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Nucleosynthesis in Asymptotic Giant Branch Stars

Mounib F. El Eid

American University of Beirut, Department of Physics, P.O. Box 11-0236, Riad El-Solh, Beirut, Lebanon, e-mail: meid@aub.edu.lb

Abstract. The nucleosynthesis in asymptotic giant branch stars (briefly: AGB) is a challenging and fascinating subject in the theory of stellar evolution and important for observations as well. This is because about half the heavy elements beyond iron are synthesized during thermal pulsation phases of these stars. Furthermore, the understanding of the production of the heavy elements and some light elements like carbon and fluorine represent a powerful tool to get more insight into the internal structure of these stars. The diversity of nuclear processing during the AGB phases may also motivate experimental activities in measuring important nuclear reactions. In this contribution, we emphasize several interesting feature of the nucleosynthesis in AGB stars which still needs further elaboration especially from theoretical point of view.

Keywords: Stellar evolution, Nucleosynthesis

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INTRODUCTION

There is no intention to review the nucleosynthesis in AGB star in this space-limited contribution. Rather, we point out some important features of this involved subject in stellar evolution. A large body of literature exists on the AGB stars. Excellent reviews dealing with general properties of AGB stars including the nucleosynthesis in these stars is given by [2] and [3]. AGB stars are important in many respects: They represent the final evolution stages of low and intermediate stars that is of stellar masses 1 to 8 M⊙, and this mass range could be extended to about 12 M⊙. They are progenitors of C-O white dwarfs and O-Ne-Mg white dwarfs. The thermal pulsation phases of these stars create environments rich of nuclear processing. The nucleosynthesis during the AGB phases plays important role in understanding the origin of the elements in the galaxy (about half of the heavy elements are produced in this site). In addition, the AGB stars are major contributors to the integral luminosity of the intermediate-age stellar systems and so helpful for understanding extragalactic populations.

Modeling the AGB phases represents an involved problem owing to the cumbersome calculations requiring very large number of time steps, and a careful description of mixing processes which should be coupled to nuclear reaction in a consistent way. Also mass loss plays an important role which leads to the formation of white dwarfs following the phase of planetary nebulae. Finally, rotational effect may also influence the mixing process in AGB stars (see recent work by [4]. Our focus here will be to describe the link between the the physical processes and nuclear burning processes using few examples.

This contribution is organized as follows. A short review of the evolution toward the
AGB phase is firstly given in sect. 1. We then describe in sect. 2 important aspects of the nucleosynthesis in AGB phase. Concluding remarks are given in sect. 3

THE EVOLUTION TO THE AGB PHASE

In the left panel of Fig. 1, an example is given showing the main evolutionary phases of a 5 M☉ star in the Hertzsprung-Russell diagram (HR diagram) with the corresponding internal structure is displaced in the right panel of this Figure. The positions 1 to 2 mark the phase of core hydrogen burning on the main sequence. After this evolutionary phase, the overall contraction of the star leads to shell hydrogen burning (SHB) surrounding the still contracting helium core (or hydrogen exhausted core, see position 3). The SHB inflates the star which evolve to the red gant branch (RGB), where core helium burning ignites (position 4). The expansion of the star leads to an overall increase of the opacity and this leads to the development of a convective envelope which reaches its maximum depth at the position 5 as seen in the right panel of Fig. 1. This so called first dredge up phase leads to a change of the surface composition of the star, because the product of SHB are mixed up to the surface. The expansion of the star weakens SHB so that the luminosity drops after the position 5. The ensuing evolution is characterized by the development of a loop ending at position 6 in the case of the 5 M☉ star. This so called blue loop is characterizing this phase of evolution in the mass range between 4 and 12 M☉. The mean reason behind triggering the blue loop is the enforcement of the SHB.

A recent study showing the sensitivity of the loop formation to convective mixing and nuclear reaction is presented by [1]. It is intersecting to note that these blue loops occur in the region of the cepheid instabilities so that available observations may be used for testing the theoretical description of their formation (see [1] for details). The core helium burning phase ends after the position 6, and the star evolves back to the RGB, where envelope convection develops again and this is the second dredge up episode which is marked in the right panel in Fig. 1. The second dredge up does not occur in stars of initial masses less than 4 M☉ in case of initial solar metallicity. After this episode the star becomes an AGB star. This phase has remarkable characteristics.

