PROCEEDINGS OF SCIENCE

Introduction to the s process and nucleosynthesis in AGB Stars

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PoS(ENAS 6)042

We review the main nucleosynthesis processes occurring in Asymptotic Giant Branch (AGB) Stars. They provide the production, in the He-rich layers above the degenerate C-O core, of intermediate-mass nuclei like ^{12}C, ^{19}F, ^{22}Ne and of heavy, neutron-rich species (the *s* elements). They also include modifications to the abundances of elements up to Mg-Al, through proton captures occurring above the H-burning shell. The uncertainties still affecting these processes (especially in terms of mixing mechanisms and mass loss rates) are briefly outlined. We also discuss in some detail the recent discovery (from young open clusters) that the abundances of neutron capture elements have continued to increase after the formation of the Sun, contrary to expectations. This fact requires some modifications of the previously accepted scenario for slow neutron captures and indicates that important contributions to the *s* process must come from very low mass AGB stars ($M \lesssim 1.5\, M_\odot$).

VI European Summer School on Experimental Nuclear Astrophysics, ENAS 6
September 18-27, 2011
Acireale Italy

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1. Introduction

AGB stars are known in Nuclear Astrophysics mainly for being the site where the dominant part of the *s*-process occurs, i.e. where the slow addition of neutrons, roughly proceeding along the valley of β-stability, produces $\sim 50\%$ of all nuclei beyond the Fe-peak [1]. There are however other elements and isotopes for which AGB stars are important manufacturing sites. We can broadly divide them into two groups: H-burning products (generated or modified in regions across and above the H-burning shell) and He-burning products (mainly produced in the underlying He-rich zones, above the degenerate C-O core). Several nuclei from both layers are the objects of direct observational tests, which provide important constraints to the nucleosynthesis mechanisms and their rates, so that in what follows we shall briefly recall the main features of these two AGB environments.

In general, quantitative estimates of AGB nucleosynthesis are still hampered by large uncertainties in some basic ingredients of stellar physics. One of them is certainly the mass loss history, which establishes the fraction of the envelope mass that can be polluted with new nuclei. Too strong mass loss rates would prevent a star from experiencing a sufficient number of ignition episodes from the He-burning shell (the so-called *thermal pulses*) before ejecting the envelope. This would strongly limit their contribution to the chemical evolution of galaxies in carbon, fluorine and *s*-elements. The knowledge of mass loss rates of AGB stars is unfortunately very poor and only now it is starting to become quantitative, thanks to recent surveys in mid-far infrared (IR) from space missions (ISO, MSX, Spitzer) and to near-IR imaging from the VMC survey of the VISTA telescope [2, 3]. As an example, Figure 1 shows how known mass loss rates (measured at radio wavelengths) can now be correlated to IR colors, in the aim of deriving trends that can then be applied to sources with unknown mass loss [4]. Despite the use of space-based observations and of the best available mass loss rates and distances, such relations still give poor constraints.

Other uncertainties concern the mixing phenomena (both convective and diffusive) that take care of transporting newly synthesized species to the surface. This problem affects both the occurrence of proton captures above the H-burning shell, and the nucleosynthesis in deeper, He-rich layers. Here the main neutron source is recognized to be the ^{13}C(α, n)^{16}O reaction, whose activation however depends on still unknown mechanisms that must inject hydrogen from the envelope into the He-rich region. These protons subsequently react on the abundant ^{12}C, producing ^{13}C. Current modeling attributes the injection episodes either to a naturally-decaying velocity profile of the convective eddies at the inner envelope border [5] or to more efficient transport induced by rotational, diffusive or magnetic phenomena [6, 7].

The same kind of phenomena have been invoked for explaining the isotopic and elemental anomalies characterizing low mass red giants, in phases subsequent to the so-called *Luminosity Bump*, when the advancement of the H-burning shell erases the chemical discontinuity left behind by the first dredge up. The coupled mixing and burning processes responsible for these peculiarities are discussed in Section 2. In Section 3 we shall instead outline the scenario of *s*-process nucleosynthesis in the He layers of AGB stars with masses in the range $1.5 - 3\ M_{\odot}$, as emerged in the past two decades. Then, in Section 4 we shall present recent results in this field, namely the discovery, from VLT observations of open clusters, that stars of very low mass ($M \lesssim 1.5\ M_{\odot}$) should be the site of even more effective neutron capture processes, which have started to domi-

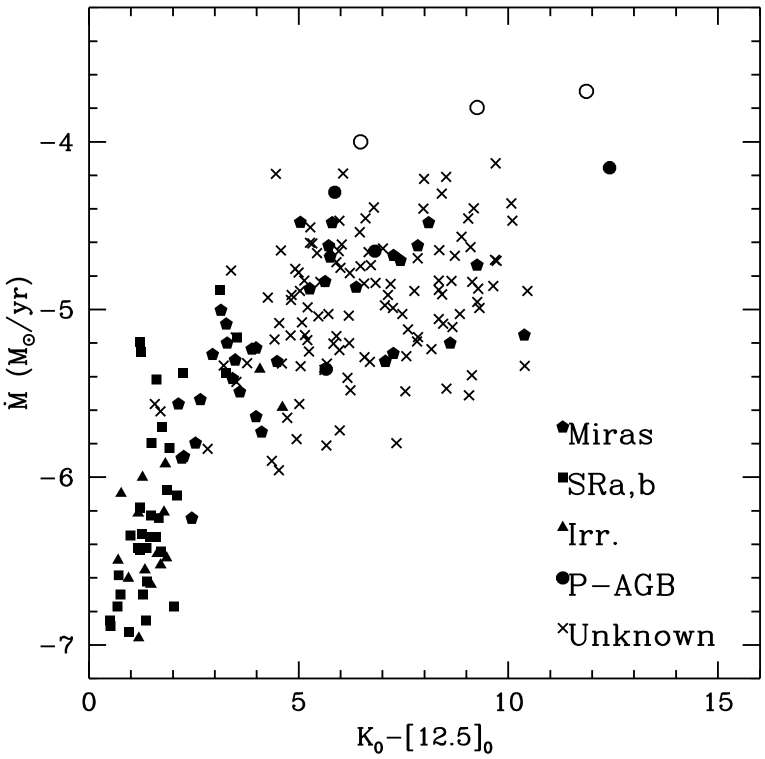

Figure 1: Mass loss rates of various classes of AGB stars, as a function of the infrared color K-[12.5] computed from ISO and MSX data. The relation is not linear and still rather disperse.

nate the Galactic evolution of heavy elements after the formation of the Sun. Preliminary models of the chemical evolution of the Galaxy including these assumptions are discussed in Section 5, while Section 6 will summarize the main conclusions and outline the basic requirements for future physical models of non convective mixing in RGB and AGB stars.

