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Lithium destruction and production observed in red giant stars*

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Abstract. According to standard stellar evolution, lithium is destroyed throughout most of the evolution of low- to intermediate-mass stars. However, a number of evolved stars on the red giant branch (RGB) and the asymptotic giant branch (AGB) are known to contain a considerable amount of Li, whose origin is not always understood well. Here we present the latest development on the observational side to obtain a better understanding of Li-rich K giants (RGB), moderately Li-rich low-mass stars on the AGB, as well as very Li-rich intermediate-mass AGB stars possibly undergoing the standard hot bottom burning phase. These last ones probably also enrich the interstellar medium with freshly produced Li.

Key words. Stars: late-type – Stars: evolution – Stars: abundances

1. Introduction

Lithium (Li) is not only important for testing big bang nucleosynthesis predictions and for studying diffusion processes in atmospheres of dwarf stars (see e.g. Korn et al. 2006, and contributions in this issue), it is also an important diagnostic tool for stellar evolution. Its abundance strongly depends on the ambient conditions because it is quickly destroyed at $T > 3 \times 10^6$ K so that it diminishes if the stellar surface is brought into contact with hot layers by mixing processes.

A nice illustration of the evolution of the Li abundance in low-mass, low-metallicity stars during their ascent on the RGB can be found in Fig. 5 of Lind et al. (2009), who investigated the globular cluster NGC 6397. The least evolved main sequence and turn-off stars define a plateau of Li abundances that is in agreement with the well-known Spite plateau (Spite & Spite 1982). A sharp drop in Li abundance

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occurs once the stars undergo the first dredge-up (FDU) on the sub-giant branch: the abundance drops asymptotically by more than an order of magnitude towards a final value of $\log\epsilon(\mathrm{Li}) \approx 1.1$, in agreement with the maximum value of 1.5 predicted by stellar models excluding atomic diffusion and rotation. This is also observed in most G-K giants in the field (Lambert et al. 1980; Brown et al. 1989; Mishenina et al. 2006), where some of these stars show Li abundances even far below the expectations (Mallik 1999). During FDU, the convective envelope is diluted by H-processed material that is devoid of Li. When the outward advancing H-burning shell reaches the discontinuity in mean molecular weight (μ barrier) left behind by FDU, the star is at the bump in the luminosity function (RGB bump), and the Li abundance is further diminished on the star's surface. This happens because the radiative layer between the H-burning shell and the convective envelope is now chemically homogeneous, so that any instability in the layer can lead to slow mixing processes (e.g. thermohaline mixing; Charbonnel & Zahn 2007) that brings the remaining Li to hot layers where it is burned. In the cluster investigated by Lind et al. (2009), the Li abundance in some stars evolved beyond the RGB bump drops to below the detection threshold at $\log\epsilon(\mathrm{Li}) \sim 0.2$. For more massive stars, the H-burning shell does not cross the μ barrier before it reaches the early AGB, when again slow mixing processes can further diminish the surface Li abundance.

However, about 1 – 2 % of the K giants have a Li abundance higher than this classical limit of $\log\epsilon(\mathrm{Li}) \approx 1.5$ and are therefore called *Li-rich* (Wallerstein & Sneden 1982; Brown et al. 1989; de La Reza et al. 1997). Because it is known that these stars underwent normal FDU, it is commonly believed that these stars cannot have retained their original Li abundance, but rather must have replenished it somehow in situ. Li destruction can turn into production if the overturn time scale for mixing between the H-burning shell and the convective envelope becomes faster than the decay of the parent nucleus ^{7}Be. This is known as the Cameron-Fowler mechanism ($^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}(e^-,\nu)^7\mathrm{Li}$; Cameron & Fowler 1971).

In this contribution we review our observational results of the Li destruction and production in red giant stars with various masses and in various evolutionary stages. We focus on three different topics here: first we present our results from a recent spectroscopic survey of Li in RGB stars in the Galactic bulge (Lebzelter et al. 2012), second we review the correlation between Li and the third dredge-up indicator technetium (Tc) in low-mass, oxygen-rich AGB stars (Uttenthaler et al. 2007b; Uttenthaler & Lebzelter 2010; Uttenthaler et al. 2011), and finally we report on the large abundance of Li detected in long-period Miras that probably undergo a phase of hot bottom burning.

