751-1713-1 ($[\text{Fe/H}]=-0.25$) |
|---------|---------------------------------|-----------------------------------|
|         | $(1)$ (2) (3) (4) (5) (6) (7)    | $(1)$ (2) (3) (4) (5) (6) (7)     |
| Li      | 4.00 ... ... 4.01 ... ...       | 4.00 ... ... 4.01 ... ...       |
| C       | 8.20 0.21 0.09 8.24 0.06 0.20   | 8.20 0.21 0.09 8.24 0.06 0.20   |
| N       | 8.33 0.94 0.18 7.95 0.37 0.16   | 8.33 0.94 0.18 7.95 0.37 0.16   |
| O       | 8.58 0.33 0.12 8.55 0.11 0.17   | 8.58 0.33 0.12 8.55 0.11 0.17   |
| NaI     | 5.95 0.15 0.08 6.12 0.13 0.14   | 5.95 0.15 0.08 6.12 0.13 0.14   |
| MgI     | 7.19 0.03 0.08 7.29 -0.06 0.13  | 7.19 0.03 0.08 7.29 -0.06 0.13  |
| Al      | 6.05 0.04 0.08 6.30 0.10 0.13   | 6.05 0.04 0.08 6.30 0.10 0.13   |
| SiI     | 6.99 -0.08 0.08 7.17 -0.09 0.14 | 6.99 -0.08 0.08 7.17 -0.09 0.14 |
| CaI     | 5.94 0.04 0.09 6.16 0.07 0.15   | 5.94 0.04 0.09 6.16 0.07 0.15   |
| ScII    | 2.70 -0.01 0.11 3.05 0.15 0.16  | 2.70 -0.01 0.11 3.05 0.15 0.16  |
| TiII    | 4.46 -0.05 0.10 4.73 0.03 0.17  | 4.46 -0.05 0.10 4.73 0.03 0.17  |
| V      | 3.33 -0.16 0.10 3.70 0.02 0.16   | 3.33 -0.16 0.10 3.70 0.02 0.16   |
| CrI     | 5.22 0.02 0.08 5.35 -0.04 0.16   | 5.22 0.02 0.08 5.35 -0.04 0.16   |
| FeII    | 7.01 0.00 0.09 7.20 0.00 0.17   | 7.01 0.00 0.09 7.20 0.00 0.17   |
| CoI     | 4.46 -0.09 0.11 4.87 0.13 0.15   | 4.46 -0.09 0.11 4.87 0.13 0.15   |
| NiI     | 5.84 0.06 0.09 5.98 0.01 0.17   | 5.84 0.06 0.09 5.98 0.01 0.17   |
| CuI     | 3.85 0.10 0.12 4.28 0.34 0.18   | 3.85 0.10 0.12 4.28 0.34 0.18   |
| ZnI     | 4.15 0.03 0.14 4.29 -0.02 0.18   | 4.15 0.03 0.14 4.29 -0.02 0.18   |
| YI      | 1.53 -0.24 0.12 1.98 0.02 0.15   | 1.53 -0.24 0.12 1.98 0.02 0.15   |
| ZrI     | 2.16 0.02 0.11 2.38 0.05 0.18   | 2.16 0.02 0.11 2.38 0.05 0.18   |
| BaII    | 2.02 0.28 0.10 2.27 0.34 0.20   | 2.02 0.28 0.10 2.27 0.34 0.20   |
| LaII    | 0.87 0.18 0.12 1.07 0.19 0.15   | 0.87 0.18 0.12 1.07 0.19 0.15   |
| CeII    | 1.24 0.10 0.14 1.35 0.02 0.19   | 1.24 0.10 0.14 1.35 0.02 0.19   |
| NdII    | 0.96 -0.05 0.17 1.49 0.29 0.22   | 0.96 -0.05 0.17 1.49 0.29 0.22   |