- Contracting core composed mainly of carbon and oxygen representin the main products of He-burning. In the core the temperature is not high enough to enable carbon ignition.
- A hydrogen-burning shell which mainly supplies the star’s luminosity.
- A helium-burning shell confined to a thin mass region, because enough helium must be present in a region of sufficiently high temperature needed for the helium fusion process, that is in excess of $10^8$ K. But since the helium burning proceeds by the triple-alpha process which is extremely temperature dependent, the resulting large energy flux cannot be transported by radiative diffusion, rather convective instability builds up. This is described in the next section in more details. In other words, the violent He-burning in a thin shell of an AGB star triggers the pulsation which is the last evolutionary phase of stars which are progenitor of white dwarfs, that is those with initial masses 1 to 8 M☉, and this mass range may extend to 12 M☉ depending on initial metallicity. In the next section, we describe the main
FIGURE 1. Evolution in the HR diagram of a 5 M⊙ star of initial solar-like composition (left panel. The evolution of the corresponding internal structure with time is shown in the right panel, black areas represent convective regions. The first and second dredge up episodes are marked in the right panel (see text for details). Part of these evolutionary calculations have been parented by [1].

FIGURE 2. Schematic picture showing the general feature of the outer layers of an AGB star during two pulsation episodes, see text for details.

ASPECTS OF NUCLEOSYNTHESIS IN AGB STARS

The effect of the first dredge up and the second dredge up is to modify the CNO abundances increasing the surface abundances of $^4$He, $^{13}$C, $^{14}$N and decreasing of those of $^{12}$C, $^{16}$O, $^{18}$O. During the thermal pulsation on the AGB, nuclear burning...
leads to the production of various elements like $^{12}\text{C}$, $^{14}\text{N}$, $^{16}\text{O}$, $^{19}\text{F}$, $^{22}\text{Ne}$, $^{23}\text{Na}$ and the products of the s-process nucleosynthesis. All these products are mixed up to the surface by the operation of the third dredge up. The description of this convective episode linked to the pulsations and to the nucleosynthesis is a challenging problem in stellar evolution. In the following we give an overview summarizing the main points.

Fig. 2 illustrates in a schematic way the evolution of an AGB stellar model through two successive pulses. Above the C-O core is the He-burning shell, while the H-burning shell is very close to the base of the convective envelope. When He-burning starts, it leads to a development of a convective zone which extends very close to the H-burning shell. The released energy flux leads to a violent expansion of the star so that the H-burning shell becomes extinct momentarily. This expansion phase leads to a deeper penetrations of the convective envelop into the region processed by the helium burning. This the phase of third dredge up which mixes $^{12}\text{C}$ to the surface. This repeated dredge up leads to carbon-rich envelope and this enable the formation of carbon stars which are believed to be the progenitors of the mainstream silicon-carbide (SIC) grains.

But there is a certain problem how to obtain the right amount of $^{13}\text{C}$ in order to activate the neutron source for the s-process via the reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$. The creation of $^{13}\text{C}$ proceeds via $^{12}\text{C}(p, \gamma)^{13}\text{C}$, thus needs the right amount of protons originating from the H-rich envelope. This situation is subtle, since the protons must diffuse beyond the edge of the convective envelope, as predicted on the basis of the Schwarzschild criterion for convection, in order to create the right amount of $^{13}\text{C}$. Too many diffused protons are not desirable since the full CN-cycle would produce $^{14}\text{N}$. Not enough diffused protons will not lead to the right amount of $^{13}\text{C}$. The question how the process of the extra mixing of proton really works remains under investigation.