2. Nucleosynthesis and mixing above the H-burning shell

Despite the cautions advanced in the Introduction, it remains true that our knowledge of the physics of Low Mass Stars (hereafter LMS) is more detailed than for more massive stars (especially those exploding as core-collapse supernovae). This is so both because less extreme conditions are involved in LMS (only H- and He-burning phases being possible in them) and because the lowest stellar masses passing through the AGB stages ($M \lesssim 2\ M_\odot$) are also the most numerous and the longest-lived, which facts offer for them ample possibilities of directly observing the chemical peculiarities induced by their in situ nucleosynthesis.

It is therefore not surprising that the abundance peculiarities of evolved stars below ~ 2 $M_\odot$ were discovered many years ago, when the first results of high resolution spectroscopy became available [8, 9]. These peculiarities, observed after the so-called *luminosity bump* of the red giant branch, include an isotopic mix of intermediate-mass elements that cannot be accounted

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for by purely convective dredge-up [10, 11]. This problem affects mainly species from lithium to fluorine. For higher-mass elements up to Mg, instead, peculiarities and anti-correlations were discovered already on the Main Sequence in old Globular Cluster stars and were again attributed to mixing phenomena occurring in previous generations of red giants [12] . Excellent reviews of these phenomena can be found in the literature [13, 14].

Non-convective circulation of material exposed to partial H burning is usually assumed to explain the above anomalies [15]. Partial p-captures in these circulating material are often called cool bottom processes (hereafter cbp). Mechanisms invoked to account for the required cbp include shear instabilities and the meridional circulation induced by rotation [16, 17]. Most models consider the chemical mixing through some diffusion-like treatment, leaving the values of the diffusion coefficient and of the mass mixed as free parameters [18]. In fact, in low mass red giants the internal structure leads us to envisage quite naturally the existence of a shear layer, at the contact between the almost rigid rotation of the stellar radiative core, and the differentially rotating convective envelope. In the past decade, however, the idea of a purely rotationally-induced mixing has undergone strong difficulties [19, 20], and has been integrated by considering thermohaline diffusion [21, 22] and magnetic-field buoyancy below the convective envelope [6].

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Whatever the mechanism is that drives cbp, Nollett et al. [23] showed that it can be approximated by a circulation occurring at a rate $\dot{M}$, and reaching down to a maximum temperature T_P, close to, but lower than, the H-burning shell temperature. In this simple scheme it was easy to show that a number of abundance anomalies observed in pre-solar oxide grains of AGB origin could be explained. This includes destruction, in the stellar envelope, of ^{18}O, production of ^{17}O (sometimes close to CNO equilibrium), and production of ^{26}Al. Any such circulation should also decrease the ^{12}C/^{13}C ratio, and increase the abundance of ^{14}N, in a percentage that is mainly a function of the circulation rate (while Al production is essentially only a function of the temperature T_P reached).

All the above abundance changes expected in low mass AGB stars can be ascribed to admixtures of envelope material and partially CNO-cycled matter originally laying above the H shell, carried to the surface by the mentioned partial mixing mechanisms. Other abundance variations are instead introduced, in more massive stars, by hot CNO cycling occurring directly at the base of the envelope (the so-called *hot bottom burning*, or hbb). The latter are qualitatively similar, but quantitatively more effective, than those found in lower masses. As an example, it was shown [24, 11] that cbp can yield ^{26}Al/^{27}Al envelope ratios of the order of 0.01; hbb at its extreme level can bring this ratio to unity [25]. It was also shown [23] that cbp can delay the formation of a C-star by burning some ^{12}C; it is expected that hbb prevents the formation of a C star completely, apart from some special and rare cases [26]. As the differences between the outcomes of cbp and of hbb are only a matter of efficiency, it might sometimes be difficult to understand which kind of progenitor mass was involved, from the observations of intermediate-mass elements alone.

A more stringent constraint might come from Mg isotopes: in massive ($M \geq 5\ M_\odot$) AGB stars efficient burning of ^{22}Ne in the He-layers produces ^{25}Mg and ^{26}Mg. The first one might be partly affected, in hbb conditions, by p-captures producing ^{26}Al; but the second should remain as a clear test. Remarkable enhancements of ^{26}Mg should occur only for rather massive AGB progenitors.

Very recently, the isotopic abundances of CNO elements produced by the combined effects of mixing and nucleosynthesis have been shown to be a strong function of the rates of some crucial nuclear processes, in particular those for the ^{14}N(p,γ)^{15}O and ^{17}O(p,α)^{14}N reactions [10]. As a

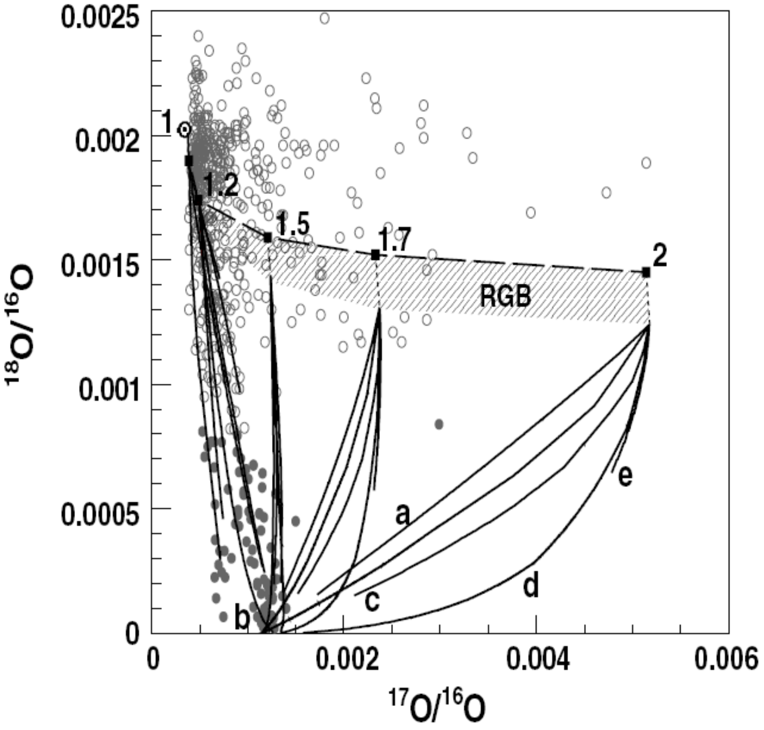

Figure 2: The oxygen isotopes of presolar oxide grains (dots) as compared to nucleosynthesis and mixing models for LMS. The long-dashed line represents the composition of various stellar masses after the first dredge up. The shaded region is the area covered by models for first-ascent red giants, while continuous lines show the trends of the composition for AGB stars for different masses and different mixing rates $\dot{M}$ in the circulation below the convective envelope. With the present choices for reaction rates, the oxide grains with the smallest concentrations of both ^{17}O and ^{18}O are explained by very low mass stars, in the range $1-1.3\,M_{\odot}$.

