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Observational constraints on s-process nucleosynthesis in massive galactic O-rich AGB stars

D. A. García-Hernández[1], P. García-Lario[1,2], B. Plez[3], A. Manchado[4], F. D'Antona[5], J. Lub[6] and H. Habing[6]

[1] ISO Data Centre. European Space Astronomy Centre, ESA. Villafranca del Castillo. Ap. de Correos 50727. E−28080 Madrid. Spain, e-mail: Anibal.Garcia@sciops.esa.int
[2] Herschel Science Centre. Research and Scientific Support Department of ESA, European Space Astronomy Centre, Villafranca del Castillo, Ap. de Correos 50727. E−28080 Madrid, Spain
[3] GRAAL, UMR 5024, Université de Montpellier 2, F−34095 Montpellier Cedex 5, France
[4] Instituto de Astrofísica de Canarias, La Laguna, E−38200, Tenerife, Spain
[5] Osservatorio Astronomico di Roma, via Frascati 33, I−00040 MontePorzio Catone, Italy
[6] Sterrewacht Leiden, Niels Bohrweg 2, NL−2333 RA Leiden, The Netherlands

Abstract. Using high resolution optical spectroscopy (R∼40,000-50,000) we have derived the Li and Zr abundances of a large sample of galactic O-rich AGB stars. Our chemical analysis shows that some stars are Li overabundant while others are not. The observed Li overabundances are attributed to the activation of the so-called "hot bottom burning" (HBB) process, confirming that they are actually massive AGB stars. However, these stars do not show the zirconium enhancement (taken as a representative for the s-process element enrichment) usually associated to the third dredge-up. Our study reveals that the s-process element abundances of the more massive O-rich AGB stars in our Galaxy are dramatically different from those found in the equivalent population of AGB stars in the Magellanic Clouds. We conclude that probably the different metallicity environment can explain the differences observed.

Key words. Stars: AGB and post-AGB – Stars: abundances – Stars: atmospheres – Stars: evolution – Stars: interiors – Nuclear reactions: nucleosynthesis, abundances

1. Introduction

The spectral evolutionary sequence M-MS-S-SC-C observed in AGB stars does not consider the case of the more massive AGB stars (M $\gtrsim$ 3−4 $M_\odot$), where the convective envelope can penetrate the H-burning shell activating the so-called "hot bottom burning" (hereafter, HBB) process, which prevents the formation of carbon stars. HBB models (Sackmann & Boothroyd 1992, Mazzitelli, D'Antona & Ventura 1999, hereafter MDV99) predict also the production of the short-lived ^{7}Li through the so-called "^{7}Be transport mechanism" (Cameron & Fowler 1971). One of the

Send offprint requests to: D. A. García-Hernández

predictions of these models is that Li should be detectable, at least for some time, on the stellar surface.

The HBB activation in massive O-rich AGB stars is supported by studies of AGB stars of the Magellanic Clouds (hereafter, MCs) (e.g. Plez, Smith, & Lambert 1993, Smith et al. 1995). These stars are actually very luminous ($-7 \leq M_{bol} \leq -6$) Li-rich stars. In our own Galaxy, only a handful of Li-rich stars have been found so far (e.g. Abia et al. 1993) and, unlike those detected in the MCs, they are not so luminous ($-6 \leq M_{bol} \leq -3.5$). Moreover, they are low-mass ($M \lesssim 2-3\ M_\odot$) AGB stars with S-, SC- and C-spectral types where HBB is not expected to be active.

Another important characteristic of AGB stars is the presence of neutron-rich elements (s-process elements like Sr, Y, Zr, Ba, La, Nd, Tc, etc.) in their atmospheres which are the consequence of the slow-neutron captures produced during the thermally pulsing AGB phase. These s-process elements are believed to be formed during the interpulse period through the $^{13}C(\alpha,n)^{16}O$ reaction (e.g. Straniero et al. 1995). ^{22}Ne is another neutron source which can be activated, but only at higher temperatures during the thermal pulses (e.g. Gallino et al. 2000). Thus, a different s-element pattern is expected depending on which neutron source is more active. According to the most recent models ^{13}C is the preferred neutron source for masses around $1-3\ M_\odot$ while for intermediate mass stars (i.e., $M \gtrsim 3-4\ M_\odot$) the neutrons are thought to be mainly released by $^{22}Ne(\alpha,n)^{25}Mg$ (see e.g. Busso, Gallino & Wasserburg 1999 for a review). In the literature, there is a strong evidence that most galactic AGB stars enriched in s-process elements have masses around 1−3 $M_\odot$ (e.g. Lambert et al. 1995, Abia et al. 2001). Unfortunately, a confrontation of the predictions made by the HBB and s-process nucleosynthesis models with observations of more massive AGB stars in our Galaxy is not yet available.

