Magnetic and non-magnetic AGB mixing for *s*-processing

Maurizio Busso[1,2,*]

[1]Department of Physics and Geology, University of Perugia, Via A. Pascoli snc, I-06125 Perugia, Italy
[2]INFN Section of Perugia, Via A. Pascoli snc, I-06125 Perugia, Italy

Abstract. I outline a few features of recent models for the formation of the neutron source ^{13}C(α,n)^{16}O in low mass stars ($1 \lesssim$ M/M$_\odot \lesssim 3$, *LMS*) ascending for the second time the Red Giant Branch, generally called *Asymptotic Giant Branch*, or *AGB* stars. I also briefly outline the nucleosynthesis results obtained trough them. The mentioned models consider the physical structure below the frequent downward extensions of the convective envelope into the He-intershell (the so-called *third dredge-up* or *TDU* episodes). There, the conditions are such that the occurrence of further mixing is strongly facilitated, due to the minimal temperature gradient. A way to induce proton mixing from the envelope (certainly not the only one) arises whenever the ambient magnetic fields expected for LMS promote the buoyancy of strongly magnetized flux tubes. I review some characteristics of the ensuing mixing episodes, mentioning how different hydrodynamical processes might yield similar effects, thus encouraging stellar physicists to verify in more detail this possibility.

1 Introduction

In another lesson at this school [1] the general picture of neutron-capture nucleosynthesis was layed down and due space was dedicated to the slow (*s*) process of neutron addition, occurring in low mass stars ($1 \lesssim$ M/M$_\odot \lesssim 3$). There, the involved evolutionary stages are those of the so-called *Asymptotic Giant Branch*, when the repeated activation of the neutron sources ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg make moderate neutron fluxes available, feeding nucleosynthesis along the valley of β stability [2, 3].

Of the two mentioned neutron sources, the first is the dominating one, but its activation is not straightforward in current stellar models, as it requires that considerable amounts of ^{13}C be available in the He-rich layers of the star, while previous shell-H burning through the CNO cycle is expected to consume carbon to minimal concentrations.

Actually, ^{12}C is abundantly reproduced in the relevant layers, thanks to He-burning occurring in a thin shell above the border of a degenerate C-O core. Then, sudden variations in the thermal properties (*Thermal Pulses*), due to instabilities occurring in *thin shell* nuclear burning [4, 5] spread the produced carbon throughout the He-rich zone (at an abundance of about $20-25\%$). Hence, what is really needed is just a mechanism introducing protons from the envelope into those layers, during the *TDU* episodes [1]. They would then be rapidly captured by ^{12}C via:

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^{+}\nu)^{13}\mathrm{C} \tag{1}$$

*e-mail: maurizio.busso@pg.infn.it

For several years the required mixing processes remained rather mysterious and their efficiency was simply parameterized [2, 6]. They need to involve a concentration of protons small enough to avoid that, after reaction (1), ^{13}C itself be efficiently destroyed by further proton captures, producing ^{14}N. Indeed, nuclear descendants of this isotope act as *neutron poisons*, preferentially absorbing rather than producing neutrons, thus making the whole mechanism inefficient.

In section 2 I report on an attempt at founding the ^{13}C formation on physical grounds, based on the known property of LMS to host magnetic fields, organized in flux tubes, maintaining a *stellar dynamo* process [7]. There, I also show some nucleosynthesis results obtained in that scenario, where a remarkable agreement with observations emerges. Basic properties of such a mixing model, suitable to be shared by other physical processes, are then presented in section 3, as a stimulous to other groups to propose complementary ways of driving slow neutron captures in AGB stars.

2 ^{13}C from magnetic buoyancy and the ensuing nucleosynthesis

Broadly speaking, it is self-evident that magnetic fields of considerable geometrical and evolutionary complexity are generated in complex electrically-conducting astrophysical fluids [8]. The explanation of the huge observational evidence that magnetic fields persist in LMS for extremely long times requires that, in the induction equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B} - \eta \nabla \times \vec{B}) \tag{2}$$

