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The ^{13}C-pocket formation and the *s*-process main component

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The $^{13}C(\alpha,n)^{16}O$ reaction is considered as the main responsible for the production of the *s*-process main component in low-mass AGB stars. Its activation requires a physical mechanism to ingest protons in the He-rich region forming a ^{13}C reservoir, or *pocket*. This was typically assumed to involve a small mass ($\leq 10^{-3}\,M_\odot$) [7], but recent observations in several astrophysical sites showed enhancements of *s*-element abundances with respect to the Sun suggesting a more effective *s*-process nucleosynthesis. This requires a more extended ^{13}C pocket covering, in mass ($\geq 4\times10^{-3}\,M_\odot$), most of the He-rich layers. Recently, we suggested that magnetic buoyancy could promote forced mixing [14, 20] to produce a ^{13}C reservoir larger than assumed so far. Here we investigate if the solar composition of neutron rich elements, from Sr to Bi, can constrain the ^{13}C-pocket extension. Stellar models at a fixed metallicity, based on a large ^{13}C reservoir reproduce the distribution of *s*-only elements within the uncertainty of 10%, also fulfilling C-star luminosity observations. Assuming this new scenario, a large production of nuclei below $A = 90$ is expected, so that $^{86,\,87}$Sr may be fully synthesized by AGB stars, while ^{88}Sr, ^{89}Y and ^{94}Zr are contributed more efficiently than before.

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1. The *s*-process in AGB-LMS

The Asymptotic Giant Branch (hereafter AGB) phase is the final evolutionary stage of low- and intermediate-mass stars (less massive than about 3 and about 8 $M_{\odot}$, respectively), following the exhaustion of helium at the center. These stars are for the second time along the Red Giant Branch (RGB) in the Hertzsprung-Russell diagram, crossing regions of low temperature (in the range $2500-4000$ K) and high luminosity.

We mainly focus our attention on the Thermally Pulsing (TP)-AGB stage because it was demonstrated to provide the suitable stellar conditions for *s*-process nucleosynthesis. Here the star has a structure characterized by an electron-degenerate $C-O$ core surrounded by two shells, the outer one made of hydrogen and the inner one of helium, burning alternatively. A large convective envelope surrounds the H-shell, extending for several hundreds of solar radii. This induces the loss of the largest part of the envelope (only about 10% of it was lost in previous phases). The two thermonuclear shells are separated by a He-rich radiative region, initially of a few $\sim 10^{-2}$ $M_{\odot}$, called *intershell*. The thickness of this layer considerably changes during the stellar evolution, decreasing down to a few 10^{-3} $M_{\odot}$ (a value strongly depending on stellar mass).

During the TP-AGB phase thermal instabilities from the He-shell occur repeatedly (their number depends on the stellar mass and is a strong function of the mass loss law assumed and of metallicity). The H-burning shell supplies the inert region below with freshly synthesized helium and CNO nuclei. Its periods of activity (interpulse periods) last for $0.05-2\times10^{5}$ yr, depending on the stellar mass. This quiet burning process is interrupted when the He-shell ignites explosively, its surplus of energy inducing a convective regime over most of the He-rich layers. This cycle repeats again and again, for a number of instablities (thermal pulses, or TPs) going from a few in LMS (low-mass stars) to tens in IMS (intermediate-mass stars). Convection associated to the pulses remixes the intershell, homogeneizing the freshly synthesized products of He-burning over its whole mass. After every pulse, the convective envelope can penetrate into the intershell to bring elements just processed to the stellar surface. In general, we refer to this phenomenon under the name of third dredge-up.

The TP-AGB stage is characterized by neutron production by means of two reactions. The $^{13}C(\alpha,n)^{16}O$ is activated during the radiative phase between two subsequent TPs; the $^{22}Ne(\alpha,n)^{25}Mg$ is instead at play inside the convective instabilities. Due to its need for high temperatures, it is only marginally activated in LMS where, even in the pulses, $T < 3\times10^{8}$ K. The neutron density, induced by the above reactions (about $10^{6}-10^{10}$ n/cm^{3}), is typical of slow neutron capture nucleosynthesis, i.e. the so-called *s*-process. This consists in a series of subsequent n-captures and beta decays in which the time scale of a (n,γ) reactions is generally longer than the half-time of β-decays (τ_{β}) of the unstable nuclei involved.