consequence of updates in the adopted compilations of reaction rates [27], for example, the ability of stellar models to reproduce the isotopic oxygen abundances in presolar oxide grains was greatly improved, and the estimates for the required stellar masses considerably reduced, so that oxide grains showing the most extreme anomalies are now attributed to very low masses, in the range $1-1.3\,M_{\odot}$ (see Figure 2).

3. Nucleosynthesis in He-rich layers and the *s* process

Stellar model calculations [28] showed that the ^{13}C nuclei produced in the radiative He-rich layers at dredge-up as a consequence of the partial mixing phenomena quoted in Section 1 burn locally before the subsequent convective pulse develops. The temperature is rather low for He-burning conditions [$(0.8-0.9)\times 10^{8}$ K], and the average neutron density never exceeds 10^{7}

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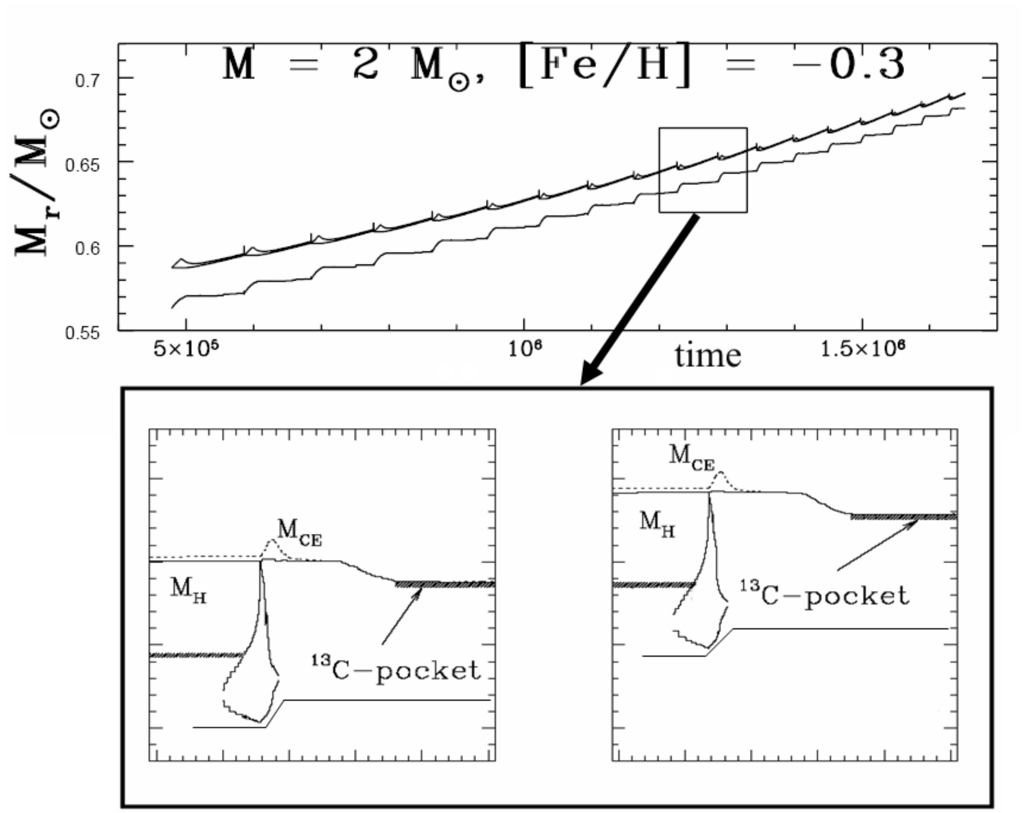

Figure 3: The top panel shows the position in mass of the He-shell, the H-shell and the base of the convective envelope in an AGB star undergoing thermal pulses. The marked zone is enlarged in the bottom panel, which shows the layers relevant to *s*-processing, across two successive pulses.

n·cm^{-3}. As a consequence of neutron captures, a pocket of *s*-enhanced material is formed and subsequently engulfed into the next pulse. Here *s*-elements are mixed over the whole He intershell by convection and are slightly modified by the marginal activation of the ^{22}Ne source. They are then brought to the surface during the following episode of dredge-up from the envelope (this is the so-called *third* dredge-up, or TDU, which is however a repetition of a few to many individual episodes, one after each He-shell instability). Such a scheme, illustrated in Figure 3, has been confirmed by all recent computations [30, 31, 5, 32].

Various physical mechanisms have been proposed to solve the problem of proton ingestion [15, 5]. None of them, however, is exempt from free parameterizations, so that the amount of ^{13}C burnt has usually been assumed as a free parameter, to be calibrated by observations. As *s*-processing affects a large number of observable elements, and depends only on few basic quantities (the neutron density, the total neutron flux, the very small cross sections of the key nuclei having *magic* neutron numbers, i.e. closing nuclear shells) observational constraints in real AGB stars are rather effective in fixing the free parameters. Moreover, the recent advent of precise isotopic measurements on pre-solar grains formed in AGB circumstellar environments helps in specifying