2. A lithium survey in Galactic bulge RGB stars

2.1. Motivation

There were two motivations for us to conduct a survey of the Li abundance along the RGB in the Galactic bulge. The first one was the discovery of Li-rich AGB stars in the outer Galactic bulge by Uttenthaler et al. (2007b). These stars were interpreted to be a result of fast mixing below the convective envelope called "cool bottom processing" (Sackmann & Boothroyd 1999) so that the Cameron-Fowler mechanism is activated. With a survey of the Li abundances in RGB stars in the bulge we aimed at checking whether a surplus of Li is already present in this earlier evolutionary stage, or if it must have been produced on the upper AGB.

The second motivation was the claim by Charbonnel & Balachandran (2000) that the mentioned Li-rich K giants are concentrated in two regions in the HR diagram: around the RGB bump region of low-mass stars (those which undergo a He-core flash at the RGB tip), and around the red clump/early AGB of intermediate-mass stars. In both these phases, in the absence of a μ barrier fast extra-mixing could connect the ^{3}He-rich convective envelope with the H-burning shell, enabling fresh

Li to be produced by the Cameron-Fowler mechanism. This Li-rich phase would be extremely short-lived, explaining the low number of Li-rich giants observed. However, most of the hitherto investigated samples were either inhomogeneous in mass or they were too small to verify these claimed distinct Li-rich episodes. Our aim was to provide a check of these claims with a large, homogeneous sample of RGB stars. The bulge contains a huge number of low-mass ($\sim 1.1 M_{\odot}$) RGB stars at roughly equal distance, hence well-constrained luminosity.

2.2. Target selection, observations, and data analysis

We selected the spectroscopic targets from a 2MASS colour-magnitude diagram (CMD) in a 25′ diameter circle towards the direction $(l, b) = (0°, -10°)$, which is the centre of the Palomar-Groningen field no. 3 (PG3). This field was chosen because also the sample of AGB stars studied by Uttenthaler et al. (2007b) is located in the PG3. The CMD of this field with an illustration of the target selection is displayed in Fig. 1. Targets were chosen along the RGB of two isochrones from Girardi et al. (2000) with ages and metallicities as indicated in the legend. Furthermore, only stars fainter than the RGB tip brightness (about $9\overset{\rm m}{.}0$ in J_0) were selected to avoid AGB stars, and a minimum brightness of $J_0 \geq 14\overset{\rm m}{.}5$ was demanded as to include also stars at or slightly below the expected RGB bump, but to keep the exposure times within reasonable limits.

The targets were observed with the FLAMES spectrograph at the VLT in the HR15 setting that covers also the Li I 671 nm resonance line. The resolving power of the spectra is 17 000. Of the 514 targets that were initially proposed for observations, 401 had spectra of sufficient quality to investigate the Li line.

The spectra were analysed with the help of COMARCS model atmospheres and spectral synthesis (Aringer et al. 2009). The stellar effective temperature was derived from the $(J - K)_0$ colour using the calibration relation established from a series of COMARCS model atmospheres (Lebzelter et al. 2012). The logarithmic surface gravity $\log g$ was derived from the isochrones in Fig. 1, assuming that the stars belong to the bulge RGB. With the main stellar parameters fixed in this way, we calculated a series of model atmospheres with a range of metallicities and synthetic spectra based on these models. The metallicity of each star was estimated by interpolating between the synthetic spectra, using a χ^2 minimisation scheme.

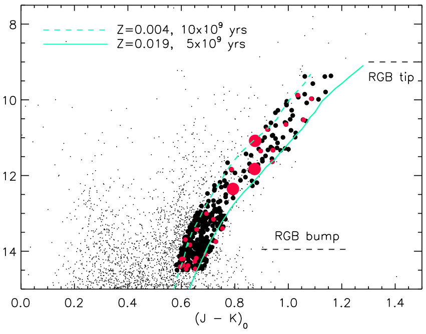

Fig. 1. CMD of the centre of the PG3 field, a 25′ diameter field towards $(l, b) = (0°, -10°)$. Big black dots represent stars that were observed in this survey, small red circles represent Li-*detected* stars, whereas large red circles represent Li-*rich* stars.