The *s*-process is responsible for the production of about half of the nuclei heavier than iron (Fe), up to bismuth (^{209}Bi). In particular, more than thirty of these nuclei are considered to be produced exclusively by slow neutron captures: they are the so-called *s*-only nuclei, usually shielded against fast decays by some stable isotope (this is the case, e.g., of ^{86}Sr, ^{87}Sr, ^{150}Sm, ^{204}Pb, etc ...). In this scenario, we tried to reproduce the solar distribution for the neutron-rich elements. For this, we look for models in which the enhancement factors of heavy nuclei are almost the same for the whole *s*-process chain. This means we want to obtain a flat distribution of production factors for the mentioned *s*-only nuclei over the whole range form Sr to Pb.

2. The ^{13}C-pocket formation

The $^{13}C(\alpha,n)^{16}O$ reaction, originally introduced by [4], is the main neutron source for producing the *s*-nuclei from strontium to bismuth in LMS. It usually takes place at relatively low temperatures ($T = 0.8 - 1.0 \times 10^8$ K) providing a neutron density of the order of $10^6 - 10^7$ n/cm^3. However, ^{13}C is not naturally present in helium enriched layers above C − O core and the amount of ^{13}C produced by H burning is by far insufficient to drive significant neutron captures. In order to activate the $^{13}C(\alpha,n)^{16}O$ reaction, two conditions must be met: i) a mechanism for injecting protons into the He-rich region must be found, so that interacting with the abundant ^{12}C they can produce ^{13}C in the He intershell; ii) the amount of ^{13}C thus obtained must burn through the $^{13}C(\alpha,n)^{16}O$ reaction in layers where the temperature is low, to maintain the neutron density low. The second issue is strongly related to the rate of the $^{13}C(\alpha,n)^{16}O$ reaction, which is diffusely discussed in [10, 11]. Entering into the details of its measurements is not the aims of this work. In this context, producing neutrons through ^{13}C-burning is more difficult than through ^{22}Ne combustion, mainly because a suitable process is necessary to bring protons into the He intershell from the convective envelope. The occurrence of the third dredge-up, forcing the hydrogen-rich and the carbon enriched layers to establish a contact, will naturally produce some mixing at the H/He interface. Moreover, possible physical mechanisms for producing a ^{13}C pocket of the suitable mass and with the appropriate abundance distribution have been extensively investigated by different authors, in order to find a secure basis for *s*-process nucleosynthesis in stars. Recent mechanisms suggested as the cause of proton penetration are: i) chemical diffusion during the interpulse phase; ii) hydrodynamical effects induced by convective overshooting [5, 8]; iii) gravitational waves [6]; iv) magnetic fields generating buoyancy [14, 20]. As a consequence of H penetration, protons can interact with ^{12}C producing the ^{13}C reservoir. This pocket is formed thanks to a limited number of proton captures, by the following chain of reactions: $^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C$. Too efficient proton captures (in presence of many protons) would activate a full CN cycling, leading to the production of ^{14}N through the reaction $^{13}C(p,\gamma)^{14}N$. This fact is of crucial importance, because ^{14}N is a very efficient absorber for neutrons (it is actually the main n-poison in typical AGB star conditions). Excessive nitrogen then hampers the captures on heavier nuclei. We notice that general consensus on a physical mechanism for the formation of the ^{13}C reservoir has not been achieved so far. For a few decades it was assumed that proton mixing during the third dredge-up could be rather shallow, forming a ^{13}C-pocket whose extension is as a free parameter, but in the range from a few to 0.001 $M_\odot$ (see e.g. [7, 19]). Such a parametric approach was fruitful, permitting the exploration of many issues related to the *s*-process. However, it did not explain well enough the Galactic chemical evolution of neutron enriched nuclei with atomic mass in the range 90 − 130, so that for them a new process had to be assumed (Light Elements Primary Process or *LEPP*).

As an example, in [16] the authors compared the observations for La and Ba with Galactic chemical evolution calculations by [18]. Although both [La/Fe] and [Ba/Fe] show large dispersion for the thick and thin disk stars, many observed points lay clearly above the trend displayed by model predictions. Another piece of evidence in the same direction came from a complementary study by [15], who found *s*-element abundances increasing with time from chemical abundance analysis of stars in the Sagittarius dwarf spheroidal galaxy (Sgr). High [La/Y] ratios, consistent with leaky-box chemical evolution model, are confirmed, but are ~ 0.3 dex larger than traditional AGB predictions. This fact represents an evidence for the necessity of a larger production of *s*-elements, possible only with more intense neutron fluxes, as provided by a more extended ^{13}C pocket. This confirms a recent proposal by our group [14]; we suggested that the ^{13}C reservoir formed at TDU be considerably larger than previously adopted, at least in AGB stars of very low mass ($M \lesssim 1.5\ M_{\odot}$). With this assumption and a chemical evolution model for the Galaxy, the above authors could reproduce very well the abundances observed in open clusters.