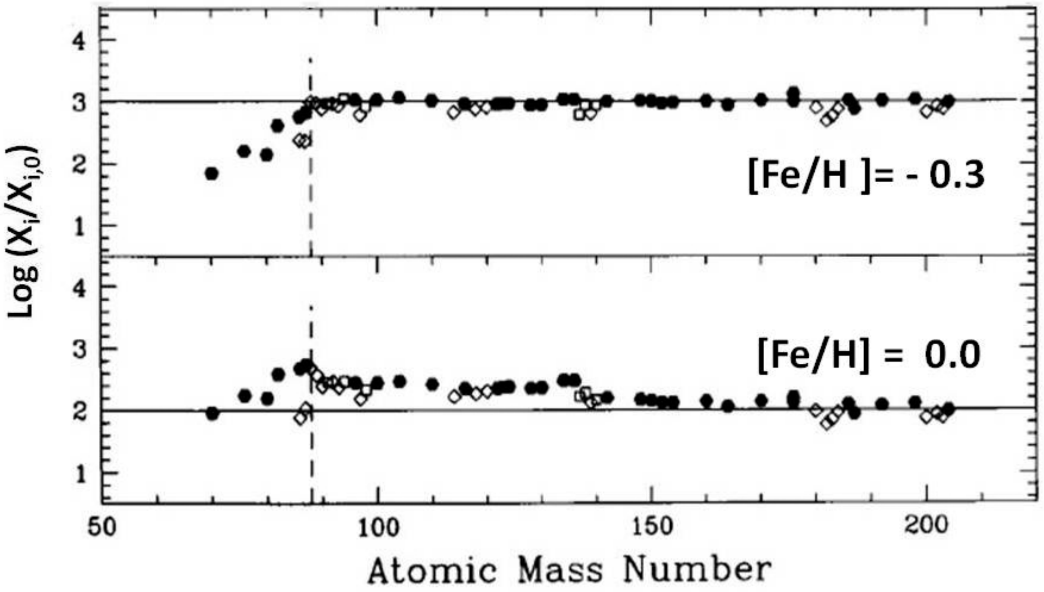

Figure 4: The distribution of abundances for heavy nuclei produced mainly (open symbols) or exclusively (black dots) by the *s* process, obtained with the *standard* (ST) choice of the ^{13}C concentration, as discussed in the text. The solar distribution is reproduced for moderately low metallicity (upper panel), while an AGB star with an initially solar composition would produce lower abundances, peaked on the *ls* elements. See [36] for details.

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the local conditions [33, 34].

In the above scenario it was shown that, for a given choice of the ^{13}C available for producing neutrons in the AGB phase, it is possible to find an appropriate metallicity [Fe/H] for which the number of neutrons per iron seed becomes adequate to allow the specific star considered to produce yields of neutron-rich nuclei mimicking the solar distribution [35, 36]. Figure 4 illustrates this fact for a choice of the mass of ^{13}C burnt per cycle that was considered as a sort of average on the basis of the data available at the end of the nineties ($M_{13} = 4 \times 10^{-6}\ M_{\odot}$); this choice was actually often called "standard" (ST). The figure refers to models where the abundance ratios among the nuclei initially present in the star are solar. Hence, obtaining constant production factors implies that the solar distribution can be adequately reproduced. In the case shown by Figure 4, this is obtained for AGB stars of half solar metallicity. Increasing the metallicity of the model, e.g. passing to [Fe/H] = 0, implies obtaining lower abundances, in a distribution peaked on the *light s* elements (Sr, Y, Zr, often called *ls*) more than on *heavy* ones (Ba, La, Ce, often called *hs*). This is so because the Fe seeds become more abundant, so that the number of neutrons *per seed* decreases.

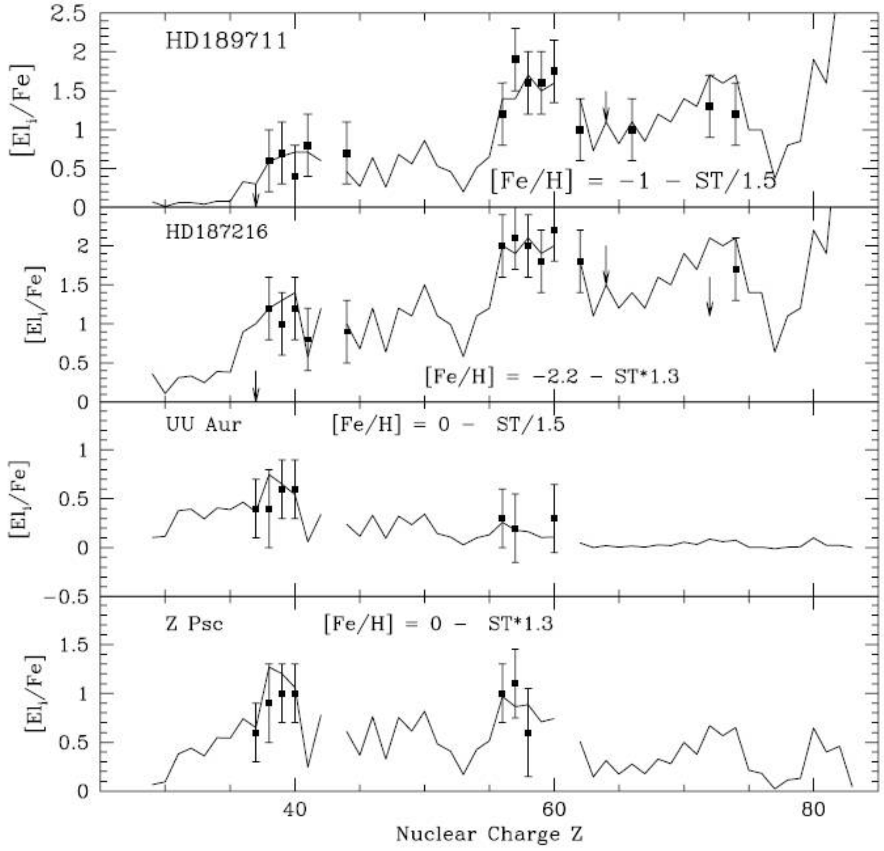

Figure 5: Fits to the observed abundances in real AGB stars, obtained by varying the mass of ^{13}C burnt per cycle within a factor of 1.5 from the ST case

In the scenario depicted above, the measured abundances of neutron-capture elements in real AGB stars could be fitted rather easily [37, 38], but required that the ^{13}C pocket could be different from star to star (examples of similar fits are shown in Figure 5, for masses of ^{13}C burnt per cycle varying within a factor of 1.5 around the ST case).

The rather satisfactory description of the *s* element distributions in the Sun and in AGB stars, despite the embarrassing problems affecting the production of the neutron source, induced in the researchers the general belief that neutron captures in AGB stars were essentially a solved problem. We shall however see in next section that this idea was actually too simplistic.

4. New observations and the need for model revisions

The first doubts on the scenario depicted so far were advanced by [39], who showed that, for ^{13}C pockets similar to those adopted previously, computations of the chemical evolution of the Galaxy failed to reproduce the solar distribution (that was instead easily obtained in single AGB

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models). In particular, those authors showed that a shortage of *ls* elements by at least 30% resulted at the epoch of the solar formation.

