Mem. S.A.It. Vol. 88, 336

Memorie della

Spectroscopic surveys of massive AGB and super-AGB stars

D. A. García-Hernández[1,2]

[1] Instituto de Astrofísica de Canarias, C/Vía Láctea s/n, E−38205, Tenerife, Spain
e-mail: agarcia@iac.es
[2] Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38206, Tenerife, Spain

Abstract. It is now about 30 years ago that photometric and spectroscopic surveys of asymptotic giant branch (AGB) stars in the Magellanic Clouds (MCs) uncovered the first examples of truly massive (> 3−4 $M_{\odot}$) O-rich AGB stars experiencing hot bottom burning (HBB). Massive (Li-rich) HBB AGB stars were later identified in our own Galaxy and they pertain to the Galactic population of obscured OH/IR stars. High-resolution optical spectroscopic surveys have revealed the massive Galactic AGB stars to be strongly enriched in Rb compared to other nearby s-process elements like Zr, confirming that Ne^{22} is the dominant neutron source in these stars. Similar surveys of OH/IR stars in the MCs disclosed their Rb-rich low-metallicity counterparts, showing that these stars are usually brighter (because of HBB flux excess) than the standard adopted luminosity limit for AGB stars (M_{bol} ∼ −7.1) and that they might have stellar masses of at least ∼6−7 $M_{\odot}$. The chemical composition and photometric variability are efficient in separating the massive AGB stars from massive red supergiants (RSG) but the main difficulty is to distinguish between massive AGB and super-AGB stars because the present theoretical nucleosynthesis models predict both stars to be chemically identical. Here I review the available multiwavelength (from the optical to the far-IR) observations on massive AGB and super-AGB stars as well as the current caveats and limitations in our undestanding of these stars. Finally, I underline the expected observations on massive AGB and super-AGB stars from on-going massive surveys like Gaia and SDSS-IV/APOGEE-2 and future facilities such as the James Webb Space Telescope.

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

1. Introduction

The first identification of truly massive (> 3−4 $M_{\odot}$) asymptotic giant branch (AGB) stars dates back to about 30 years ago (Wood, Bessel & Fox 1993). 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 are 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 1993, for

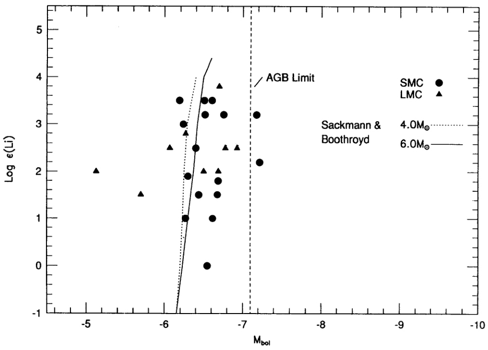

Fig. 1. Li abundances (derived by Smith et al. 1995) as a function of M_{bol} in O-rich HBB AGB stars in both Magellanic Clouds. Solar metallicitiy model abundances for HBB from Sackmann & Boothroyd (1992) are shown for two stellar masses. Adapted from Smith et al. (1995).

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 (see Figure 1), which confirmed the activation of the hot bottom burning (HBB) process 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 shows that the Li-rich HBB stars in the SMC display very low C isotopic ratios (very near to the equilibrium values) as expected from HBB models. However, these stars are not rich in Rb but rich in other s-process elements like Zr and Nd (see Table 5 in Plez, Smith & Lambert 1993). This suggests that these low-metallicity HBB stars produce s-process elements via the ^{13}C neutron source (see also Abia et al. 2001). More recently, 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]~ -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 (logε(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).

Figure 2 displays the Rb abundances obtained by García-Hernández et al. (2006) versus the V_{exp}(OH). The V_{exp}(OH) can be used as a distance-independent mass indicator in OH/IR stars. The strong Rb enhancement (up to $\sim$100 times solar) confirms the activation of the ^{22}Ne neutron source in massive AGBs. The AGB nucleosynthesis models can reproduce the observed correlation between the Rb abundances and the stellar mass. However, they cannot explain the extremely high Rb abundances seen in the more extreme stars (García-Hernández et al. 2006).

More recently, a few massive Galactic AGB stars at the beginning of the thermally pulsing phase have been identified, permitting us to study the nucleosynthesis at the early AGB stages (García-Hernández et al. 2013). These stars are super Li-rich (logε(Li) up to $\sim$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.

