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Introduction to Asymptotic Giant Branch Stars

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Introduction to Asymptotic Giant Branch Stars

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Abstract. A brief introduction on the main characteristics of the asymptotic giant branch stars (briefly: AGB) is presented. We describe a link to observations and outline basic features of theoretical modeling of these important evolutionary phases of stars. The most important aspects of the AGB stars is not only because they are the progenitors of white dwarfs, but also they represent the site of almost half of the heavy element formation beyond iron in the galaxy. These elements and their isotopes are produced by the s-process nucleosynthesis, which is a neutron capture process competing with the β^- radioactive decay. The neutron source is mainly due to the reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. It is still a challenging problem to obtain the right amount of ^{13}C that can lead to s-process abundances compatible with observation. Some ideas are presented in this context.

1. Introduction

Observations of M-type stars show their spectra dominated by molecular spectra, such as TiO. The observations of carbon stars show that the $\text{C/O} > 1$ in contrast to normal stars or interstellar medium. In other words, these stars are carbon rich due to the third dredge up during the thermal pulsations of AGB stars described below in sect.3.

Another spectral peculiarity of cool giants is enhanced bands of s-process elements, in particular ZrO, which again indicates the role of the third dredge up. Note that stars showing bands of ZrO and TiO are called MS stars. An interesting element produced in AGB stars is ^{19}F by neutron capture process. A famous element usually quoted is the Technetium (^{99}Tc) with half-life time of $2 \cdot 10^5$ yrs. This s-process element serves as direct observational evidence of a new heavy element produced in a star. More about the s-process in the extended talks by M. Lucaro in this proceeding. The luminosity can reach values more than 10,000 solar luminosity and bolometric magnitudes is in the range $M_{bol} = -3.6 - 7.61$.

The HR diagram of globular clusters showing the existence of AGB stars is a fundamental demonstration of their formation. Due to the limited space for this contribution, we only summarize some important issues related to the AGB stars. Their evolutionary route is described in sect.2., the main characteristics of the AGB evolution is given in sect.3, concluding remarks are presented in sect.4.

2. The evolution to the AGB stage

Every star formed in the universe must evolve through the phase of core hydrogen burning either by the proton-proton chain for stars of masses $M \leq 2.0 M_{\odot}$, or by the CNO cycle for higher masses. This evolutionary phase has deep meaning. It is characterized by the low efficiency



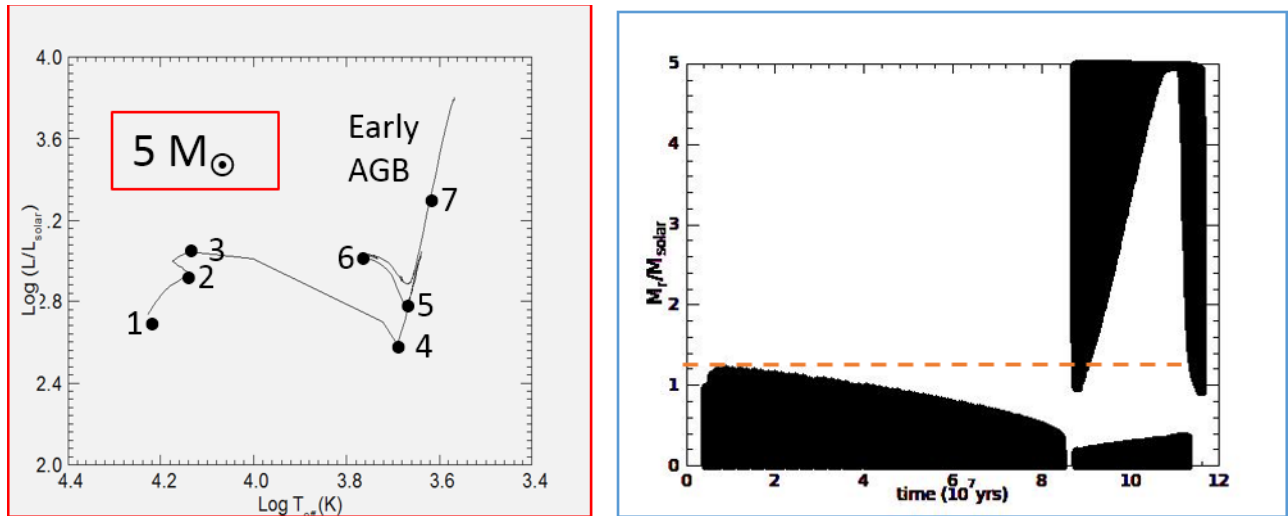


Figure 1. Evolution of a $5 M_{\odot}$ star of solar-like initial composition in the HR diagram (left panel), and its internal structural evolution with time (right panel). Note that the black regions are convective. This calculation was carried up to the early AGB stars. The first extension of the outer convective envelope marks the *first dredge up*, and the send downward penetration marks the *second dredge up*. Details of such calculations including other masses are described in [4]

of nuclear burning, namely the rate of transformation of H to He of 0.71%. This is the mass difference in synthesizing helium from four protons. This number is one of six numbers shaping the universe [1]. The main characteristics of the evolution of stars which reach the AGB stage is as follows:

- The relevant mass range for this type of evolution is $(1 - 10) M M_{\odot}$. It is a real challenging task to discuss this mass range. One distinguish between the normal AGB stars which are the progenitors of the carbon/oxygen (or C/O) white dwarfs, which do not evolve though the carbon burning phase. A review paper on AGB stars is given by [2]. The so called super-AGB stars are the massive ones, which evolve through carbon burning to form electron degenerate oxygen/Neon (or O/Ne) white dwarfs. The stars which do not end as O/Ne white dwarfs belong to the electron capture supernovae. It is rather surprising to read in a very recent preprint [14] the following remarks: the initial mass range for entering the super-AGB phase is $(7 - 9) M_{\odot}$ as obtained by [5] with assumed initial solar metallicity, but the critical mass for carbon ignition could decrease to $5.4 M_{\odot}$ according to [6]. The reason for this strong variation is attributed to the treatment of the convective boundary mixing and to the yet uncertain C12+C12 reaction rate. In any case, the mass range representing the progenitors of the O/Ne white dwarfs seems to be rather narrow.
- The inspection of Fig.1 reveals the evolutionary phases till the early AGB stage. The main sequence phase occurs between the positions 1 to 2 corresponding to core hydrogen burning occurring in a convective core of decreasing mass as shown in the right panel of Fig.1, where hydrogen transformed to helium. This phase is followed by shell hydrogen burning (H-burning). The released energy leads the star to evolve to the red giant branch (RGB), from positions marked 3 to 4. The expansion leads to an increase of the opacity causing the enveloper to become convective and start penetrating the stellar layers to mix the product

of shell H-burning to the surface as seen in the right panel of Fig. 1 (details of this subject is found in a recent work by [3]. this stage is marked as *first dredge up* (FDUP). Core He-burning starts at position 4 in the Fig. 1 and the star ascends the RGB. The core He-burning diminishes the role of the H-burning shell, so that the luminosity drops to position 5 in Fig. 1. But what happens subsequently between positions 5 and 6 is the occurrence of a loop to higher effective temperature, the so called "blue loop" triggered by the increasing energy production in the hydrogen burning shell encountering higher hydrogen abundance created by the FDUP. This episode is described in details in the paper by ([4], [3]). The major part of core He-burning occurs in the neighborhood of position 6 in Fig. 1. The evolution proceeds back to the RGB, where a second *second dredge up occurs* (SDUP), before the star evolves to position 7 marked as early AGB stage. It is emphasized that the SDUP occurs only in stars of masses $\geq 4 M_{\odot}$, since the envelope convection does not extend to the processed layers by the H-burning shell in these relatively lower mass stars.

- When the star reaches the *early AGB stage* (about position 7 in Fig. 1), it has the structure consisting of a C/O core, a helium shell and a hydrogen shell. The luminosity of the star is mainly supported by the H-burning shell, which becomes weaker due to the expanding outer layers. This leads the star to contract until the He-rich thin layers become hot enough to ignite He in a thin stellar region. The large energy release by the triple alpha-process characterizing the He-burning cannot be transported by radiation with the result that a helium convective zone develops and forces the star to expand. This marks the thermal pulsation of the AGB phase of evolution. In other words, thermal pulsation is an a double shell burning with short (order of years) rather violent He-flash and a long phase (greater than 30,000 years) of shell-hydrogen burning. In the next sect., we give some comments on the AGB evolution describing some open problems.

3. Remarks on the AGB evolution

This evolutionary phase is the most complicated in this context due to the many involved physical effects (description of convective mixing and burning, mass loss, equation of state, opacities and numerical treatment). We use Fig. 2 to describe the main characteristics of this type of evolution. This Fig. shows two consecutive thermal pulses in a schematic way. After He-ignition in the thin He-shell and the formation of the convective He-burning shell, the convective envelope recedes in mass and the H-burning shell becomes severely reduced in its efficiency. However, the gradually decreasing efficiency of He-shell burning causes the envelope to contract, so that the H-burning shell recovers its role in determining the star's luminosity. Following this contraction, the convective envelope penetrates toward the Helium and carbon rich layers. When this happens, protons are mixed into these layers (marked proton mixed downward in Fig. 2) and can interact with carbon to produce ^{14}N by the CNO cycle, and also neutrons by the reaction the reaction chain shown in Fig.2. The produced neutrons enable the formation of the main component of the s-process, and the production of the element ^{19}F as well.