It was also suggested that the formation of a larger ^{13}C pocket can be driven by the magnetic buoyancy. Considering our specific purpose, we can represent a rotating AGB star as an inner degenerate core behaving as a rigid-body, and an intermediate, differentially-rotating layer below the convective envelope. This structure can power a magnetic dynamo, suitable to induce the buoyancy of magnetized domains that reach the envelope, as it actually occurs in the Sun [17]. The formation of toroidal magnetic fields near the border of the rigid-body core by a dynamo mechanism provides a further energy input. Indeed, the rising velocity will depend on the magnetic field intensity of the rotating star and this is promising in order to obtain a model without free parameters. In other words, the ^{13}C pocket might be fixed from the physical quantities defining the stellar structure. Essentially, “magnetic buoyancy” occurs because the magnetized material is less dense than the one surrounding it. This simple model, promoting a matter transport proceeding “from bottom to top” in the star, should involve most of the He-rich region, above the C – O core, implying a larger production of *s*-elements as a result of a higher abundance of the ^{13}C.

Conservation of mass across the convective border would then guarantee that a downward flux of envelope material occurs, with an initial abundance $X_{\rm H} = 71\%$ in mass (assuming an almost solar composition). In this way, a certain quantity of protons can penetrate into regions enriched in helium and ^{12}C allowing the production of layers enriched in ^{13}C and others mainly containing of ^{14}N, depending on the mass of protons left by mixing in different zones. An exponential profile is assumed for the proton penetration down to about $6 \times 10^{-3}\ M_{\odot}$ [20]. The ensuing ^{13}C pocket contains $4.2 \times 10^{-5}\ M_{\odot}$ of ^{13}C, almost entirely confined in the first $4 \times 10^{-3}\ M_{\odot}$. The extension is more than a factor of 3 larger than the largest case discussed by [3].

3. The *s*-process main component

We are mostly interested in those isotopes of the atomic mass range $85 \lesssim A \lesssim 209$, which are almost exclusively produced by slow neutron captures. It turned out that their solar abundances are reproduced by our new model with the same level of accuracy as possible before [1, 2]. However, in addition our scheme now also reproduces the chemical evolution of the Galaxy, an achievement that was previously impossible. The calculations were obtained by using the NEWTON nucleosynthesis code, in which we adopted new reaction rate estimates for the two main neutron sources, ([11, 13], respectively). We also included the most recent cross sections for neutron capture reactions (n, γ), as provided by the KaDONIS database verion 1.0; we used solar abundances as suggested by [12].

The enhancement factors with respect to the initial composition found at the last computed pulse in model stars of low mass are shown in Figure 1. In particular, we performed stellar nucleosynthesis computations for models of 1.5, 2 and 3 $M_{\odot}$ with a metallicity slightly lower than

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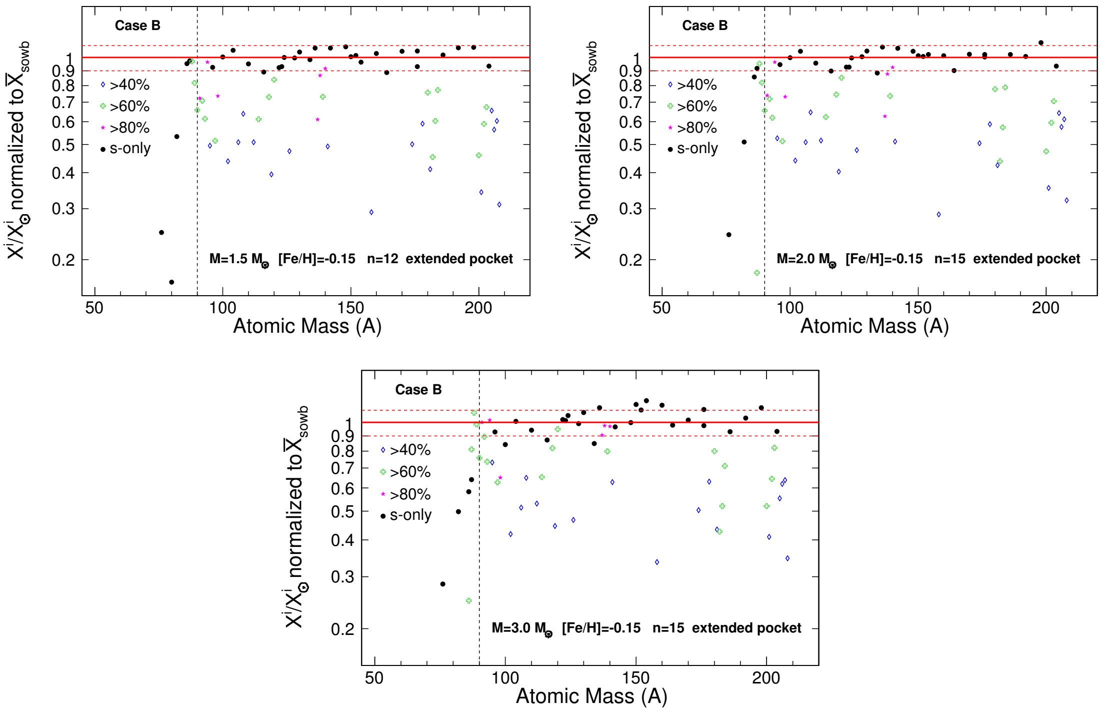