2. Selection of the sample

The best galactic candidates to study the HBB activation and the s-process nucleosynthesis in massive AGB stars are the so-called *OH/IR stars*, luminous O-rich AGB stars extremely bright in the infrared, showing a characteristic double-peaked OH maser emission at 1612 MHz. These stars are also known to be very long period variables (LPVs), sometimes with periods of more than 500 days and large amplitudes of up to 2 bolometric magnitudes. However, they experience very strong mass loss rates (up to several times $10^{-5}\ M_\odot yr^{-1}$) and most of them are usually heavily obscured at this stage by thick circumstellar envelopes, making optical observations very difficult.

Thus, a large sample (102) of long-period (300−1000 days), large amplitude variability (up to 8−10 magnitudes in the V band), late-type (> M5) O-rich AGB stars displaying OH maser emission with a wide range of expansion velocities (from just a few km s^{-1} to more than 20 km s^{-1}) was carefully selected. Stars were included in the sample if satisfying at least one of the above conditions and ideally as many of them as possible, which guarantees that they are actually massive stars in the final stages of their AGB evolution. Consistently, stars in the sample display strong IR excesses detected by IRAS.

3. Optical observations and results

High resolution optical echelle spectra (R∼40,000–50,000) were obtained for all stars in the sample during several observing periods in 1996–1997. The two-dimensional frames containing the echelle spectra were reduced to single-order one-dimensional spectra using the standard ECHELLE software package as implemented in IRAF. Because of the very red colours of the sources observed, the S/N ratios achieved in the reduced spectra can strongly vary from the blue to the red orders (10-20 at ∼6000 Å while >100 at ∼8000 Å).

We detected the presence of the Li I resonance line at 6708 Å in 25 of the sources in the sample with a wide variety of strengths, while we did not find any signature of this line in 32 of the stars. The remaining 45 stars were too red or simply the optical counterpart was not found at the moment of the observations, being heavily obscured by their thick circumstellar envelopes.

In general, all stars (with or without lithium) show extremely red spectra with the flux level falling dramatically at wavelengths shorter than 6000 Å. In addition, the spectra are severely dominated by strong molecular bands mainly due to titanium oxide (TiO), as a consequence of the very low temperature and the O-rich nature of these stars. The TiO veiling effect is so intense that it is very difficult to identify individual atomic lines in the spectra of these stars with the exception of the Li I line at 6708 Å, the Ca I lines at 6122 and 6573 Å, the K I line at 7699 Å, the Rb I line at 7800 Å and a few strong Fe I lines. Calculating the radial velocities associated to the few atomic lines seen in our spectra, we conclude that the Li and Ca atomic lines and the TiO molecular bands must be formed deep in the stellar atmosphere, while the K I and Rb I absorption lines usually have circumstellar components. The presence of a circumstellar contribution to the observed K I and Rb I lines was actually found to be a common feature among the O-rich AGB stars in the sample. The elemental abundance of Rb in these stars is of special importance because it can be used as a neutron density indicator (see Section 5.2). Synthesis of the spectral region around the resonance line of Rb I at 7800 Å will be presented elsewhere.

Interestingly, the bandheads of ZrO (i.e. those at 6474 and 6495 Å) seem to be absent in all spectra. This is shown in Figure 1 where we show the spectral region around the ZrO bandheads at 6474 and 6495 Å. These ZrO bandheads (as well as those corresponding to other s-element oxides such as LaO or YO) are very strong in galactic S-stars and in massive MC AGB stars.