Recent spectroscopic measurements in open clusters made clear that the above problems were actually more serious than previously believed. Indeed, they showed a growth of s-process abundances in the Galaxy by about 0.2dex after the era of the Sun's formation; this fact is again outside the reach of *s*-process and chemical evolution models based on the parameterisations of the ^{13}C pocket advanced in the past. The observations [40, 41] actually indicated that those models were insufficient in explaining not only the abundances of *ls* nuclei, but also those of the *hs* ones. It became evident that stars with neutron exposures larger than previously considered had to be invoked.

The stellar systems from which this conclusion was drawn belonged to the Galactic thin disk, where the age-metallicity relation is essentially flat and rather dispersed. For this reason, and for the limited values of the observed *s*-process enhancement, the general trend now emerging could be identified only thanks to the knowledge of the cluster ages, allowing one to show the abundances as a function of time, not of metallicity. Chemical [42, 39] and chemo-dynamical [43] models of the Galaxy, based on the scenario emerged in the nineties, foresee that s-process isotopes, after reaching a peak slightly before the formation of the Sun, should display a decrease and then reach a plateau in their concentration with respect to iron [X_i/H].[1] Contrary to this prediction, the data showed a late increase of neutron-rich element abundances.

It was then suggested [7] that explaining the abundances in open clusters would require that the contributing stars, once born at (or after) the star formation peak characterizing the early phases of the Galactic disk evolution, begin to contribute to the chemical evolution of the Galaxy only near the epoch of the solar formation and after it, so that chemical evolution models not considering them remain valid for earlier epochs. This sets their required mass to the small range $1.3 - 1.5$ $M_\odot$. If born at higher-than-solar metallicity, such objects would barely activate, during the AGB stages, the TDU necessary to carry He-burning products to the surface. However, the efficiency of TDU increases for decreasing metallicity, so that at progressively lower values of [Fe/H] stars of progressively lower mass can contribute.

Using the same stellar models [44] often adopted as reference previously, Maiorca et al. [7] made then the hypothesis that very low mass stars could activate the ^{13}C source more effectively, with an extension of the layer interested by proton penetration at dredge-up larger by a factor of four with respect to what happens for higher masses ($M \gtrsim 1.5$ $M_\odot$). These last can profit, as constraints, of presently-existing, *s*-process rich AGB stars in the solar neighborhood, which can be used for calibration purposes [45, 46]. For lower masses, instead, the observations of open clusters provided the first quantitative hints on their s-process efficiency.

5. The new s process

Maiorca et al. [7] then computed chemical evolution models for the Galaxy introducing the mentioned assumption of an enlarged ^{13}C-pocket in stellar masses of $1.3 - 1.5$ $M_\odot$.

The resulting, increased *s*-process yields (i.e. the contributions in solar masses from the AGB stellar winds to the ISM) for those low mass stars are shown in Figure 6, in comparison to those of

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[1] $[X_i/\mathrm{H}]_{star} = \log(X_i/\mathrm{H})_{star} - \log(\mathrm{X}\ \ _i/\mathrm{H})_\odot$

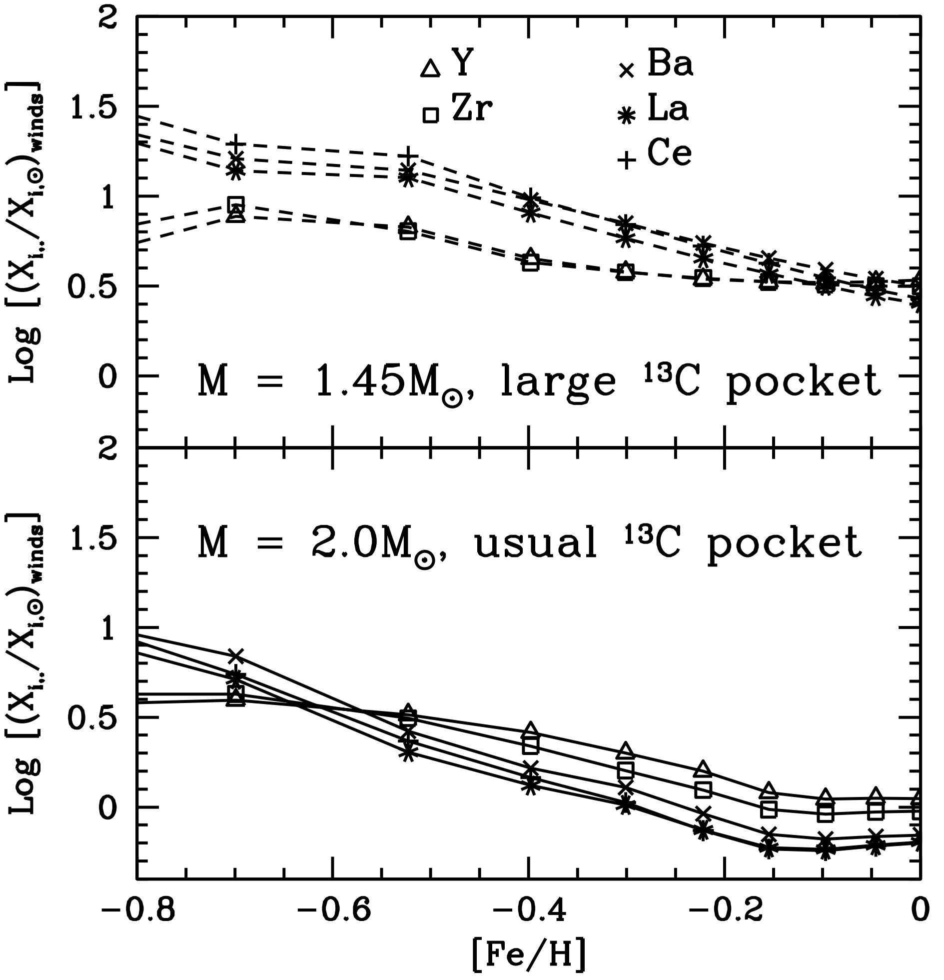

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Figure 6: *Upper panel*: The s element contributions from a stellar mass below 1.5 $M_\odot$, expressed as production factors in the stellar winds with respect to the solar composition, adopting the extended ^{13}C pocket described in the text. *Lower panel*: the same contributions as obtained in higer masses with the standard assumptions by [42] for the ^{13}C pocket.

more massive stars, which were left essentially unchanged with respect to the previous scenario. The upper panel of the figure, in particular, shows the case of a 1.45 $M_\odot$ star, which has still a rather efficient dredge up at solar metallicities. A star of, say, 1.3 $M_\odot$ would instead contribute only in previous epochs, because at solar metallicity its TDU is essentially switched off. Figure 6 shows that the behavior with metallicity of the stellar wind composition, for the new ^{13}C pocket, is remarkably different than before, both in the absolute values and in the ratios of the *hs* to the *ls* concentrations. The different trends explain why, starting around the time of the Sun's formation, the chemical evolution of *s* elements can now change completely with respect to previous calculations.