Second method pertains to asteroseismology for differentiating RGB stars with H-shell burning from stars of red clump with He-core burning (Bedding et al. 2011). Unfortunately, the stars in the current study are not in the Kepler survey field. However, secondary calibration based on LAMOST and APOGEE spectra of stars that have Kepler asteroseismic data and which are classified as either red clump or RGB stars (Ting et al. 2018) is found to be an useful tool. Oscillations in red giants vary depending on core density. The average period spacing between oscillations of gravity mode (g-mode) and acoustic pressure mode (p-mode), and the frequency separation ($\Delta \nu$) between $p$-modes are found to be key parameters to separate RC stars of He-core burning from those of H-shell burning RGB stars. Stars with $\Delta P \geq 150$ and $\Delta \nu \leq 5$ have been classified as RC stars (Bedding et al. 2011; Vrard et al. 2016). The criterion is often termed as gold standard for segregating RC and RGB stars. (Ting et al. 2018) estimated $\Delta P = 275$ and $\Delta \nu = 4.04$ for HD 24960 and $\Delta P = 249.3$ and $\Delta \nu = 4.18$ for TYC 1751-1713-1 suggesting that both the stars belong to the RC. Using the estimated seismic parameters ($\Delta P$, $\Delta \nu$), other stellar parameters such as $v_{\text{max}}$, mass and Radius of the stars (See Table 3) have been derived using equations given in Kjeldsen & Bedding (1995). We found $M = 1.27 \, M_\odot$ for HD 24960 and $M = 1.26 \, M_\odot$ for TYC 1751-1713-1 which are very close to the values obtained using the stellar evolutionary tracks.
Figure 4. Model SED fits (continuous line) of TYC 1751-1713-1 and HD 24960 with observed fluxes (filled circles).

Figure 5. Observed Hα of profiles show no asymmetry. Central line is a bisector of profiles.

Figure 6. Location of two super Li-rich stars (filled squares) in the HR diagram. Shown are the MESA evolutionary tracks Paxton et al. (2011) for masses 1.2, 1.3 M⊙ with corresponding metallicities.

are expected to have lower C compared to stars which are still on the RGB phase. For example ratios of [C/N] versus [Fe/H] can be used to separate RC stars from RGB stars (see Masseron et al. 2017; Hawkins et al. 2016). In Table 4, we have given values of [C/N] and [Fe/H] of our two stars along with seven other known Li-rich giants, of which evolutionary phase for six stars is known based on asteroseismic analysis, and based on CMD for one in open cluster Trumpler 5. We have shown all of them in a plot (see Figure 7) of [C/N] versus [Fe/H] of asteroseismically classified normal RC and RGB stars. The two stars in our study with [C/N] ≤ −0.25 show that they are indeed RC stars.
Asteroseismic parameters derived from spectral calibration. Period spacing and frequency separation are directly adopted from Ting et al. (2018). Mass, radius, log g and luminosity have been derived using scaling relations.

|            | HD 24960 | TYC1751-1713-1 |
|------------|----------|----------------|
| ΔP [sec]   | 275.99   | 249.31         |
| Δν/μHz     | 4.04     | 4.18           |
| νmax/μHz   | 33.86    | 35.30          |
| M [M⊙]     | 1.27     | 1.26           |
| R [R⊙]     | 11.25    | 10.96          |
| log g      | 2.44     | 2.46           |
| log(λ/λ⊙)  | 1.80     | 1.78           |

3 DISCUSSION

Derived abundances of Li, ratios of [C/N] and $^{12}$C/$^{13}$C of two stars in this study, HD 24960 and TYC 1751-1713-1, along with six other known RC giants are summarized in Table 4. All of them have three features in common: a) Large Li abundance which is about 1 or 2 orders of magnitude more than the maximum predicted value of A(Li)=1.5 dex on RGB (Iben 1967a; Lagarde et al. 2012), and 2 to 3 orders of magnitude more than the generally observed values in post bump stars (Lind et al. 2009b), b) low $^{12}$C/$^{13}$C ratios which are a factor of 2 to 3 lower (except for KIC 4937011, see table 4) than the predicted values suggesting some kind of extra mixing post 1st dredge-up episode, c) low [C/N] values ( ≤ −0.25), indicating stars have evolved through the RGB tip and are in RC phase (Hawkins et al. 2018). However, Li-rich giant, KIC 2305930, though it is a bona fide RC star based on asteroseismic data, has [C/N] value which is positive falling in the category of RGB stars (see Figure 7).