4. Chemical analysis

Our analysis combines state-of-the-art line blanketed model atmospheres and synthetic spectroscopy with extensive linelists. We have used the spherically symmetric, LTE, hydrostatic 'MARCS' model atmospheres for cool stars and the 'TURBOSPECTRUM' spectral synthesis code (Alvarez & Plez 1998) to derive the Li and Zr (taken as representative of all other s-process elements) abundances in those stars for which an optical spectrum could be obtained.

From an exhaustive study of the influence of the variations of the fundamental stellar parameters (e.g. T_{eff}, log g, M, z, ξ, C/O, etc.) on the synthetic spectra and from our knowledge of the main characteristics of our stars we obtained the most adequate initial set of parameters as well as their plausible range of variation, and we constructed a grid of MARCS model spectra.

Thus, we first determined by χ^2 minimisation which of the spectra from our grid of models provided the best fit to the observations in the 6670−6730 Å and the 6455−6499 Å spectral regions. The goal was to fit the overall shape of the spectra including the TiO bandheads, which are very sensitive to variations in the effective temperature. Then, the Li and Zr abundances were derived by fitting the Li I resonance line at ~6708 Å and the ZrO molecular bands at 6474 Å and 6495 Å, respectively. As an example, the best fit in the 6455−6499 Å spectral region around the ZrO bandheads is presented in Figure 2 for the star IRAS 11081−4203.

5. Discussion

5.1. Li and Zr abundances

Our chemical abundance analysis shows that half of the stars show Li overabundances in the range log ε(Li)~0.5−3.0[1]. A very similar range of Li overabundances is found in the massive O-rich AGB stars studied in the MCs (e.g. Plez, Smith, & Lambert 1993). The Li overabundances observed are interpreted as a signature of the activation of the so-called "hot

[1] Li abundance in the scale 12+log N(Li). Note that the uncertainty in the Li abundances derived is estimated to be of the order of 0.4−0.6 dex. This error reflects mostly the sensitivity of the derived abundances to changes in the atmospheric parameters taken for the modelling.

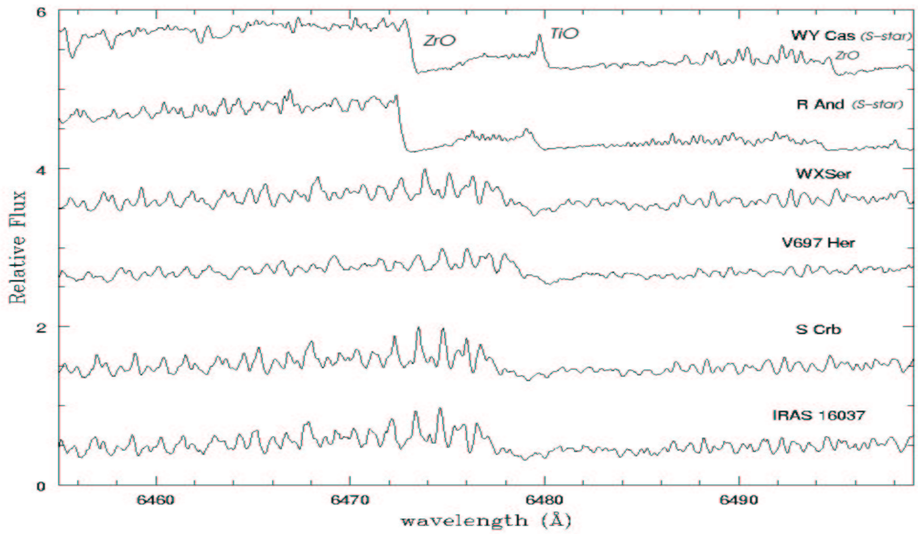

Fig. 1. High resolution optical spectra of sample stars displaying the lack of the ZrO absorption bands at 6474 and 6495 Å compared with two galactic S-stars (WY Cas and R And). WX Ser (IRAS 15255+1944) and V697 Her (IRAS 16260+3454) are Li-detected while S CrB (IRAS 15193+3132) and IRAS 16037+4218 are Li non-detected. The absorption band at ~6480 Å corresponds to the TiO molecule.