The results obtained at metallicities typical of the Galactic disk, for predominantly-*s* elements at the two major *s*-process abundance peaks are shown in Figure 7 as a function of metallicity (left panels) and of time (right panels). The left panels represent the traditional way of looking

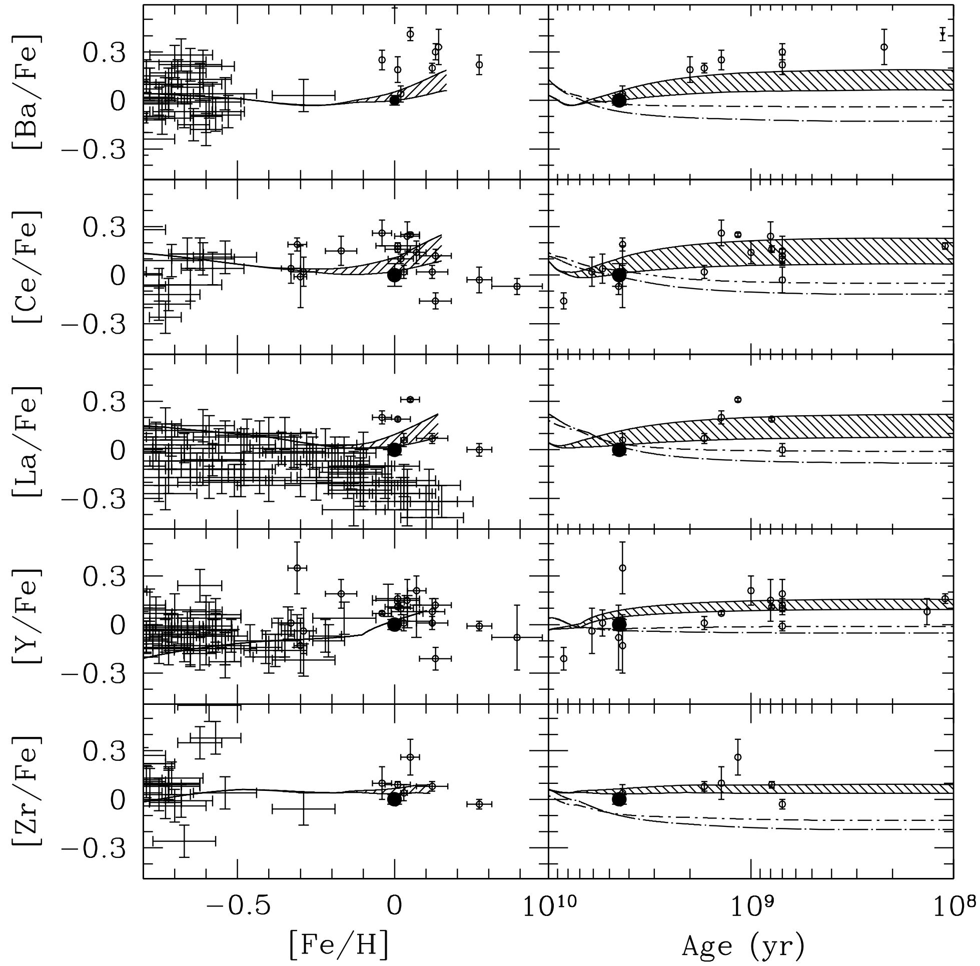

Figure 7: The Galactic chemical enrichment in light s elements (Y and Zr) and in heavy s elements (Ba, La and Ce) from our chemical evolution model as compared to the observations by [41]. The left panels show the abundances as a function of [Fe/H] [data for single stars, shown by crosses roughly corresponding to the uncertainty, are from the SAGA database [47]]. In the right panels the abundances for the clusters are plotted as a function of stellar ages: only this second technique reveals the trend. Note that the solar abundances are reproduced for all elements within the uncertainties. Dash-dotted lines show two cases (with slightly different parameters) of the evolution of abundances, in which the extension of the ^{13}C pocket suggested by [7] is not included. They are clearly insufficient to explain the data.

at the chemical evolution, but their trends (and the quality of the agreement between models and data) are masked by the large scatter in the metallicity at every age. Only when the evolution in time is properly reconstructed (right panels) the evolutionary behavior is unveiled. This is however possible only for our cluster data: for field stars a precise value of the age is not available and older observations, present in the left panel, cannot be plotted as a function of time.

It should be clear, from the right panels of Figure 7, that the extra production from low masses provides the previously missing tool to account for the recent observations in young open clusters. In the curves plotted we tried to roughly estimate the sensitivity to the most crucial parameter, i.e.