(where η indicates the coefficient of Ohmic diffusivity) a dynamically-consistent velocity field $\vec{u}$ is found with inductive properties capable of sustaining $\vec{B}$ against dissipation. This is the *dynamo problem* of stellar plasmas, extensively discussed in many papers, e.g. in [9]. For our purposes, it is sufficient to remember the simple model developed, in a purely toroidal geometry, by [10], where the geometrical simplification permitted to derive exact $3D$ analytical solutions for magnetic buoyancy. From these solutions Trippella et al. [11] demonstrated that, at the bottom of a TDU episode, a penetration of protons can occur, with a mass distribution described by the relation:

$$\Delta M_p \simeq X_p \frac{4\pi \rho_E}{\alpha} [r_e^2 - \frac{2}{\alpha} r_e + \frac{2}{\alpha^2}] - [r_p^2 - \frac{2}{\alpha} r_p + \frac{2}{\alpha^2}] e^{-\alpha(r_e - r_p)} \tag{3}$$

Here, r_p and r_e are the values of the stellar radius at maximum penetration and at the envelope border, ρ_e is the average gas density at the convective border and X_p is the fractional mass of protons in the envelope. In the formula, the parameter α is adjusted so that proton pollution is limited to zones of viscosity small enough that the treatment by [10] of an almost ideal MHD holds. This depends on the stellar parameters of the case considered, but the polluted mass is normally around $0.004 - 0.005$ M$_\odot$: see [12] for details.

The resulting proton abundance profile in the affected region is illustrated in Figure 1 (i). When H burning restarts in the shell above these layers, it produces the distribution of ^{13}C and of ^{14}N shown in Figure 1 (ii).

Nucleosynthesis models for Galactic stars, computed by assuming the presence, at each TDU episode, of a ^{13}C reservoir from equation (3), were presented recently by [12, 13]. When adopting nuclear inputs for neutron-capture cross sections and for weak interaction rates as discussed in [14] and after averaging over standard choices for the Initial Mass Function and for the Star Formation Rate, it is possible for such models to reproduce the solar abundance distribution of heavy elements quite well, obtaining a remarkable consistency with the complementary predictions of fast neutron captures (the *r*-process).

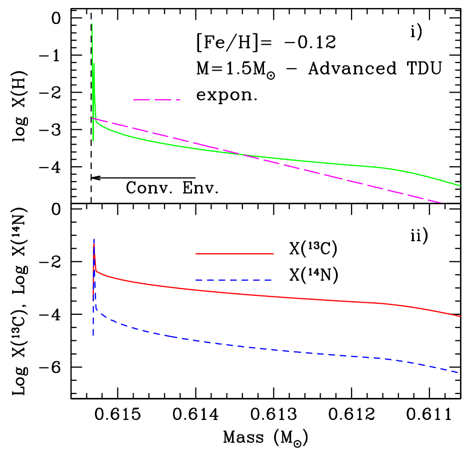

Figure 1. Upper panel: the reservoir (often called *pocket*) of protons mixed from the envelope, as a consequence of magnetic buoyancy computed according to [10, 11]. Lower panel: the ensuing distribution of ^{13}C and ^{14}N, established after burning is restarted in the H shell . As indicated in the label, the plot refers to an intermediate evolutionary stage of a 1.5 M$_{\odot}$ Thermall-Pulsing (TP) AGB star of almost solar metallicity

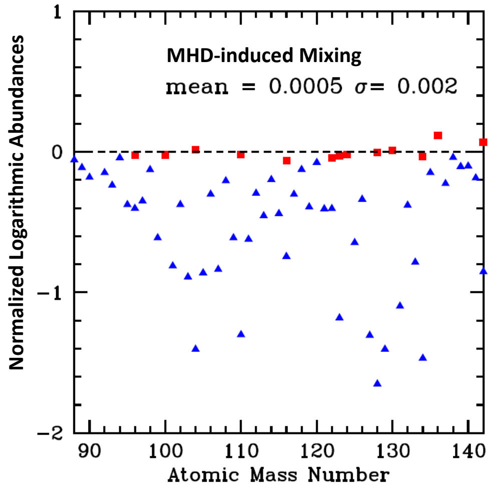

Figure 2. Predictions of the solar fractional abundance distribution from the models of stellar and galactic *s*-process nucleosynthesis discussed in the text, for nuclei from ^{88}Sr to ^{142}Ce.

This is shown in Figures 2 and 3.

Displayed in Figure 2 are the logarithms of solar abundance fractions due to *s*-processing, in the mass range 88 $\lesssim$ A $\lesssim$ 142, resulting from the computations outlined above (see [15] for details). The nuclei shielded from fast decays (*s*-only isotopes) are indicated in red. As is seen in the figure, models for galactic *s*-process nucleosynthesis computed with ^{13}C pockets derived as in Figure 1 correctly predict for them abundance fractions close to unity. Blue triangles then represent the ensuing *s*-fractions of other nuclei, to be compared with expectations from the *r* process.