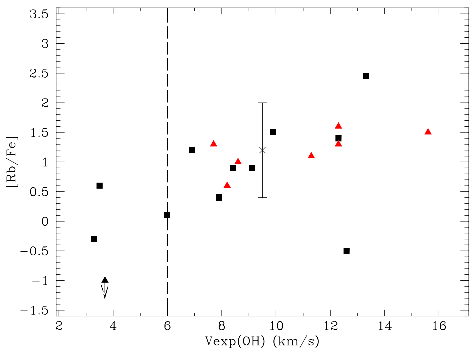

Fig. 2. Rb abundances in massive Galactic AGB stars, as obtained by García-Hernández et al. (2006), versus OH expansion velocity (V_{exp}(OH)). The abundance estimates that correspond to the photospheric abundance needed to fit the stellar component are shown with red triangles. A maximum error bar of ±0.8 dex is also shown for comparison. The star with high V_{exp}(OH) and no Rb, which does not follow the correlation observed is TZ Cyg, which possibly is a non-AGB star as it is not a long period, Mira-like variable. Adapted from García-Hernández et al. (2006).

2. Metallicity effects

The metallicity has a strong impact in the chemical evolution of massive AGB stars. Table 1 summarizes the observational properties of massive AGB stars in the Galaxy and the MCs. There are differences in the dust production, dredge-up efficiency and AGB lifetime with metallicity. Also, the HBB is activated for lower initial masses at lower metallicity. The Galactic stars are s-process poor with very high Rb/Zr ratios typical of high neutron density and the ^{22}Ne neutron source. On the other hand, the MCs stars are rich in s-elements but Rb-poor, with low Rb/Zr ratios characteristic of the lower neutron density of the ^{13}C neutron source.

But, where are the low-metallicity Rb-rich AGB counterparts? In 2009, we carried out a high-resolution optical spectroscopic survey of luminous obscured O-rich stars (including most of the known OH/IR stars) in the Magellanic Clouds and we found the low-metallicity Rb-rich massive AGB counterparts (García-Hernández et al. 2009). These stars display extremely high Rb abundances (from $\sim 10^3$ to 10^5 times solar). Interestingly, the Rb abundance jumps at a M_{bol} of −7 (see Fig. 3 in García-Hernández et al. 2009); a result that it is very useful to distinguish such stars in other Local Group galaxies.

3. Massive AGB or super-AGB stars?

AGB evolutionary models for the LMC predict the very luminous massive AGB stars mentioned above and the contribution of HBB to the luminosity explains their luminosities in excess of the AGB theoretical limit. According to these models, the Rb-rich AGBs in the LMC could have progenitor masses of at least 6−7 $M_\odot$ (see Fig. 7 in Ventura, D'Antona & Mazzitelli 2000) so it is actually not clear if they are massive AGB or super-AGB stars.

Indeed, both massive AGB and super-AGB stars can be easily separated from massive red supergiants (RSGs) by using the photometric variability or the chemical composition from high-resolution spectroscopy. However, the theoretical nucleosynthesis models predict massive AGB and super-AGBs to be chemically identical. In both types of stars, the HBB dominates and the s-process nucleosynthesis is mainly driven by the ^{22}Ne neutron source. Doherty et al. (2017) present the s-process predictions for super-AGB stars at several metallicities. It is clear that the s-process pattern of super-AGB stars is identical to the one expected in massive AGB stars, with Rb being by far the most abundant s-process element.

4. The Rb problem

The detection of Rb-rich AGB stars in the MCs (García-Hernández et al. 2009) uncovered a Rb problem that has two parts: i) the extremely high Rb overabundances observed ([Rb/Fe]∼3−5 dex); and ii) the large [Rb/Zr] (≥3−4) ratios. The standard theoretical models (e.g., van Raai et al. 2012) are far from matching the observational results and within the framework of the s-process it is not possible to overproduce Rb without co-producing Zr at similar levels.

Table 1. Main observational properties of Galactic HBB AGB stars compared to those of Magellanic Clouds (MCs) HBB AGB stars. Differences are attributed to metallicity effects.

	Dust production	Dredge-up	AGB lifetime	HBB activation	[s/Fe]	Neut. density	Neut. source
Galaxy	efficient	inefficient	small # of TPs	for M>4M$_\odot$	<0.5 dex	high	^{22}Ne
MCs	inefficient	efficient	large # of TPs	for M>3M$_\odot$	>0.5 dex	low	^{13}C

These standard theoretical models qualitatively describe the observations of Rb-rich AGB stars in both the MCs and our Galaxy, in the sense that increasing Rb abundances with increasing stellar mass and decreasing metallicity are theoretically predicted (see Table 2 in García-Hernández et al. 2009). However, the Rb abundance and the [Rb/Zr] ratio do not reach extreme values.