With the stellar parameters fixed in this way, we synthesised spectra, assuming varying Li abundances to fit the observed spectra. Lithium was detected in 30 stars, three of which are Li-*rich* according to the criterion established in the Introduction ($\log \epsilon(\text{Li}) > 1.5$), and 27 are Li-*detected* ($\log \epsilon(\text{Li}) \leq 1.5$). The most Li-rich sample star has a Li abundance at the level of $\log \epsilon(\text{Li}) = 3.2$, in agreement with the cosmic value, and should therefore be regarded as *super* Li-rich. A comparison of spectra of a Li-rich star, a Li-detected star, as well as a Li-poor star is presented if Fig. 2 of Lebzelter et al. (2012).

2.3. Results

Figure 1 also summarises the main results of this survey. The Li-detected stars distribute all along the RGB, from below the RGB bump up to the tip. We cannot discern a distinct episode of Li enrichment, neither at the RGB bump luminosity nor anywhere else. The three Li-rich stars are clearly brighter than the RGB bump and the red clump: the faintest of them is $\sim 1\overset{\mathrm{m}}{.}4$ brighter than the bump, and $\sim 0\overset{\mathrm{m}}{.}7$ brighter than the bright red clump (note that there are two red clumps present in the outer Galactic bulge, see Nataf et al. 2010; McWilliam & Zoccali 2010). If the Li-rich stars are genuine Galactic bulge stars, and there is no reason to doubt this, then they are connected to neither the RGB bump nor the red clump phase of evolution.

This casts some doubt on the claim by Charbonnel & Balachandran (2000) that a distinct phase of Li enrichment occurs in the evolution of low-mass stars at the RGB bump. There are a number of studies that draw similar conclusions. Gonzalez et al. (2009) identify 13 bulge stars with a detectable Li line, two of which are Li-rich, among a sample of ~ 400 stars. Their sample stars are $\sim 0\overset{\mathrm{m}}{.}7$ brighter than the horizontal branch red clump. If these stars are indeed connected to the RGB bump phase, they would more likely belong to the foreground disc, at a distance of ~ 4.6 kpc. Monaco et al. (2011) searched their sample of 824 thick disc candidates for the presence of Li, and found five Li-rich stars. Although only spectroscopic distance estimates are available for these stars, they clearly distribute all along the RGB, not connected to any distinct evolutionary phase. Alcalá et al. (2011) report on the detection of a Li-rich, low-mass M giant close to the RGB tip. Finally, Ruchti et al. (2011) report the discovery of a number of metal-poor, Li-rich giants distributed in a large range of luminosities, only some of which might be connected to the RGB bump. There is growing evidence that argues against a distinct Li-rich episode connected to the RGB bump of low-mass red giants. Other parameters such as magnetic fields and the presence of planets might also play an important role (Gonzalez 2010).

On the other hand, Kumar et al. (2011) searched 2000 giants in the Galactic disc, and find that the Li-rich objects among them are connected to the red clump. This result can be reconciled with the evidence discussed in the previous paragraph if the stars in the sample of Kumar et al. (2011) are on average more massive than the stars in the other samples. For instance, bulge giants have a typical mass of $1.1 M_{\odot}$, whereas most Li-rich stars in the sample of Kumar et al. (2011) have masses $> 1.6 M_{\odot}$. In fact, also Kumar et al. (2011) do not find stars of $\sim 1.0 M_{\odot}$ that are clearly connected to either the RGB bump or red clump phase (see their Fig. 2).

Uttenthaler et al. (2007b) identified four AGB stars in the PG3 field with Li abundance of $\log \epsilon(\mathrm{Li}) = 0.8, 0.8, 1.1$, and 2.0, among a sample of 27 long-period AGB variables. The fraction of stars with detectable Li line (18.8%) on the upper RGB ($J_0 < 12\overset{\mathrm{m}}{.}0$) is similar to that found among AGB stars ($4/27 = 14.8\%$). It is possible that the Li-rich AGB stars inherited their Li from the preceding RGB phase. Indeed, the three Li-rich stars identified in Lebzelter et al. (2012) could be early AGB stars instead of RGB stars because they are brighter than the RC. Because it is impossible to separate RGB and early AGB stars by means of our photometric and spectroscopic data alone, asteroseismological methods would be needed to define their precise evolutionary state.