The main problem with this scenario is to get the right amount of ^{13}C during the interphase period. It is a problem of the proton mixing into the carbon-rich layers. Too many mixed protons is not desirable, since the CN cycle would operate producing ^{14}N , which acts as neutron poison. While few mixed protons is also not desirable, since not enough amount of ^{13}C is produced. But how are the protons mixed? and how extended is the mixed region?. One way is to use a diffusion process for proton mixing with exponentially decreasing diffusion coefficient. This treatment has been suggested by the multidimensional fluid simulation of [13]. However, to use such a description in the one-dimensional calculation can only be done in a parameterized way.

We cannot discuss all aspects of neutron production in the AGB phases in this short contribution. We just summarize interesting features of recent investigations. In the work by

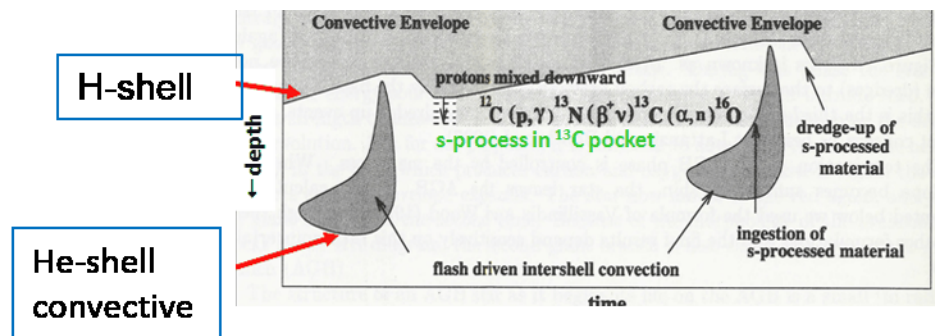


Figure 2. Schematic illustration of two consecutive thermal pulses of an AGB star. Similar graph is found for example in the paper by [2], see text for description of the Figure

[7], there is an interesting distinction between the low-mass AGB stars (LMS) of initial masses $< 4 M_{\odot}$ and more massive ones (IMS) with respect to the neutron source. In case of the LMS, the neutron source is dominated by the reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$, which emphasizes the amount of produced ^{13}C , usually termed ^{13}C pocket. The larger the core mass on the AGB, the lower the ^{13}C amount, owing to the narrower intershell layers. For example, this pocket is four times smaller than in case of a $6 M_{\odot}$ star compared to a $2 M_{\odot}$ star according to [11]. In contrast, in case of the IMS, larger temperatures are found ([7]) at the base of the convective He-shell during the pulse, so that the reaction $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ is activated. An indication of this activation is the Rubidium (^{87}Rb) enhancement, whose production is by-passed during the radiative ^{13}C burning because of the ^{85}Kr branching ([11]). It is amazing to find out that in case of LMS an overshooting at the bottom of the convective He-shell could also activate the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction (see discussion in [12]). Indication of this kind of burning could be done by analyzing the ratio of the Zirconium isotopes $^{96}\text{Zr}/^{94}\text{Zr}$ which can be measured in SiC grains. The point here is that along the Zr isotopic chain, two unstable isotopes are encountered, ^{93}Zr with a lifetime of 1.5 My, and ^{95}Zr with lifetime of 64 day. In other words, only released neutrons from the ^{22}Ne neutron source can produce ^{96}Zr .

Finally, we mention the most recent considerations, those by [8] and [9]. A new approach is suggested dealing with the ^{13}C production. These authors argue that for long time the adopted amount of ^{13}C was taken to be about $10^{-3} M_{\odot}$. However, an amount about four times larger seems to be required to explain the chemical evolution of the s-process species. The suggestion is to consider the effect of the magnetic field. According to the recent paper by [9], the buoyancy of magnetized plasma structures promotes down-flow of envelope material to ensure mass conservation. This can lead to a more extended ^{13}C pocket. Such consideration rely on the analytic solution of the ideal magnetohydrodynamic equations presented by [10]. Such calculations as they are presented are free of parametrization. Multidimensional simulations seem to be useful in order to justify this conclusion.

4. Summary

Some remarkable features of the evolution on the AGB are as follows:

- Stronger He-shell flashes give rise to deeper dredge up, which also depends on the envelope mass, thus on the mass loss rate during pulsations.
- How does a simultaneous treatment of burning and mixing affect the third dredge up?
- higher luminosity during pulsation is related to deeper dredge up
- The neutron source via the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction is dominant only in the low-mass AGB's

of initial mass $< 4 M_{\odot}$. For the more massive AGB's, the reaction $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ becomes an effective neutron source influencing the branchings along the s-process path.

- The effect of the magnetic field on the mixing process on the AGB adds a new physical ingredient indeed. As mentioned above, it seems that magnetohydrodynamic processes at the bottom of the convective envelope promote a down flow of the proton-rich material into the carbon-rich layer to produce larger amount of ^{13}C . In this case, no parameterized extra mixing at the edge of the envelope would be required. A final word is to say: modeling of the AGB phases of stars remains an interesting and challenging topic in Astrophysics

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