With the recent findings of new super Li-rich red clump stars, a question arises whether there is a single mechanism that is responsible for all the Li-rich RGB stars, or there are multiple mechanisms for Li enhancement depending on their evolutionary phase on RGB. To answer this question it is necessary to have evolutionary phase unambiguously determined. Presently, there are just 7 giants which are reported as Li-rich for which evolutionary phase is determined based on asteroseismic analysis (see Table 4). Of which giant KIC 9821612 reported by Jofrè et al. (2015) is the only RGB Li-rich giant. Also, KIC 9821612 stands out from other Li-rich giants in Table 4 by having least amount of Li abundance A(Li)=1.80 dex. Recent analysis by (Takeda & Tajitsu 2017) also gives similar mean abundance of A(Li) = 1.76 dex. With the commonly applied criterion of A(Li) > 1.5 dex, KIC 9821612 can be qualified as a Li-rich giant. However, as mentioned in Jofrè et al. (2015), its abundance is at the limit of normal Li-rich giants of A(Li) ≤ 1.8 dex if we take into account recent studies (e.g. Ruchti et al. 2011; Liu et al. 2014). Given its relatively higher value of $^{12}$C/$^{13}$C coupled with its position in HR diagram, below the bump, it is important to understand whether this star is genuinely Li-rich i.e. its photosphere is enriched with Li while star is on RGB either by external or through in-situ mechanisms. Also, one can’t rule out the possibility of insufficient dilution of Li from its initial value. On other hand, its reported overabundances of $\alpha$- and $r$-process elements seem to be in odds with its RGB evolutionary phase. A more detailed study of this star is necessary to understand its Li-rich classification.

There are two main hypotheses for Li-excess in RGB stars. One being the in-situ nucleosynthesis and subsequent extra mixing, and second is external origin. The apparent concentration of a large number of Li-rich giants at luminosity bump as reported by observations (Charbonnel & Balachandran 2000; Casey et al. 2016; Ruchti et al. 2011) led to construction of many theoretical models around in-situ nucleosynthesis and extra-mixing at the bump. Note, extra-mixing is also responsible for observed severe depletions of Li and very low values of $^{12}$C/$^{13}$C and [C/N]. However, under some special conditions models (e.g. Palacios et al. 2001; Denis senkov & Herwig 2004; Eggleton et al. 2008; Denissenkov & Merryfield 2011; Denissenkov 2012) predict high levels of Li abundances seen in Li-rich stars. Given the relatively longer stellar evolutionary time scales at the bump and the expected brief life span of enhanced Li, models seem to explain the reported observational results: a) concentration of Li-rich stars at the bump, b) very few or lack of Li-rich stars in between the bump and RGB tip.

The above scenario may explain Li-rich stars if they are either at the bump or just evolved off the bump. In case of Li-rich giants at red clump, it would be difficult to explain sustaining of Li abundance at the level shown in Table 4.

Figure 7. Plot of [C/N] vs [Fe/H] of known normal RC (red open circles) and RGB (black open circles) stars. Li-rich RC stars from Table 4 are shown as red filled circle and the lone Li-rich RGB star KIC 9821622 is shown as filled black circle. Black solid and black dashed lines are running median of [C/N] abundance of RC star KIC 9821622 is shown as filled black circle. Black solid and RGB stars, respectively. Note, two stars in this study (large filled red circles) are well within RC regime of the plot.
as stars evolve from the bump to the clump. The continued deep convection post-bump evolution seems to rapidly deplete remaining Li from 1st dredge-up or Li that has been produced at the bump. This has been well illustrated by observations (e.g. Lind et al. 2009a). Also, relatively much shorter Li depletion time scales compared to stellar evolutionary time scales from the bump to red clump (e.g. Bharat Kumar et al. 2015) add to the argument in favour that the enhanced Li at the bump is very unlikely to survive all the way to red clump.