Another interesting result of our observations is that there is a trend for the Li-*detected* stars of decreasing Li abundance with decreasing temperature, from which the Li-*rich* stars deviate (Fig. 2). This is in qualitative agreement with what Gonzalez et al. (2009) found in their sample, our sample extends this trend to lower temperatures. At a given temperature, our Li abundances are on average somewhat lower than those of the Gonzalez et al. (2009) sample. As elaborated on by them, the trend is not an artefact due to a correlation between temperature determination and abundance measurement. Furthermore, it is not connected to the decrease of the Li detection threshold with decreasing temperature, as most of the Li abundances are clearly above the thresold. This trend of decreasing Li abundance may be understood in the contect of the parametric mixing models presented in Palmerini et al. (2011, see their Fig. 1).

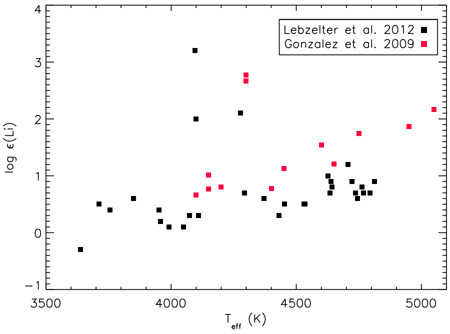

Fig. 2. Li abundance ($\log \epsilon$(Li)) versus effective temperature of the sample stars. Black symbols are stars from the survey of Lebzelter et al. (2012), red symbols are stars from the study of Gonzalez et al. (2009). The Li-rich stars deviate from the trend of decreasing Li abundance with decreasing temperature defined by the Li-*detected* stars.

2.4. Mass loss

There are claims in the literature that the Li-rich giant phenomenon could be accompanied by and connected with an episode of enhanced mass loss (de La Reza et al. 1996, 1997). We therefore searched for indicators of mass loss from our Li-rich sample stars. A comparison of the profile of the Hα line of Li-rich and Li-poor stars showed that there are no asymmetries in the lines of the Li-rich stars. This suggests that the *gas* mass-loss rate from these stars is not enhanced, within the resolution and S/N limits of our spectra.

An excess of flux in the mid-IR is an indicator for *dusty* mass loss. We therefore searched the Wide-field Infrared Survey Explorer (WISE) point source catalogue[1] for counterparts of our Li-rich stars. The $K-$ [12μm] colour is particularly sensitive to warm dust around stars. The result for our sample stars is shown in the upper panel of Fig. 3. The Li-rich stars, represented by red diamond symbols, have a $K-[12]$ colour consistent with zero, i.e. no enhanced dust mass-loss rate.

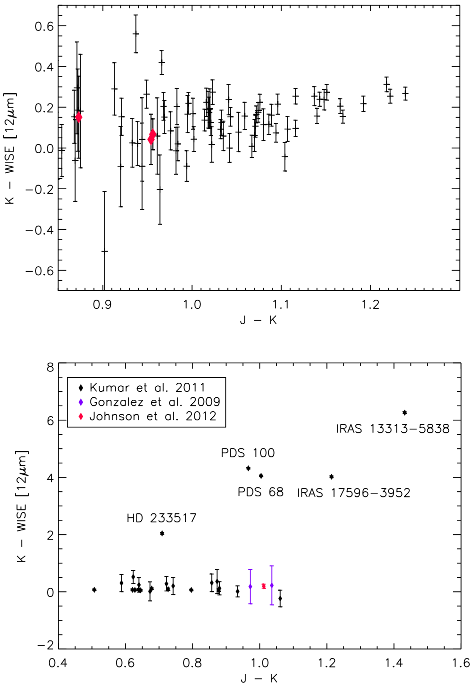

Fig. 3. *Upper panel:* $K-[12]$ vs. $J-K$ colour-colour diagram for the sample of Lebzelter et al. (2012). The Li-rich stars are represented by red diamond symbols. *Lower panel:* The same diagram for Li-rich stars from the literature, as indicated in the legend. The marked objects are discussed in the text (Sect. 2.4). Note the change in scales between the panels.