### comments on the s-process in AGB stars

When describing the s-process in a standard way, the neutron density is relatively low of the order of $10^8\text{cm}^{-3}$. In this case, $\beta^-$-decay follows always the neutron capture and branching to more neutron rich nuclei is inhibited. However, branching along the s-process path can be demonstrated using the Zirconium isotopes (Zr) with mass numbers A=90 to 96. Along this path, the isotope $^{93}\text{Zr}$ has a relatively long half-lifetime of 1.5 My, while $^{95}\text{Zr}$ has a half-life time of only 64 days. At a neutron density below $3 \times 10^8\text{cm}^{-3}$, $^{95}\text{Zr}$ decays into $^{95}\text{Mo}$ over $^{95}\text{Nb}$, but for higher neutron densities, the reaction $^{95}\text{Zr}(n, \gamma)^{96}\text{Zr}$ becomes effective and leads to a subsolar ratio of $^{96}\text{Zr}/^{94}\text{Zr}$ found in SiC grains, which seem to have been formed in the carbon-rich envelopes of AGB stars ([6]). In this context, it is interesting to note that the neutron source delivered by the $^{22}\text{Ne}$ existing in the helium zone via the reaction $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ may be needed to achieve the branching to $^{96}\text{Zr}$, if the Zr isotope ratios are produced in low mass AGB stars below 3 to 4 $\text{M}_\odot$ ([6]). The activation of this source may occur by a kind of overshooting (or extra mixing)
at the base of the pulse driven convective helium burning zone (see Fig. 2). This is an interesting link between mixing and burning in AGB stars. It is clear that well known nuclear reaction rates are needed in the study of this scenario.

**Fluorine synthesis in AGB stars**

Another important nucleosynthesis process is that of the fluorine (19F) production in AGB stars which is essentially a neutron capture process. This element is produced by the reaction chain: 14N(α, γ)18F(β+ν)18O(p, α)15N(α, γ)19F. The protons are produced by the reaction 14N(n, p)14C, while the neutrons are liberated by 13C(α, n)16O. The last reaction in this chain needs a temperature range of (2 − 3) × 10^8 K. Thus, it occurs during the pulse in low mass AGB stars below about 3 M_☉, or in intershell region in more massive ones. This means that the fluorine production is linked to the s-process in AGB stars and to their structure of different masses.

**On the Li production in AGB stars**

The last item to be present concerns some comments on the Lithium (Li) production in AGB star. This is a delicate issue indeed. It is a process which occurs during the so called hot bottom burning (HBB). This is an envelope convective burning, where the convective envelope reaches the top of the H-burning shell (see Fig. 2). But such a process does not occur unless the initial stellar mass is above 4 M_☉ in case of initial solar-like metallicity, but it could as low as 2 M_☉ for zero initial metallicity ([7]. The HBB is very sensitive to mass loss by stellar wind which can reduce the mass of the envelope so that the HBB will be shut off. The temperature required for HBB is at least 10^7 K, which means that only very small mass range of the order of 10^-4 M_☉ is involved. The process of HBB is difficult to describe, because it requires time-dependent mixing coupled to nuclear burning. Important consequences of HBB are particularly the Li production, and the prevention of the formation of carbon stars, since carbon is processed to nitrogen via the full operation of the CNO cycle. Therefore, understanding the nature of HBB helps to constrain the stellar mass range for carbon stars.

The Li production is a challenging physical process. It occurs via the PPII chain: 3He(α, γ)7Be(e^-ν)7Li. The production of Li requires high temperature to create 7Be, and mixing to transport it to cooler region to enable electron capture. It seems that HBB can facilitate this process. But modeling this scenario should take into account the competition between the turn-over time scale (or convective time scale) and the nuclear burning time scale which needs weak interaction as well. It seems that the time scale for the alpha capture on 3He is much longer than the convective time scale implying that 3He will be homogeneous in the envelope but not 7Be or 7Li. The net effect is that Li is destroyed when passing through the bottom of the envelope and is replenished by 7Be produced at the bottom of the envelope by
\[ ^3\text{He} + \alpha. \] It is clear that this process will go on as long as the \(^3\text{He}\) reservoir is not exhausted

**CONCLUSIONS**

We have shortly described some features of the nucleosynthesis in AGB stars to illuminate its importance for the theory of stellar evolution and to motivate some activities in nuclear astrophysics dealing with measuring the rates of key reactions. The main impact on the theory is the consistent coupling between the mixing processes by standard convection and eventually rotationally induced mixing and nuclear burning. Elaboration of modeling the AGB stars is needed concerning mass loss, convection including extra mixing to determine the convective boundaries, and last not least considering possible uncertainties in relevant nuclear reaction rates.

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