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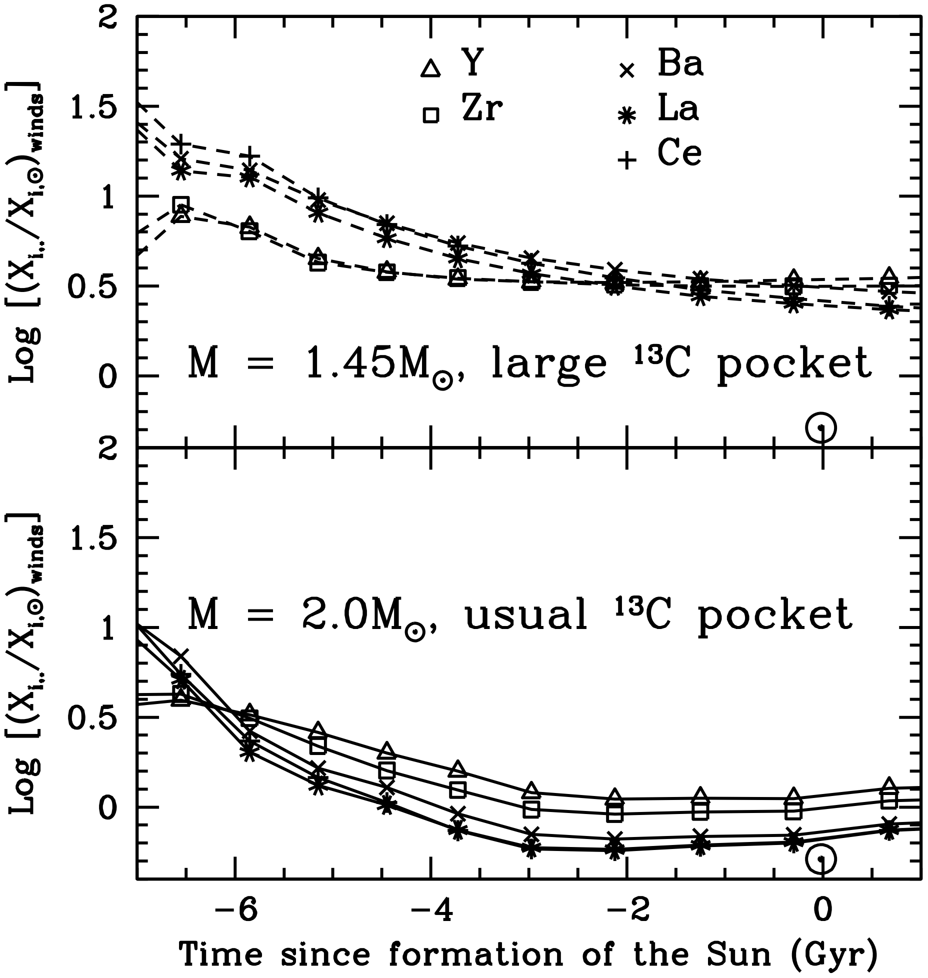

Figure 8: The same enhancement factors in the stellar winds shown in Figure 6, but represented as a function of the time before the formation of the Sun, using our age-metallicity relation. *Upper panel*: A low mass star like the one shown, with a lifetime of about 2.7Gyr, can contribute with constant efficiency to the solar abundances of Y, Zr, Ba, La and Ce, because up to 3 Gyr before the solar formation the production factors of these elements in the winds of AGB stars with very low mass were very similar. *Lower panel*: More massive stars, with a small ^{13}C pocket, do not play any role at high metallcities because of their negligible yields.

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the abundance of ^{13}C burnt. The range bracketed by the curves for each element corresponds to a variation by 20% around the average value ($X_{13} = 4\times10^{-3}$) of the ^{13}C abundance in the He layers of very low mass stars ($M \lesssim 1.5\ M_\odot$).

The attempt by [7], although preliminary, has the notable extra property of providing also an explanation for those parts of the solar abundances that were previously missing (and sometimes attributed to an unknown process called *LEPP*, for *Light Element Primary Process*). This newly-obtained general agreement between observations and models can be understood if one transforms Figure 6 into a plot as a function of time, using the age-metallicity relation provided by the chemical evolution model (see reference [7] for details). This is shown in Figure 8. As one can see, the small region at the right side of Figure 6 (for [Fe/H] values larger than about -0.2), where the yields of *ls* and *hs* nuclei are similar (closer than about 0.2dex, i.e. within the uncertainties of the predictions), is now shown to last for more than 3 Gyr. According to [48], such an interval allows for the complete evolution of stars in the range $1.4-1.5\ M_{\odot}$. As mentioned, at [Fe/H] $\simeq -0.2$ to -0.1 these stars do have TDU; hence, they can play, in the new scenario, a dominant role. They actually affect the solar composition with equal production factors for *ls* and *hs* elements, thus reproducing correctly the solar distribution. Notice that at the times and metallicities mentioned more massive stars have no longer any role on s-processing, because their yields are close to zero (see the lower panel in Figure 8).

6. Looking for a physical model of the n-source formation

One should then verify weather the new hypothesis on *s* processing, based on very low mass AGB stars, is realistic. There are actually good reasons for believing so, although a detailed model has still to be developed. Let us briefly illustrate why.

First of all, we have shown in Section 2 that stellar masses in the range $1 \lesssim M/M_{\odot} \lesssim 1.5$ have to play an important role also in proton-capture nucleosynthesis and must do so thanks to very effective non-convective mixing episodes. In particular, Figure 2 shows that these masses explain the oxygen isotopic mix in those presolar oxide grains that have very little ^{18}O. In general, these conclusions better specify something that was already known from the record of carbon isotope ratios in old stars, requiring that deep mixing mechanisms be at play in red giants, with an efficiency that increases for decreasing stellar mass [49].

Now, the ^{13}C pocket is formed below TDU, in a phase where H-burning is shut down; the interested layers of the star are the same previously affected by deep mixing above the H-burning shell and the structure of the radiative zone where protons have to penetrate is similar, especially in its being completely homogenous thanks to the previous development of pulse-driven convective mixing. There is no real reason why any circulation process previously active in those zones could not be active also at TDU, driving proton penetration and the formation of the ^{13}C reservoir. The layers involved in our suggested ^{13}C pocket (extending to $4 \times 10^{-3}\ M_{\odot}$ below the convective border) have temperature and density conditions similar to those previously found above the H-burning shell (T of a few 10^7 K, ρ up to a few g/cm^3), while much smaller values characterize the envelope border ($T < 10^7$ K, $\rho \sim 0.1$ g/cm^3). For the highest circulation rates previously explored in deep mixing calculations (those explaining the composition of oxide grains, i.e. $\dot{M} = 1-3\times10^{-6}\ M_{\odot}$/yr), these conditions imply average velocities of a few cm/sec [11]. At these speeds, in the time available at TDU (a few hundred years) those deep layers can indeed be put in connection with the envelope, establishing a suitable proton penetration.

Hence, a fast non-convective circulation of the type already shown to be active in the H-rich layers of very low mass stars might be sufficient to form a ^{13}C pocket of the extension required for explaining the s-process abundances observed in young open clusters and the previously missing parts of the solar s-element distribution. Moreover, at TDU the relevant layers are progressively cooler and less dense for decreasing stellar mass, so that a mixing efficiency increasing for lower masses is plausible. Higher stellar masses, with less efficient circulation episodes and shorter

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lifetimes, would remain important contributors to s processing only before the era of the Sun's formation.

We conclude by mentioning that, according to the discussion by [10, 11], mixing at the speeds necessary for very low mass stars (and, we add, necessary to form in the short time interval of TDU a large ^{13}C pocket) is not possible for the most commonly-adopted transport mechanisms: neither for rotationally-driven shear, nor for thermohaline mixing. This last process [21, 22] is actually switched off at TDU, because no molecular weight inversion is present. Hence we believe that the need of extended ^{13}C reservoirs in low mass stars might be another element added to the evidence that fast instabilities in undulatory processes must be at play. Phenomena of this kind, possibly associated with magnetic buoyancy [6, 50] can offer an alternative that might be capable of providing a unique explanation to the several requirements for deep mixing emerging from the observations of red giant stars or of their descendants.