We also searched for the WISE 12 μm fluxes of Li-rich stars reported in the literature to compile a similar diagram for them. Most of these literature data come from Tables 1 and 2 of Kumar et al. (2011), where Table 2 is itself a collection of literature data (see their paper for references), but also the Li-rich stars reported by Gonzalez et al. (2009) and Johnson et al. (2012) are included. The release of the WISE all-sky catalogue has to be awaited to also include the Li-rich stars from other studies (e.g. Monaco et al. 2011; Ruchti et al. 2011). The result of this exercise is displayed in the lower panel of Fig. 3. It is clear that most stars form a sequence of photospheric colours ($K-[12] \approx 0$), only few stars deviate from this sequence, most of which are not normal K giants. For instance, IRAS 13313-5838 is a well-known post-AGB star. It is possible that

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[1] `http://irsa.ipac.caltech.edu/`

its strong 671 nm line is actually not caused by Li, but rather by Ce (Reyniers et al. 2002). Also IRAS 17596-3952 is a post-AGB candidate. Both PDS 68 and PDS 100 (aka V859 Aql) are probably T Tauri stars. In that case they would still carry their primordial Li abundance in the photosphere, which naturally is higher than the Li abundance expected for K giants. Only HD 233517 is a K-type giant with a dust disk of unknown origin around it.

Thus, we think that warm dust (~ 300 K) is not generally present around Li-rich stars. However, Kumar et al. (this issue) find that the mass-loss rate, as infered from IRAS photometry, correlates with Li abundance, albeit with a large scatter. We cannot exclude the presence of cool dust by investigating the $K - [12]$ colour, however the fraction of Li-rich stars with a considerable amount of warm dust around them must be low.

3. Correlation between lithium and technetium in low-mass AGB stars

Technetium (Tc) is an element that has only radioactively unstable isotopes, its logest-lived isotope produced by the s-process in low-mass AGB stars is ^{99}Tc with $\tau_{1/2} \approx 2.1 \times 10^5$ yrs. If absorption lines of this element are identified, it is a clear sign of recent or ongoing s-process close to the core of the star, and of a deep-mixing phenomenon called the third dredge-up (3DUP). We refer to Uttenthaler et al. (2007a) and references therein for details on the s-process and 3DUP, as well as on previous observational results. Here we concentrate on the correlation between the presence of Li and Tc in the atmospheres of low-mass AGB stars.

Two of the Li-detected bulge AGB stars of Uttenthaler et al. (2007b) also show Tc in their spectra (3DUP occurring), while two other stars showing Li are Tc-poor (no 3DUP). Furthermore, there are two stars in this sample that do have Tc, but no Li. In this bulge sample, Tc is found only in stars with long pulsation periods ($P \gtrsim 300$ d) and high luminosities. Also Li is confined to the more luminous and long-period objects ($P \gtrsim 280$ d). This already shows that there must be some connection between the presence of Li and Tc in low-mass AGB stars, although there is no 1:1 correlation. The high abundance of Li in one of the Tc-poor bulge AGB stars was explained in Uttenthaler et al. (2007b) by a fast mixing process below the convective envelope ("cool bottom processing") that drives the Cameron-Fowler mechanism.

A sample of 26 oxygen-rich (C/O<1), putative low-mass AGB stars in the Galactic disc is available from Uttenthaler & Lebzelter (2010) and Uttenthaler et al. (2011). Also in this combined sample, the fraction of Li-detected stars is higher among the stars with Tc than among the stars without Tc (80.0% compared with 43.8%). Unfortunately, the luminosities of Galactic disc stars are not well constrained, but also in this sample the tendency for a star to have Li is higher at longer pulsation period.

However, recent standard models of AGB evolution (Karakas et al. 2010) suggest that the observational picture could also be explained without invoking cool bottom processes: ^{7}Be-rich matter would be mixed to the surface naturally by 3DUP events, where it decays to ^{7}Li; the highest Li abundance would be found already *before* efficient 3DUP of C and s-elements takes place ($\log\epsilon(\mathrm{Li}) = 1.8$ in a $1.8 M_\odot$ model). The Li- and Tc-poor stars in the disc sample (9 out of 26) can then be interpreted as stars in which the Li abundance was diminished in the previous stellar evolution to below the detection threshold, and which did not (yet) undergo any "Be dredge-up". In the 7 stars with Li but without Tc, Be-rich matter was already dredged-up from regions close to the H-burning shell, but the convective envelope did not yet reach the regions where the s-process takes place. Only stars in the more advanced stages, which show both Li and Tc (8 out of 26 in this disc sample), dredge up also s-process enriched matter besides ^{7}Be. This evolution is supported by the fact that most stars seem to follow the evolution from (Li-poor,Tc-poor) → (Li-rich,Tc-poor) → (Li-rich,Tc-rich). Only two stars in this sample do have Tc but no Li, which poses a small problem to this theoretical framework. Either these stars have already lost all their ^{3}He, or the Li is destroyed by slow mixing in the inter-pulse phase between the 3DUP events.