Alternately, accretion of Li-rich material from substellar objects such as planets or brown dwarfs may enhance photospheric Li abundance (Alexander 1967). Since planet engulfment can happen anywhere along the RGB a single mechanism may be sufficient to explain reported Li-rich stars along RGB: sub-giants (Li et al. 2018), below the bump (Adamów et al. 2014; Casey et al. 2016), at the bump (Charbonnel & Balachandran 2000), between the bump and the RGB tip, even at the red clump. External scenarios explain relatively high occurrence of Li-rich stars either at bump or at the clump may be due to relatively longer evolutionary time scales at the respective phases.

Though, at the outset, the external hypothesis seems to explain Li excess, there are genuine concerns on its ability to explain the level of Li excess observed in stars by Li-rich material accretion alone. For example Aguilera-Gómez et al. (2016) shows a maximum limit of A(Li) = 2.2 dex in RGB stars by way of accretion of substellar companion of mass lower than $15M_J$ in a regime where extra-mixing does not operate. Above this mass limit, Li is expected to be depleted in the interiors of substellar objects (Chabrier et al. 1996). Also, Siess & Livio (1999) computations showed enhancement of photospheric Li abundance by mixing Li rich material of sub stellar objects of masses as high as 0.1$M_⊙$ to meet observed levels of Li. Result from these studies, in the absence of induced mixing, imply that multiple number of planets and/or substellar objects are required to reach the level of Li abundances observed in super Li-rich giants. However, one can’t rule out the possibility of merger induced extra-mixing that brings up Li produced in H-burning shell. Yet, we don’t have evidence for such large accretion of external material in the form of enhanced metal abundances such as Fe-peak elements. One of the key evidences for the addition of external Li rich material is the enhanced abundance of $^6$Li which has not been observed either in RGB stars or in main sequence dwarfs with planets (Reddy et al. 2002). Also, models based on external events predict infrared excess as well as enhanced rotation as a consequence of accretion process which do not seem to be evident in many of the Li-rich stars (Bharat Kumar et al. 2015; Rebull et al. 2015). Of course, IR excess may not be a stringent criterion as Li and dust shells evolve on different time scales (Bharat Kumar et al. 2015). As per vsini values, as shown in Table 4 among 9 Li-rich giants at least 4 stars do show projected vsini which are two to three times of the average observed values for K giants (e.g. de Medeiros et al. 1996).

In case of two stars in this study and other RC giants in Table 4, their very large Li abundance and relatively shorter Li depletion time scales suggest that the Li enhancement event occurred very recently either by material accretion or by in-situ nucleosynthesis, and subsequent mixing. In case of in-situ, He-flash at the RGB tip could be an alternate site to the luminosity bump for excess Li seen in RC stars. He-flash at RGB tip, an immediate preceding phase of red clump phase, is a significant event on RGB at which He ignition at the core begins. There are couple of studies that dealt with nucleosynthesis during He-flash and its effects on stellar photosphere abundances. For example, Mocák et al. (2011) show show injection of hydrogen into He-layers and mixing up of interior material with outer layers resulting in very low $^{12}C/^{13}C$, large Li abundances, and enhanced N. Models also predict enhanced C as well. In case of external scenario, one can think of merger events closer to the tip. Zhang & Jeffery (2013) explored mergers of He white dwarfs with He-core of RGB stars to explain Li in early AGB stars, and predict enhanced Li and lower $^{12}C/^{13}C$ values along with infrared excess for certain combination of masses of He-WD and central He-cores.

### 4 CONCLUSION

We discovered two new super Li-rich K giants with $A(Li) \approx 4.0$ dex and argued their evolutionary phase as red clump using secondary calibration based on asteroseismic and spectroscopic data, and Gaia astrometry. The two stars add to the growing list of Li-rich red clump giants. Large Li abundances coupled with their RC evolutionary phase and shorter Li depletion imply that the Li enhancement occurred very recently either by internal nucleosynthesis during He-
flashed at the RGB tip or by external events such as merger of sub-stellar objects near the tip. Including two stars in this study there are 8 Li-rich K giants for which RC evolutionary phase is firmly established. Of which five are super Li-rich stars with $[\text{Li}]/\text{Fe} \geq 3.2$ dex including two from this study. KIC 9821622 is the only Li-rich RGB star reported whose evolutionary phase is based on asteroseismology. Though the numbers are too small to deduce firm conclusion, it would be interesting to comment on the large difference in number of known Li-rich giants among RC and RGB phases. Whether the difference in numbers is due to large difference in stellar evolutionary time scales between the two phases; red clump evolutionary time scales are relatively much longer compared to the bump time scales (Bharat Kumar et al. 2015). A systematic survey of Li among the known RGB and GC giants is warranted to find clues for the origin of Li-excess. A larger survey in this direction is under progress, and will be published elsewhere.