Acknowledgements. We are grateful to the organizers of the School for a very fruitful and stimulating meeting. This research was developed in the framework of the activities for the ESF Eurogenesis collaboration (Coordinated Research Project CoDUstMas).

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References

[1] Käppeler, F., Gallino, R., Bisterzo, S., & Aoki, W. 2011, *Rev. Mod. Phys.* **83**, 157.

[2] Cioni, M.R. et al. 2011, *A&A* **527**, 116

[3] Gullieuszik, M., Groenewegen, M.A.T., Cioni, M.-R.L., et al. 2011, *A&A* **537**, 105

[4] Guandalini, R., Busso, M.,Ciprini, S., Silvestro, G. and Persi, P. 2006, *A&A* **445**, 1069

[5] Cristallo, S. et al. 2009, *ApJ* **696**, 797.

[6] Busso, M., Wasserburg, G.J., Nollett, K.M., & Calandra, A. 2007, *ApJ* **671**, 802.

[7] Maiorca, E., Magrini, L., Busso, M., Randich, S., Palmerini, S., & Trippella, O. 2012, *ApJ* (in press) [2011arXiv1112.5290]

[8] Gilroy, K.K., & Brown, J.A. 1991, *ApJ* **371**, 578

[9] Pilachowski, C. A., Sneden, C., Booth, J. 1993, *ApJ* **407**, 699

[10] Palmerini, S., La Cognata, M., Cristallo, S., & Busso, M. 2011, *ApJ* **729**, 3.

[11] Palmerini, S., Cristallo, S., Busso, M. et al. 2011, *ApJ* **741**, 26

[12] Gratton, R.G., Bonifacio, P., Bragaglia, A., Carretta, E., Castellani, V., Centurion, M., Chieffi, A. et al. 2001, *A&A* **369**, 87

[13] Kraft, R.P. 1994, *PASP* **106**, 553

[14] Charbonnel, C. 2004, in Origin and Evolution of the elements, ed. A. McWilliams & M. Rauch, (Pasadena: Carnegie Observatories), p. 59

[15] Herwig, F. 2005, *ARA&A* **43**, 435

[16] Zahn, J.-P. 1992, *A&A* **265**, 115

[17] Denissenkov, P.A., Da Costa, G.S., Norris, J.E., Weiss, A. 1998, *A&A* **333**, 926

[18] Denissenkov, P.A., & Tout, C.A. 2000, *MNRAS* **316**, 395

[19] Palacios, A., Talon, S., Charbonnel, C., Forestini, M. 2003, *A&A* **399**, 603

[20] Goriely, S., & Siess, L. 2004, *A&A* **421**, L25

[21] Eggleton, P.P., Dearborn, D.S.P., & Lattanzio, J.C. 2006, *Science* **314**, 1580.

[22] Eggleton, P.P., Dearborn, D.S.P., & Lattanzio, J.C. 2008, *ApJ* **677**, 581.

[23] Nollett, K.M., Busso, M., Wasserburg, G.J. 2003, *ApJ* **582**, 1036

[24] Wasserburg, G.J., Busso, M., Gallino, R., Nollett, K.M 2006, *Nucl. Phys. A.* **777**, 5.

[25] Karakas, A.I., & Lattanzio, J.C. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4, Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories.

[26] Frost, C.A., Cannon, R.C., Lattanzio, J.C., Wood, P.R. & Forestini, M. 1998, *A&A* (Letters) **332**, L17

[27] Adelberger, E.G., Garcia, A., Robertson, R.G.H. et al. 2011, *Rev. Mod. Phys.*, **83**, 195

[28] Straniero, O., Chieffi, A. Limongi, M., Busso, M. et al. 1997, *ApJ* **478**, 332

[29] Gallino, R. et al., 1998, *ApJ* **497**, 388

[30] Goriely, S., & Siess, L. 2001, *A&A* **378**, 25

[31] Lugaro, M., Herwig. F., Lattanzio, J. C., Gallino, R., & Straniero, O. 2003, *ApJ* **586**, 1305

[32] Bisterzo, S. et al. 2010 *MNRAS* **404**, 1529

[33] Gallino, R., Busso, M., & Lugaro, M. 1997, in Astrophysical Implications of the Laboratory Studies of Presolar Material, ed. T. Bernatowicz & E. Zinner (Woodbury, N.Y.: AIP), 115

[34] Amari, S., Nittler, L.R., Zinner, E., Gallino, R., Lugaro, M., Lewis, R.S. 2001, *ApJ* **546**, 248

[35] Arlandini, C. et al. 1999, *ApJ* **525**, 886.

[36] Busso, M., Gallino, R., & Wasserburg, G.J. 1999, *A*RA&A **37**, 231

[37] Busso, M., Gallino, R., Lambert, D. L., Travaglio, C., Smith, V.V. 2001, *ApJ* **557**, 802

[38] Busso, M., Gallino, R., Straniero, O. and Abia, C. 2004,in Origin and Evolution of the elements, ed. A. McWilliams & M. Rauch, (Pasadena: Carnegie Observatories), p. 67

[39] Travaglio C., Gallino, R., Busso, M., & Gratton, R. 2001, *ApJ* **549**, 346

[40] D'Orazi, V. et al. 2009, *ApJ* **693**, L31.

[41] Maiorca, E. et al. 2011, *ApJ* **736**, 120.

[42] Travaglio, C., Galli, D., Gallino, R., Busso, M., Ferrini, F., & Straniero, O. 1999, *ApJ* **521**, 691

[43] Raiteri, C.M. et al. 1999, *ApJ* **518**, L91.

[44] Straniero, O., Domínguez, I., Cristallo, S., & Gallino, R. 2003, *PASP* **20**, 389

[45] Abia, C., Busso, M., Gallino, R. et al. 2001, *ApJ* **559**, 1117

[46] Abia, C., Domínguez, I., Gallino, R., et al. 2002, *ApJ* **579**, 817

[47] Suda, T. et al. 2008, *PASJ* **60**, 1159.

[48] Domínguez, I. et al. 1999, *ApJ* **524**, 226.

[49] Busso, M. et al., 2010, *ApJ* **717**, L47

[50] Nordhaus, J. et al. 2008, *ApJ* **684**, L29.

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