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Observations of Li-rich giant stars in the Galaxy and in the Magellanic Clouds

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Abstract. The Lithium content in stars is very sensitive to the internal stellar conditions. Indeed, Lithium is readily destroyed in the interiors of low-mass main-sequence (MS) stars and the Li in the convective envelope is progressively depleted. The Li abundance at the stellar surface was expected to be further depleted after stars leave the MS and experience the first dredge-up. However, it is now almost 40 years ago that the first (surprising) detections of Lithium-rich cool giants were reported in the literature. Lithium-rich cool giants have been mainly detected both in our Galaxy and in the Magellanic Clouds, with a few examples in other galaxies. The Li-rich cool giant stars are mainly low-mass stars near the 'bump' in the red giant branch (RGB) phase or intermediate-mass stars on the asymptotic giant branch (AGB). Here I review the available spectroscopic observations of Li-rich giant stars in the Galaxy and in the Magellanic Clouds with a special emphasis on the intermediate-mass Li-rich cool giants on the AGB phase. Finally, I highlight the recent results regarding Li production on the RGB phase as obtained by on-going massive spectroscopic surveys such as Gaia-ESO, LAMOST and GALAH as well as the expected observations with future spectroscopic surveys like WEAVE and 4MOST.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

Lithium is observed at several evolutionary stages and types of stars. In low-mass red giants, the tidal interaction between binary stars and even planet engulfment seem to be the most accepted Li production scenarios today (see e.g. Casey et al. 2019). Here we mainly focus on the Lithium observations on even more evolved and massive stars. This is, pulsating stars at the asymptotic giant branch (AGB) phase (see Karakas & Lattanzio 2014 for a review). At the end of the AGB phase, low- and intermediate-mass ($1 \leq M \leq 8\ M_{\odot}$) stars experience thermal pulses (TPs) and strong mass loss. The strong mass loss efficiently enriches the interstellar medium (ISM) with specific isotopes and dust grains. The main processes of nucleosynthesis take place during the thermal pulsing phase on the AGB just before they form planetary nebulae. In particular, Lithium is theoretically predicted to be produced by "hot bottom burning" (e.g. Sackmann & Boothroyd 1992; Mazzitelli, D'Antona & Ventura 1999) in the more massive ($> 3{-}4\ M_{\odot}$) and O-rich AGB stars.

The first identification of truly massive ($> 3-4$ $M_{\odot}$) AGB stars dates back to about 40 years ago (Wood, Bessel & Fox 1983). Photometric surveys of AGB stars in the Magellanic Clouds (MCs) uncovered the first examples of very luminous O-rich AGB stars, while the C-rich AGB stars were generally found to be much fainter. These stars were found to be long-period variables (of Mira type) with periods between ~500 and 800 days and enriched in heavy neutron-rich s-process elements. They were found to be concentrated in a narrow luminosity range, with bolometric magnitudes (M_{bol}) between −7 and −6, being consistent with relatively high-mass progenitors (see Wood, Bessel & Fox 1983, for more details). Subsequent high-resolution optical spectroscopic surveys of visually bright AGB stars in both MCs (LMC and SMC) discovered that these stars are rich in Li, which confirmed the HBB activation in these stars (see e.g., Smith & Lambert 1989, 1990; Plez, Smith & Lambert 1993; Smith et al. 1995).

A more detailed chemical abundance analysis was carried out by Plez, Smith & Lambert in the early nineties. This study showed that the Li-rich HBB stars in the SMC display very low C isotopic ratios ($^{12}C/^{13}C$ ratios very near to the equilibrium values of ~3−4) as expected from HBB models. However, these stars were not rich in Rb but rich in other s-process elements like Zr and Nd (see Table 5 in Plez, Smith & Lambert 1993). This suggested that these low-metallicity HBB stars produce s-process elements via the ^{13}C neutron source (see also Abia et al. 2001). More recently, McSaveney et al. (2007) studied the near-IR spectra of Li-rich LMC AGBs and they could get N in two stars. The high N enrichment found provided the first observational confirmation of primary N production by the combination of HBB and the third dredge-up. Also, HBB stars have been identified in the very low-metallicity dwarf galaxy IC 1613 (Menzies, Whitelock & Feast 2015). One of these stars, G3011, displays a strong Li line and it is very likely Li-rich (see Fig. 2 in Menzies, Whitelock & Feast 2015). The average metallicity of IC 1613 is even lower than the SMC, down to $[Fe/H] \sim -1.6$ dex, but the HBB stars are likely younger and more metal-rich.