5 ACKNOWLEDGEMENT

We thank anonymous referee for his suggestions which improved the paper. Funding for LAMOST (www.lamost.org) has been provided by the Chinese NDRC. LAMOST is operated and managed by the National Astronomical Observatories, CAS.

REFERENCES

Adamów M., Niedzielski A., Villaver E., Wólszczan A., Nowak G., 2014, A&A, 569, A55
Agúndez-Gómez C., Chanamé J., Pinsonneault M. H., Carlberg J. K., 2016, ApJ, 833, L24
Alexander J. B., 1967, The Observatory, 87, 238
Allende Prieto C., Lambert D. L., Asplund M., 2001, ApJ, 556, L63
Asplund M., Grevesse N., Sauval A. J., Scott P., 2009,ARA&A, 47, 481
Bedding T. R., et al., 2011, Nature, 471, 608
Bharat Kumar Y., Singh R., Eswar Reddy B., Zhao G., 2018, ApJ, 858, L22
Brown J. A., Sneden C., Lambert D. L., Dutcher Jr. E., 1989, ApJS, 71, 293
Carlberg J. K., Smith V. V., Asplund M., 2001, ApJ, 556, L63
Carlberg J. K., et al., 2015, ApJ, 802, 7
Casey A. R., et al., 2016, MNRAS, 461, 3336
Castelli F., Kurucz R. L., 2004, ArXiv Astrophysics e-prints.
Castelli F., Gratton R. G., Kurucz R. L., 1997, A&A, 318, 841
Cayrel R., 1988, in Cayrel de Strobel G., Spite M., eds, IAU Symposium Vol. 132, The Impact of Very High S/N Spectroscopy on Stellar Physics. p. 345
Chabrier G., Baraffe I., Plez B., 1996, ApJ, 459, L91
Charbonnel C., 1994, A&A, 282, 811
Charbonnel C., 2005, in Barnes III T. G., Bash F. N., eds, Astronomical Society of the Pacific Conference Series Vol. 356, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis. p. 119
Charbonnel C., Balachandran S. C., 2000, A&A, 359, 563
Christensen-Dalsgaard J., 2015, MNRAS, 453, 666
Denissenkov P. A., 2012, ApJ, 753, L3
Denissenkov P. A., Herwig F., 2004, ApJ, 612, 1081
Denissenkov P. A., Merryfield W. J., 2011, ApJ, 727, L8
Denissenkov P. A., VandenBerg D. A., 2003, ApJ, 593, 509
Denissenkov P. A., Pinsonneault M., MacGregor K. B., 2009, ApJ, 696, 1823
Drake N. A., de la Reza R., da Silva L., Lambert D. L., 2002, AJ, 123, 2703
Eggleton P. P., Dearborn D. S. P., Lattanzio J. C., 2006, Science, 314, 1580
Eggleton P. P., Dearborn D. S. P., Lattanzio J. C., 2008, ApJ, 677, 581
Gaia Collaboration Brown A. G. A., Vallenari A., Prusti T., de Bruijne J. H. J., Babusiaux C., Bailer-Jones C. A. L., 2018, preprint, (arXiv:1804.09345)
Gilroy K. K., 1989, in Bulletin of the American Astronomical Society. p. 790
Gilroy K. K., Brown J. A., 1991, ApJ, 371, 578
González Hernández J. I., Bonifacio P., 2009, A&A, 497, 497
Green G. M., et al., 2015, ApJ, 810, 25
Hawkins K., Masseron T., Jofré P., Gilmore G., Elsworth Y., Hekker S., 2016, A&A, 594, A63
Hawkins K., Ting Y.-S., Walter-Rix H., 2018, ApJ, 853, 20
Hinkle K., Wallace L., Valenti J., Harmer D., 2000, Visible and Near Infrared Atlas of the Arcturus Spectrum 3727-9300 A