The extremely high Rb enhancements and [Rb/Zr] ratios are likely artefacts of the abundance analysis. So, the adopted hydrostatic model atmospheres likely fail to represent the real stars. More realistic model atmospheres for extreme AGB stars have been developed; i.e., taking into account the presence of a circumstellar envelope with a radial wind (Zamora et al. 2014). The main result of these new pseudo-dynamical (extended atmosphere) models is that the effect of the circumstellar envelope is dramatic and the new Rb abundances are much lower (sometimes by orders of magnitude) than those obtained with classical hydrostatic models (e.g., García-Hernández et al. 2006, 2009). On the other hand, Zr is practically non affected by the presence of the circumstellar envelope and the Zr abundances with pesudo-dynamical models are nearly solar; i.e., very similar to those from the hydrostatic ones. This is because the ZrO bandhead used in the chemical analysis is formed deeper in the atmosphere and much less affected than Rb (see Zamora et al. 2014).

The Rb abundances in the full sample of massive AGB stars in our Galaxy have been recently re-calculated with these extended atmosphere models by Pérez-Mesa et al. (2017). The results are shown in Figure 3, which compares the abundances with hydrostatic models with the new ones with pseudo-dynamical models. An important result is that the Rb abundances strongly depend on the mass-loss rate, which is unknown for these stars. Thus, in order to break the degeneracy in the model fits, accurate mass-loss rate estimates in these stars (e.g., by observing the CO rotational lines in the radio domain) would be needed.

In short, the new Rb abundances and [Rb/Zr] ratios derived with more realistic AGB model atmospheres significantly resolve the problem of the mismatch between the observations of massive Rb-rich AGB stars and the theoretical predictions. The new [Rb/Fe] abundances and [Rb/Zr] ratios range from 0.0 to 1.3 dex and from −0.3 to +0.7, respectively (see Fig. 11 in Pérez-Mesa et al. 2017). These ranges are in good agreement with the synthetic results of the Monash models; both the standard (van Raai et al. 2012; Karakas & Lugaro 2016) and the delayed superwind models (Karakas, García-Hernández & Lugaro 2012). However, the FRUITY[1] AGB models predict too low Rb abundances, being at odds with the observational evidence.

Also, we very recently re-calculated the abundances of Li by using these pseudo-dynamical models (Pérez-Mesa et al.; these proceedings). 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, which further confirm the HBB activation in massive AGBs of our Galaxy. In this case, the much lower Li column density as compared to Rb, likely

[1] FUll-Network Repository of Updated Isotopic Tables and Yields: http:// fruity.oa-teramo.inaf.it/.

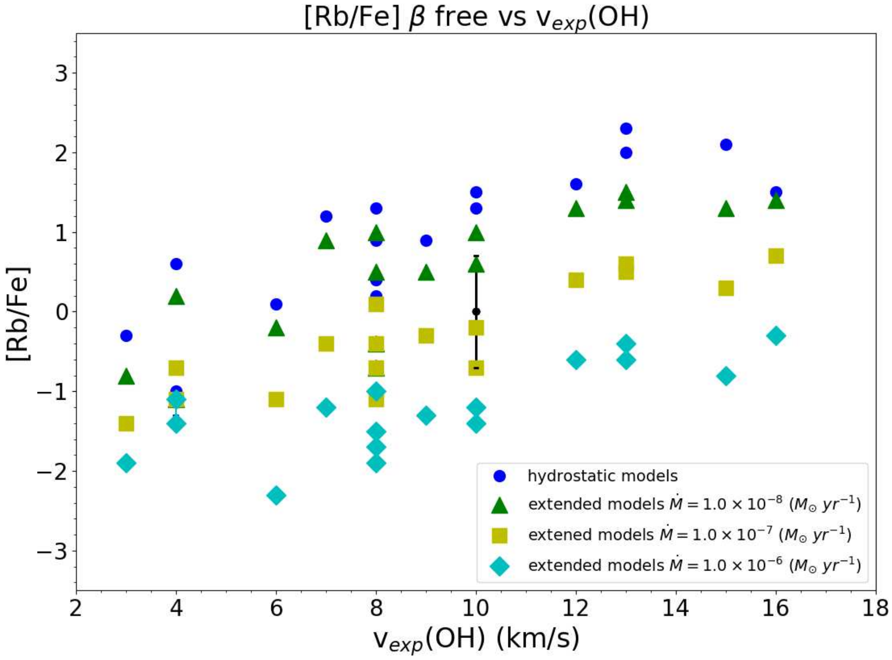

Fig. 3. Rb abundances vs. the expansion velocity (v_{exp}(OH)) for extended model atmospheres with $\dot{M}$ = 10^{-8}, 10^{-7} and 10^{-6} $M_\odot yr^{-1}$ (green triangles, yellow squares and cyan diamonds, respectively), as obtained by Pérez-Mesa et al. (2017), in comparison with those obtained by García-Hernández et al. (2006) from hydrostatic models (blue dots). Adapted from Pérez-Mesa et al. (2017).

explains the results with extended atmosphere models.