In our own Galaxy, high-resolution optical spectroscopic surveys of very luminous OH/IR stars were carried out about 10 years ago (García-Hernández et al. 2006, 2007). Most of the stars with periods longer than 400 days and OH expansion velocities (V_{exp}(OH)) higher than 6 kms^{-1} were found to be Li-rich; with the Li abundances ($\log\varepsilon$(Li)) ranging from ∼1 to 3 dex, which confirm them as massive HBB AGB stars. These massive Galactic AGB stars, however, are not rich in the s-element Zr (García-Hernández et al. 2007). In strong contrast with the SMC HBB stars, these Galactic stars displayed strong Rb overabundances; [Rb/Fe] ranging from 0 to 2.6 dex (see García-Hernández et al. 2006). In short, the more massive O-rich AGB stars of our Galaxy display strong Rb overabundances with only mild Zr enhancements, as expected from the strong activation of the Ne^{22} neutron source (García-Hernández et al. 2006).

García-Hernández et al. (2009) carried out a high-resolution optical spectroscopic survey of luminous obscured O-rich stars in the Magellanic Clouds and found the low-metallicity Rb-rich massive AGB counterparts. These stars are Li-rich and display extremely high Rb abundances. AGB evolutionary models for the LMC (Ventura, D'Antona & Mazzitelli 2000) predict these very luminous massive AGB stars and the contribution of HBB to the luminosity explains their luminosities in excess of the AGB theoretical limit ($M_{bol} \sim -7.1$). According to the models, these Rb- and Li-rich AGBs in the LMC could have progenitor masses of at least ~6−7 $M_{\odot}$.

More recently, a few massive Galactic AGB stars at the beginning of the TP phase have been identified, permitting the study of the nucleosynthesis at the early AGB stages (García-Hernández et al. 2013). These stars are super Li-rich ($\log\varepsilon$(Li) up to ~4 dex) and the strong Li is seen together with the complete lack of the s-process elements Rb, Zr, and Tc, as predicted by the theoretical models. This confirms that HBB is strongly activated at the early AGB stages and that the s-process is dominated by the ^{22}Ne neutron source.

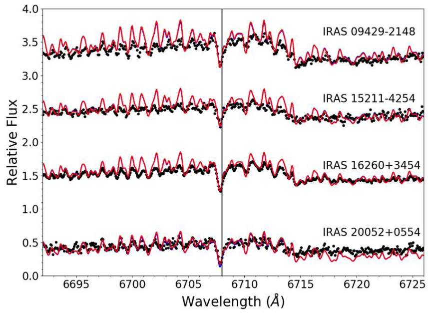

Fig. 1. Li I 6708 Å spectral regions in four massive Galactic Li-rich AGB stars. The hydrostatic models (blue lines) and the pseudo-dynamical models (red lines) that best fit the observations (black dots) are shown. The location of the Li I lines is indicated by a black vertical line. Adapted from Pérez-Mesa et al. (2019).

2. Exploratory pseudo-dynamical models

The extremely high Rb enhancements and Rb/Zr ratios observed in massive Li-rich AGBs could be artefacts of the abundance analysis and the adopted model atmospheres could fail to represent the real stars. Our research group at the IAC has been working on the development of more realistic model atmospheres for extreme AGB stars. For this, we started taking into account the presence of a circumstellar envelope (see Zamora et al. 2014; Pérez-Mesa et al. 2017 for more details).

The main result of our new pseudo-dynamical models is that the effect of the circumstellar envelope is dramatic and the new Rb abundances are much lower by orders of magnitude than those obtained with classical hydrostatic models. Also, the derived Rb abundances strongly depend on the mass loss and the expansion velocity. On the other hand, Zr is practically non affected by the presence of the circumstellar envelope and the Zr abundances with pseudo-dynamical models are nearly solar and very similar to those from the hydrostatic ones. This is because the ZrO band-head used in the chemical analysis is formed deeper in the atmosphere and much less affected than Rb.