Hobbs L. M., Thorburn J. A., Rebull L. M., 1999, ApJ, 523, 797
Iben Jr. I., 1967a, ApJ, 147, 624
Iben Jr. I., 1967b, ApJ, 147, 650
Ishihara D., et al., 2010, A&A, 514, A1
Jofré P., Petrucci R., García L., Gómez M., 2015, A&A, 584, L3
Kirby E. N., Guhathakurta P., Zhang A. J., Hong J., Guo M., Guo R., Cohen J. G., Cunha K., 2016, ApJ, 819, 135
Kjeldsen H., Bedding T. R., 1995, A&A, 293, 87
Knauth D. C., Federman S. R., Lambert D. L., 2003, ApJ, 586, 268
Kumar Y. B., Reddy B. E., Lambert D. L., 2011, ApJ, 730, L12
Lagarde N., Deccresin T., Charbonnel C., Eggenberger P., Ekström S., Palacios A., 2012, A&A, 543, A108
Lambert D. L., Reddy B. E., 2004, MNRAS, 349, 757
Li H., Aoki W., Matsuno T., Bharat Kumar Y., Shi J., Suda T., Zhao G., 2018, ApJ, 852, L31
Lind K., Asplund M., Barklem P. S., 2009a, A&A, 503, 541
Lind K., Primas F., Charbonnel C., Grundahl F., Asplund M., 2009b, A&A, 503, 545
Liu Y. J., Tan K. F., Wang L., Zhao G., Sato B., Takeda Y., Li H. N., 2014, ApJ, 785, 94
Martell S. L., Shetrone M. D., 2013, MNRAS, 430, 611
Masseron T., Lagarde N., Muglio A., Elsworth Y., Gilmore G., 2017, MNRAS, 464, 3021
Mészáros S., Avrett E. H., Dupree A. K., 2009, ApJ, 138, 615
Mocák M., Siess L., Müller E., 2011, A&A, 533, A53
Monaco L., et al., 2014, A&A, 564, L6
Moshir M., et al., 1990, in Bulletin of the American Astronomical Society. p. 1325
Palacios A., Charbonnel C., Forestini M., 2001, A&A, 375, L9
Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2011, ApJS, 192, 3
Paxton B., et al., 2018, ApJS, 234, 34
Ramírez I., Allende Prieto C., 2011, ApJ, 743, 135
Rebull L. M., et al., 2015, AJ, 150, 123
Reddy B. E., Lambert D. L., Lawes C., Gonzalez G., Covey K., 2002, MNRAS, 335, 1005
Reddy B. E., Tomkin J., Lambert D. L., Allende Prieto C., 2003, MNRAS, 340, 304
Reddy B. E., Lambert D. L., Allende Prieto C., 2006, MNRAS, 367, 1329
Ruchti G. R., et al., 2011, ApJ, 743, 107
Siess L., Livio M., 1999, MNRAS, 308, 1133
Silva Aguirre V., et al., 2014, ApJ, 784, L16
Skrutskie M. F., et al., 2006, AJ, 131, 1163
Smiljanic R., et al., 2018, preprint, (arXiv:1805.07077)
Sneden C. A., 1973, PhD thesis, THE UNIVERSITY OF TEXAS AT AUSTIN.
Takeda Y., Tajitsu A., 2017, PASJ, 69, 74
Ting Y.-S., Hawkins K., Rix H.-W., 2018, ApJ, 858, L7
Vrard M., Mosser B., Samadi R., 2016, A&A, 588, A87
Wiese W. L., Fuhr J. R., Deters T. M., 1996, Atomic transition probabilities of carbon, nitrogen, and oxygen: a critical data compilation
Wright E. L., et al., 2010, AJ, 140, 1868
Zhang X., Jeffery C. S., 2013, MNRAS, 430, 2113
de Laverny P., Gustafsson B., 1998, A&A, 332, 661
de Medeiros J. R., Da Rocha C., Mayor M., 1996, A&A, 314, 499

This paper has been typeset from a TEX/LATEX file prepared by the author.