Finally, we note that the far-IR Herschel observations of extreme Galactic OH/IR stars also confirm the HBB nature of these stars. The O and C isotopic ratios obtained from the observed water and CO lines are consistent with HBB (see e.g., Justtanont et al.; these proceedings).

5. On-going spectroscopic surveys and future facilities

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 about 20,000 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 APOGEE-2 survey is the continuation of APOGEE-1, which already observed more than 150,000 stars. It is composed by two identical instruments in both hemispheres. APOGEE-2 will observe more than 300,000 stars (mainly RGB and AGB stars). Only a few detailed chemical analysis (from high-resolution near-IR spectroscopic data) of massive AGB stars have been carried out so far (e.g., McSaveney et al. 2007). Thus, APOGEE-2 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. New discoveries are also expected; e.g., the very recent identification of very low-metallicity HBB-AGB stars towards the Galactic bulge (Zamora et al., in preparation).

In addition, we are now in the Gaia era. Gaia is expected to provide the distances (and so the luminosities) for all types of Galactic AGB stars, giving strong constraints to the AGB theoretical models. For example, the luminosities would help to better distinguish massive AGBs from the more luminous super-AGB stars. However, we anticipate that this is going to be rather difficult because these stars are very faint (and strongly variable) in the optical Gaia bands.

Finally, the future James Webb Space Telescope (JWST) will be much more sensitive than Spitzer, with access to the near-IR range. This mission will permit near- and mid-IR spectroscopic studies of individual massive AGB and super-AGB stars in Local Group galaxies. Such observations would permit to study their dust chemical composition, mass-loss rates, dust production, as well as their temperatures and possibly abundances (see Boyer; these proceedings).

6. Summary

In summary, multiwavelength (from the optical to the far-IR) spectroscopic observations confirm the HBB and ^{22}Ne activation in massive AGBs (and super-AGB stars). Accurate mass-loss rates in these stars can break the degeneracy of the more realistic extended model atmospheres developed for these stars, which will permit more reliable Rb abundances. At present, we can efficiently distinguish between massive AGBs and RSGs; by using the photometric variability information and the chemical composition from high-resolution spectroscopic observations. However, massive AGB stars are chemically identical to super-AGBs and actual observational samples may contain super-AGB stars. On-going massive spectroscopic (and photometric) surveys like SDSS-IV/APOGEE-2 and Gaia as well as future facilities like the JWST will contribute to a better understanding of massive AGB stars and perhaps to the first unambiguous detection of a super-AGB star.

Acknowledgements. DAGH acknowledges support provided by the Spanish Ministry of Economy and Competitiveness (MINECO) under grant AYA−2014−58082−P. DAGH was also funded by the Ramón y Cajal fellowship number RYC−2013−14182.

References

Abia, C., et al. 2001, ApJ, 559, 1117
Blanton, M. R., et al. 2017, AJ, (arXiv:1703.00052)
Doherty, C. L., et al. 2017, PASA, (in press; arXiv:1703.06895)
García-Hernández, D. A., et al. 2006, Science, 314, 1751
García-Hernández, D. A., et al. 2007, A&A, 462, 711
García-Hernández, D. A., et al. 2009, ApJ, 705, L31
García-Hernández, D. A., et al. 2013, A&A, 555, L3
Karakas, A. I., García-Hernández, D. A., & Lugaro, M. 2012, ApJ, 751, 8
Karakas, A. I., & Lugaro, M. 2016, ApJ, 825, 26
McSaveney, J. A., et al. 2007, MNRAS, 378, 1089
Menzies, J. W., Whitelock, P. A., & Feast, M. W. 2015, MNRAS, 452, 910
Pérez-Mesa, V. et al. 2017, A&A, 606, A20
Plez, B., Smith, V. V., & Lambert, D. L. 1993, ApJ, 418, 812
Sackmann, I.-J., & Boothroyd, A. I. 1992, ApJ, 392, L71
Smith, V. V., & Lambert, D. L. 1989, ApJ, 345, L75
Smith, V. V., & Lambert, D. L. 1990, ApJ, 361, L69
Smith, V. V., et al. 1995, ApJ, 441, 735
van Raai, M. A., et al. 2012, A&A, 540, A44
Ventura, P., D'Antona, F., & Mazzitelli, I. 2000, A&A, 363, 605
Wood, P. R., Bessell, M. S., & Fox, M. W. 1983, ApJ, 272, 99
Zamora, O., et al. 2014, A&A, 564, L4