Also, we very recently re-calculated the abundances of Li in Galactic massive O-rich AGBs by using these pseudo-dynamical models (Pérez-Mesa et al. 2019). The main finding is that the Li abundances are only slightly affected by circumstellar effects and the Li abundances are practically identical to those previously obtained with hydrostatic models by García-Hernández et al. (2007), which further confirm the HBB activation in solar metallicity massive AGBs of our Galaxy. In this case, the low Li content, as compared to Rb, likely explains the results with pseudo-dynamical models. Figure 1 displays some spectra of massive Li-rich AGBs and the best model fits around the Li I line at 6708 Å.

3. Independent confirmation of HBB in massive AGBs

The activation of HBB and Li production in Galactic massive AGBs can be independently confirmed by the CNO elemental and isotopic abundances as obtained from high-resolution spectroscopy in the near-IR. However, the modelling of the more evolved and extreme (dusty) AGB stars is challenging. This is due to several issues such as, for example, the fact that the observed near-IR spectra are usually veiled by hot dust emission.

In order to avoid this problem, we have observed a few (5) massive and (super) Li-rich AGBs at the beginning of the TP phase at high-resolution (R~50,000) in the near-IR with the GIANO spectrograph at the 3.6m TNG telescope (La Palma, Spain) (Pérez-Mesa et al. 2020). This is because such stars are less dusty and bluer, displaying simpler spectra that are more easy to model, but already showing the strong effects of HBB. A sample H-band spectrum together with the best synthetic spectrum are shown in Figure 2. The spectra are still very complicated to model and precise atomic and molecular linelists of molecules like CO, CN, OH, and water are needed. Interestingly, Pérez-Mesa et al. (2020) report the CNO elemental/isotopic abundances in the five early massive and Li-rich AGB stars studied so far. Their most important results are the high-N and low carbon isotopic ratios ($^{12}C/^{13}C < 10$) observed

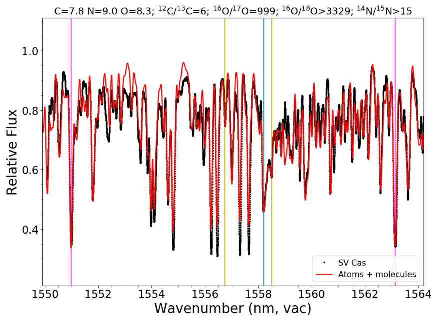

Fig. 2. The observed TNG/GIANO spectrum (black dots) of a Galactic massive Li-rich AGB star at the beginning of the TP phase and the best synthetic fit (red line) in the spectral region around 1157 nm, which is used to determine the CNO abundances in these stars. Adapted from Pérez-Mesa et al. (2020).

in all stars, which provides an indenpendent confirmation of the activation of HBB in massive Li-rich AGBs at solar metallicity.

It is to be noted here that we have also explored the circumstellar effects on the CNO abundances and isotopic ratios, finding that such effects are negligible in the near-IR. This is not surprising if we consider that the near-IR (e.g. H-band) spectral lines are formed deeper in the atmosphere where the circumstellar effects (and other effects like NLTE) are less severe than in the optical domain.

Finally, we would like to note that the far-IR Herschel observations of extreme (optically obscured) Galactic OH/IR stars also confirm the HBB nature of these stars. The oxygen and carbon isotopic ratios obtained from the observed water and CO lines are consistent with HBB (see Justtanont et al. 2013, 2015).

4. Li-rich carbon AGB stars

Remarkably, from the nineties we also know the existence of some, in principle lower mass and C-rich AGB stars that display Lithium (e.g., Abia et al. 1991, 1993, 2003). Such stars are also present in the Magellanic Clouds (e.g. Smith et al. 1995) and they only represent ∼1−2% of the C-rich AGBs, being usually super Li-rich. They still represent a puzzle and several possibilities have been proposed in the literature to explain their origin. Some of the possible scenarios include: i) thermally pulsing AGB stars with progenitor masses close to the limit for HBB; or ii) early AGB stars experiencing a non-standard mixing process, like the so-called “Cool bottom processing” (CBP) (see e.g. Abia et al. 2003 and references therein).

5. Results from on-going spectroscopic surveys

The SDSS-IV/APOGEE-2 is an on-going massive spectroscopic survey of Galactic giant stars in the near-IR H-band (see Blanton et al. 2017 and references therein). The resolution is around 22,500 and the H-band permits to obtain the abundances of up to 15 elements by using molecular (e.g., OH, CO and CN) and atomic lines. The abundances of some s-process elements like Nd and Ce as well as the C isotopic ratios can be also obtained in an important fraction of the stars observed. The SDSS-IV/APOGEE-2 survey will permit better studies of the HBB, third dredge-up and the s-process in massive AGB stars by observing a larger number of stars; especially in the inner Galaxy and the MCs. Also, studies of the mixing processes in RGB stars (including the Li-rich ones) will be possible.