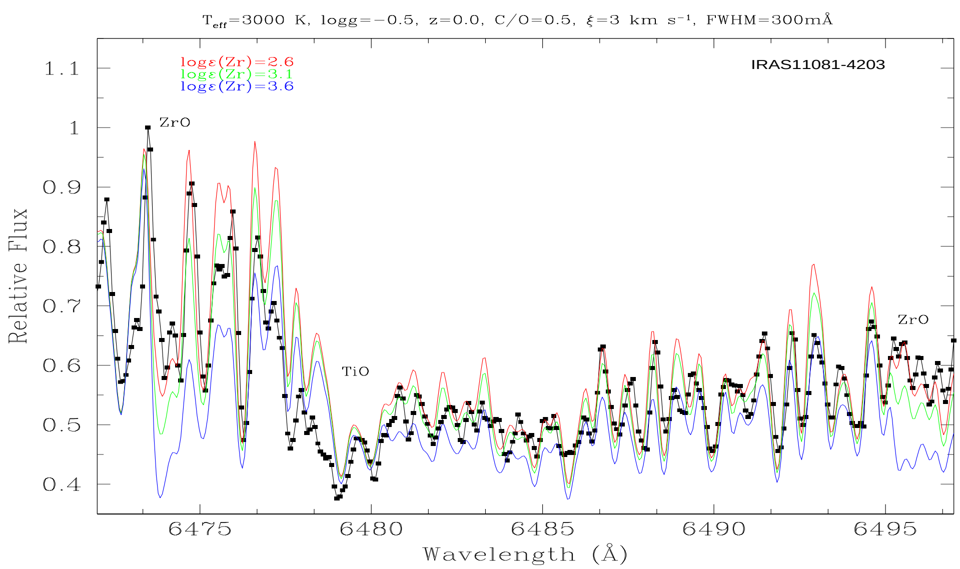

Fig. 2. Synthetic and observed spectra in the region 6460−6499 Å for the star IRAS 11081−4203, one of the Li detected stars in our sample. The synthetic spectra corresponding to [Zr/Fe]=+0.0, +0.5, and +1.0 dex (or log ε(Zr)=2.6, 3.1, and 3.6 dex, respectively) are shown. The Zr abundance derived from this spectrum was log ε(Zr)=2.6 which corresponds to the solar value. The parameters of the best model atmosphere fit are indicated in the top label.

bottom burning" (HBB), confirming that they are massive AGB stars (M $\gtrsim$ 4 $M_\odot$ according to MDV99 HBB models).

The non-detection of the ZrO molecular bands at 6474 Å and 6495 Å in any of the stars analysed imposed severe upper limits to the zirconium abundance ([Zr/Fe]<0.0−0.25 for $T_{eff} \geq 3000$ K and [Zr/Fe]<0.25−0.50 for $T_{eff} < 3000$ K). If the Zr enhancement is taken as a representative for the s-process enrichment, our results indicate that the massive AGB stars in our Galaxy are not S-stars.

5.2. s-process nucleosynthesis

The s-element abundance pattern generally found in galactic low-mass MS, S, and C(N-type) AGB stars (∼1−3 $M_\odot$, e.g. Lambert et al. 1995, Abia et al. 2001) can only be understood if the $^{13}C(\alpha,n)^{16}O$ reaction is the main neutron source at the origin of s-process nucleosynthesis. This reaction takes place in radiative conditions during the interpulse phase at low neutron densities ($N_n \lesssim 10^7$ cm^{-3}) and relatively low temperatures (T $\lesssim$ 3 x 10^8 K) (see e.g. Busso, Gallino & Wasserburg 1999 and references therein). In low-mass AGB stars only a minor contribution from the marginal activation of the reaction $^{22}Ne(\alpha,n)^{25}Mg$ during the convective thermal pulses is expected (see e.g. Gallino et al. 2000, Straniero et al. 2000). The ^{22}Ne neutron source requires higher temperatures (T $\gtrsim$ 3.5 x 10^8 K) and generally takes place at higher neutron densities ($N_n \gtrsim 10^{10}$ cm^{-3}). Thus, the $^{22}Ne(\alpha,n)^{25}Mg$ reaction is expected to be efficiently activated only in AGB stars of M $\gtrsim$ 3−4 $M_\odot$. The higher neutron density required by the $^{22}Ne(\alpha,n)^{25}Mg$ reaction strongly favours the production of neutron-rich nuclides like ^{86}Kr, ^{87}Rb, and ^{96}Zr because of the operation of a branching in the s-process path at ^{85}Kr (see Beer & Macklin 1989 for more details) which modifies the s-element production pattern.