Figure 1: The production factors of *s*-elements with respect to initial abundances, in the He-intershell layers, after the last computed thermal pulse. The three panels show stellar models of 1.5, 2 and 3.0 $M_\odot$ using the extended ^{13}C pocket mentioned in the [20]. This model allows obtain a nearly-solar distribution using a smaller number of cycles and a higher metallicity ([Fe/H] $\simeq -0.15$) than permitted by past models. For the sake of simplicity, we display only nuclei with expected *s*-process contributions larger than 40%. The two red dashed horizontal lines represent the fiducial interval.

solar. According to the so-far expected percentage production by slow neutron captures, we used different symbols and different colors to distinguish the isotopes in Figure 1. The inset legend helps to understand how much each isotope is fed by the *s*-process, while "n" represents the number of the computed thermal instabilities and M refers to the stellar mass, varied in the interval from 1.5 to 3 $M_\odot$. A vertical dashed line was drawn to indicate the starting point for the main component, conventionally defined at A = 90 [9]. The results were then weighted by using the Salpeter's Initial Mass Function (IMF). In order to construct the (weighted and normalized) average production from the whole mass range, we then normalized the results by dividing for the average over-production of *s*-only nuclei unaffected by reaction branchings (the reference is the central red full line in Figure 1). Since Salpeter' equation favours the stars with lower masses, the average values are very similar to those of the 1.5 $M_\odot$ model. We therefore confirm the common assumption that models for this stellar mass offer on average rather typical conditions for producing the main component.

However, the solar distribution (Case B in [20]) shows substantial differences with respect to previous attempts (Case A, see [20]). This is particularly true when we consider the nuclei with $A < 90$: the new scenario provides a higher contribution for them with respect to what was suggested in the past. This allows us to assume that the strontium isotopes are already a part of the main component. In particular, adopting the new model of the ^{13}C pocket, ^{86}Sr and ^{87}Sr have a *s*-process contribution of about 100%. Other isotopes (such as ^{88}Sr, ^{89}Y and ^{94}Zr), which are located near neutron magic numbers, are more efficiently produced by slow-neutron captures then in previously published models.

We notice that an extended ^{13}C pocket allows us to reproduce the main component at high metallicity (about [Fe/H] ~ -0.15) and assuming a limited number of pulses, in accord with the theoretical Luminosity Function of C stars. The adopted metallicity is typical of the Galactic disk and corresponds to stars born over a vary long time interval (a few Gyr), characterized by a large number of LMS stars. The contributions provided by this type of stars, with a large ^{13}C pocket, are therefore the dominant ones in the Galaxy and their solar-like distribution should be a typical occurrence in the Galactic disk. In conclusion, we can state that nucleosynthesis from AGB stars with extended ^{13}C pockets (about 6×10^{-3} $M_{\odot}$), reproduces well the solar distribution, without invoking any extra-process like the so-called solar LEPP [19]. Moreover, the higher number of neutrons available also fulfils the requirements posed by young open clusters and by observations of Dwarf Speroidal Galaxies. The above discussion gives us an opportunity to identify crucial tests that should be made, from which a conclusive judgement can be derived on the real extension of the ^{13}C pocket. Among them we stress the importance of comparisons with presolar grain abundances and with observation of post-AGB stars.

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