Regarding the RGB stars, Singh et al. (2019) have very recently reported that the sample of Li-rich giants with both LAMOST spectra and Kepler data are all in the red clump (RC), in their core-helium burning phase. Figure 3 (adapted from Singh et al. 2019) displays the location of the these Li-rich giants in the H-R diagram as compared to other giants and non-giant stars in the LAMOST and/or Kepler fields.

Additional recent results on red giants from optical spectroscopic surveys are the following: 1) Smiljanic et al. (2018), using the Gaia-ESO survey, have reported 20 new Li-rich giants, but they covered different evolutionary stages like stars at the RGB bump, RC stars, early or binary AGBs or even stars with planet engulfment events (see also the contribution by L. Magrini, these proceedings); 2) Casey

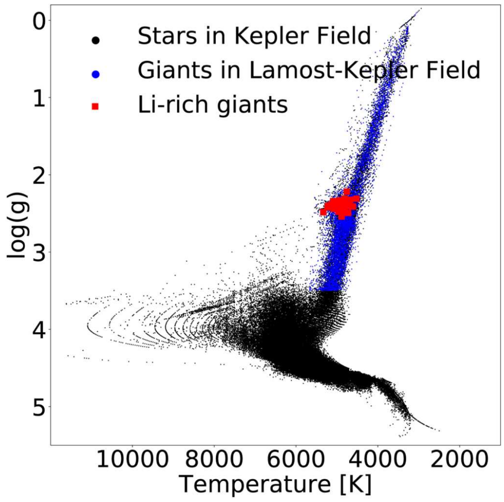

Fig. 3. The sample of 12,500 RGB stars (blue symbols) with both LAMOST spectra and Kepler data, along with the entire sample from the Kepler catalog as background (black symbols). The red symbols represent the Li-rich giant stars at the red clump. Adapted from Singh et al. (2019).

et al. (2019), using LAMOST data, have reported 2330 Li-rich giants, with 80% of them being red clump stars (see also Singh et al. 2019). Their favourite scenarios are the tidal spin-up by binary companion and the planet engulfment (see also the contribution by H. Yan, these proceedings).

In addition, the high-resolution (R∼28,000) spectroscopic survey GALAH is providing data for one million stars and it can provide the abundances from up to 30 elements; from Lithium to Europium. Indeed, Deepak & Reddy (2019) have recently reported 335 new Li-rich giants, suggesting that the origin of Li production may lie at the RGB tip during the Helium flash.

6. Future spectroscopic surveys relevant for Li-rich giants

What about the future? The WEAVE survey will use the William Herschel 4.2 meter telescope on the island of La Palma (Spain). It will consists on two optical (∼4000−9500 Å) spectroscopic surveys at medium- and high-resolution (around 5,000 and 20,000, respectively) and it is expected to observed millions of stars, especially in the outer Galactic disk. So, more observations of Li-rich giants are expected but this survey will cover many different topics such as Galactic Archaeology, Stellar, Circumstellar and Interstellar Physics, and Galaxy Clusters, among others. In a similar way but in the Southern Hemisphere, the ESO's 4MOST survey will use the VISTA 4.1 meter telescope in Chile. It will consists also on two optical (∼3700−9500 Å) spectroscopic surveys at medium- and high-resolution (around 5,850 and 19,500, respectively). There will be some open time (∼30% of the time available) and RGB stars out to about 50 kiloparsecs (even the faintest stars for Gaia) are expected to be observed.

7. Summary

In summary, the multiwavelength (from the optical to the far-IR) spectroscopic observations confirm the HBB activation (and Li production) in massive O-rich AGBs at different metallicities. However, the origin of the few (super) Li-rich C-rich AGBs still remains a puzzle. The Li production in RGB stars is mainly observed at the RC (the core-He burning phase), with the tidal spin-up by binary companion plus the planet engulfment being the favourite scenarios. There are several on-going and future spectroscopic surveys, but the most relevant for Lithium are in the optical; the on-going LAMOST and GALAH surveys as well as the upcoming WEAVE and 4MOST surveys.

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