According to the nucleosynthesis theoretical models, ^{96}Zr is expected to be overproduced at high neutron density through of the ^{95}Zr branch. In particular, the ^{96}Zr/^{94}Zr ratio is very sensitive to the neutron burst by the ^{22}Ne neutron source (e.g. Lambert el al. 1995, Lugaro et al. 2003b). Our chemical analysis shows that the bandheads of ZrO at 6474 and 6495 Å would be detected even for a very modest Zr enhancement regardless the Zr isotopic composition, and this is not observed in any star in the sample. This might be related to the precise neutron density in these stars for which a detailed model is required. The critical density for the activation of the ^{95}Zr branch (e.g. $N_n \gtrsim 2$ x 10^{11} cm^{-3}, Lugaro et al. 2003b) is about an order of magnitude higher than that of the ^{85}Kr controlling the Rb production ($N_n \gtrsim 3$ x 10^{10} cm^{-3}, Lambert et al. 1995). The maximum bottom temperature (and so, the neutron density; e.g. Gallino et al. 1998) increases with the TP number and thus, an important enhancement of ^{96}Zr in more advanced TPs would be expected. In this case, our observations suggest that the neutron density during the thermal pulsing phase may not exceed the critical density to activate efficiently the ^{95}Zr branch controlling the ^{96}Zr abundance in the stars observed. This would be consistent with these stars experiencing only very few thermal pulses during their AGB evolution. In any case, the Rb abundances are needed in order to reach any firm conclusion about the dominant neutron source at the origin of the s-process nucleosynthesis in these massive O-rich AGB stars. This is because the total Rb abundance and the relative abundance of Rb to other elements as well as Sr, Y and Zr are very sentitive to the neutron density and can vary by 1 order of magnitude depending on whether the $^{13}C(\alpha,n)^{16}O$ or the $^{22}Ne(\alpha,n)^{25}Mg$ reaction is more active (see e.g. Tomkin & Lambert 1999).

5.3. Comparison with the O-rich AGB stars in the Magellanic Clouds

The situation is quite different for the massive O-rich AGB stars in the MCs. Although ∼80% of them are also Li-rich, indicating that, indeed, they are HBB stars, these stars are s-element enriched (S-stars) in contrast with the results found in our galactic sample.

The different s-process element enrichment observed in the MCs with respect to our Galaxy may be just a consequence of the different metallicity. First, nucleosynthesis models predict a higher efficiency of the third dredge-up in low metallicity atmospheres (e.g. Herwig 2004) with respect to those with solar metallicity (e.g. Lugaro et al. 2003a). Second, mass loss, if driven by radiation pressure on the dust grains, might be less efficient with decreasing metallicity (Willson 2000). In that case, longer AGB lifetimes would be expected in the MCs. This would explain why even the more massive AGB stars in the MCs show a strong s-process enrichment in contrast to their galactic counterparts. In our Galaxy the only AGB stars showing a similar overabundance in s-process elements seem to be the result of the evolution of low-mass stars ($M \lesssim 2-3\ M_{\odot}$), while no or very litle s-process enhancement is observed in galactic AGB stars with higher main sequence masses.

Finally, the lower critical mass needed to develop HBB (e.g. $M > 3\ M_{\odot}$ at the metallicity of the LMC, compared to the $\sim 4\ M_{\odot}$ limit in our Galaxy) would favour the simultaneous detection of s-process elements and Li enrichment in a larger number of AGB stars in the MCs, as it is actually observed. In contrast to their MC counterparts, Li-rich massive AGB stars in our Galaxy would evolve so rapidly (because of the strong mass loss) that there is no time for a significant enhancement in s-process elements.

6. Conclusions

In summary, our results suggest that the dramatically different abundance pattern found in AGB stars belonging to the MCs and to our Galaxy can be explained in terms of the different metallicity conditions under which these stars evolved. This is the first observational evidence that the chemical evolution of massive AGB stars may be strongly modulated by metallicity. A complete description and discussion of these results as well as their evolutionary consequences will be given in García-Hernández et al. (2006, submitted). Obviously, theoretical models trying to describe the evolution of massive AGB stars must be able to reproduce the observational features here shown.

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