The correlation between Li and Tc was also studied among S-stars (C/O~1) by Vanture et al. (2007). However, the situation is more complex there because of extrinsic S-stars (whose s-elements come from binary mass transfer), and because some stars might produce their large amount of Li by hot bottom burning.

4. Lithium production by hot bottom burning in long-period Miras

Bright red giant stars with very strong Li lines have been detected in the Magellanic clouds (Smith et al. 1995), but also in the Milky Way galaxy (García-Hernández et al. 2007). These are interpreted as being intermediate-mass stars ($M \gtrsim 4 M_\odot$) in which the H-burning takes place under convective conditions, called "hot bottom burning" (HBB). This allows for the Cameron-Fowler mechanism to produce large amounts of Li.

In our study of the evolutionary state of Miras with changing pulsation periods (Uttenthaler et al. 2011), we also identified stars that have a very strong Li 671 nm line and are thus candidates for intermediate-mass AGB stars undergoing HBB. The best example for this is the long-period Mira R Nor ($P \sim 500$ d). Besides the high Li abundance ($\log \epsilon(\mathrm{Li}) = 4.6$; Uttenthaler et al. 2011), indicators of a high mass are the secondary maximum in its light curve, the high luminosity, and the relatively small distance to the Galactic plane. Interestingly, R Nor was found to be Tc-poor. This could be a sign of either low dredge-up efficiency in intermediate-mass AGB stars, or the operation of the ^{22}Ne neutron source, which would hardly produce any Tc.

In our search for more Miras that could be intermediate-mass AGB stars, we found a UVES spectrum of R Cen, a long-period Mira that is also known to change its pulsation period (Hawkins et al. 2001). Figure 4 shows a comparison between the spectrum of R Nor and R Cen around the Li 671 nm line. The spectra are remarkably similar, even though the stars were observed with two different instruments, approximately ten years apart. Thus, we may assume that the stars have very similar Li abundance. Just as R Nor, R Cen has a period of $P \sim 500$ d (although the period may have halved in the recent years because the primary minima became much shallower) and is at a very small distance to the Galactic plane (only 8 pc), all of which are indicators of a relatively high mass of R Cen ($M \sim 4 M_\odot$). Also R Cen has no Tc.

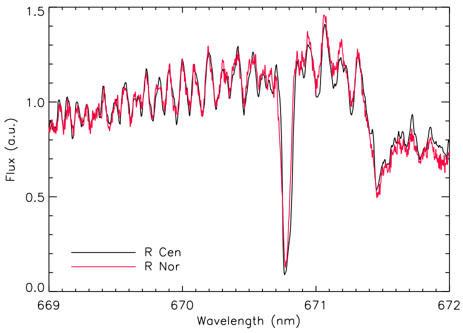

Fig. 4. The spectra of R Cen and R Nor around the Li 671 nm line.

A number of atomic resonance lines in both R Nor and R Cen (Na D doublet, Li 6708 Å, K 7700 Å) show blue-shifted absorption components from circumstellar material, indicating that these stars are losing mass. Thus, they might be in a phase where they pollute the interstellar matter with Li-rich material.

5. Conclusions and outlook

The phenomenon of the Li-rich K giants is still mysterious. Despite more and more such stars are being found in diverse stellar systems, no satisfactory explanation can be given for them. A step forward would be to determine precise luminosities, for which precise distances are required. Parallax measurements of many such stars will become available in the Gaia era. Furthermore, it would be of great help to know whether these stars are preferentially H-shell burning RGB or He-burning early AGB stars. The tools of asteroseismology can distinguish between these evolutionary stages (Bedding et al. 2011).

The Li-rich long-period Miras should be studied in more detail in the future. Only few observational constraints of the evolution of intermediate-mass stars on the AGB are available at the moment. However, they potentially play an important role in the evolution of Li in the Galaxy and in star clusters because of their very high Li abundance and high mass-loss rate. They might be responsible for polluting the intra-cluster gas of globular clusters (Lind et al. 2009), thus they are of importance on a larger scale.

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