Such a comparison was performed by [15], by adopting the site-independent *waiting point* approach to fast neutron captures, with updated inputs for nuclear masses and decay rates. Figure 3 shows the discrepancies between the two sets of predictions. For the sake of the comparison, from *r*-process computations yielding expectations X_r for the nuclei in the given mass interval, the *s*-process *residuals*:

$$X_s = 1 - X_r \tag{4}$$

were derived. Then the ratios among the data of Figure 2 and these last estimates are shown in Figure 3. It is evident that a remarkably consistent view of neutron captures emerges, with few outlying nuclei. The peculiar nuclear problems affecting each of them was then discussed by [15] in the light of possible new measurements aimed at resolving these remaining discrepancies.

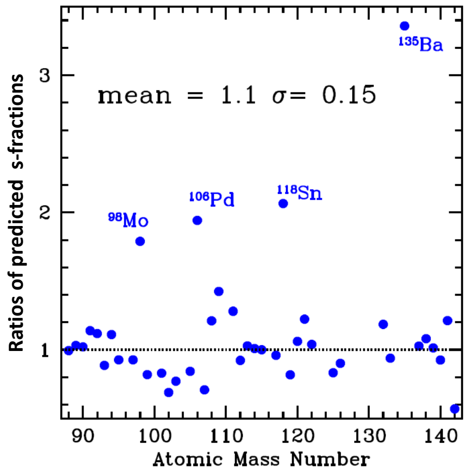

Figure 3. Discrepancies between the expectations of solar abundance fractions from slow neutron captures derived from the models discussed here and the *s*-residuals computed from *r*-process models according to relation (4).

The complementary results obtained by [14] in comparing *s*-process model predictions from the above scenario with isotopic ratios of heavy nuclei measured in presolar SiC grains of AGB origin [16] added further credibility to the global picture.

3 Characteristics of mixing models needed for AGB *s*-processing

In the proton distribution of Figure 1, panel i), the local concentration is very low (see the comparison, in the figure, with a purely exponential profile). This implies that, at the re-ignition of H-burning in the shell, proton captures do occur on ^{12}C producing ^{13}C, but minimal traces of ^{14}N can be synthesized (Figure 1, panel ii). Hence, neutrons made available by the $^{13}C(\alpha,n)^{16}O$ source remain largely unfiltered by intermediate-mass *poisons*, that would mainly result as daughters of ^{14}N-induced reactions.

These peculiarities of the models are crucial to obtain good agreement with various observations (see discussion in [11, 12, 15]). They induce remarkble differences with respect to previous models.

- First of all, the concentration of ^{19}F, produced from reactions starting at nitrogen, is strongly reduced with respect to what was obtained with exponential-like ^{13}C pockets. This fact favors agreement with fluorine observations [17].
- The extended ^{13}C pockets obtained in the above scenario make the nucleosynthesis of heavy nuclei from the ^{13}C(α,n)^{16}O source more efficient than before.
- A lower ^{14}N concentration also implies a reduced formation of ^{22}Ne, and a reduced efficiency of neutron captures in the warmer conditions of the thermal pulses, induced by the chain:

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}. \tag{5}$$

  The available neutrons are therefore primarily released by the ^{13}C(α,n)^{16}O reaction, at very low neutron densities. The type of neutron captures descending from this situation implies in general less-pronounced branchings with respect to previous AGB models. This fact favors agreement with presolar grain isotopic ratios, as shown in [14].

All this ultimately descends from the fact that, in the models discussed, protons penetrate exponentially *in density* (equation (12) in [11]), not in mass. This introduces the quadratic terms in equation (3), implying an extended profile with a concentration of ^{13}C lower than in previous models (e.g. lower than in [3]).

As mentioned, the scenario depicted starts from the fact that the temperature gradient below TDU is not steep. Should temperature follow a profile less steep than $1/r$, this would produce *naturally* an expansion, as described by Parker in his seminal works on the solar wind [18, 19]. In [10] it was shown that, with a slightly steeper gradient of T, a non-static equilibrium forcing mixing is in any case induced by a magnetic field (hence a Lorentz force) varying in time.

This discussion implies therefore that any other hydrodynamical mechanism operating in the mild T gradient below TDU and introducing in the plasma forces varying in time, might be suited to induce mixing processes similar to the ones described here.

I strongly encourage stellar physicists to further verify this possibility, thus expanding our understanding of AGB mixing and of the neutron captures induced by it.

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