Neutron sources and neutron-capture paths in asymptotic giant branch stars

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Abstract.
Roughly half of the abundances of the elements heavier than iron in the cosmos are produced by slow neutron captures (the \( s \) process) in hydrostatic conditions when the neutron density is below roughly \( 10^{13} \text{ n/cm}^{-3} \). While it is observationally well confirmed that asymptotic giant branch (AGB) stars are the main site of the \( s \) process, we are still facing many problems in the theoretical models and nuclear inputs. Major current issues are the effect of stellar rotation and magnetic fields and the determination of the rate of the neutron source reactions. I will present these problems and discuss the observational constraints that can help us to solve them, including spectroscopically derived abundances, meteoritic stardust, and stellar seismology. Further, I will present evidence that the \( s \) process is not the only neutron-capture process to occur in AGB stars: an intermediate process is also required to explain recent observations of post-AGB stars.

1. Introduction
Atomic nuclei in the Universe cover a huge variety of chemical properties, masses, abundances, and origins: from the very light H and He, which were made during the Big Bang, to Be, B, and Li, which are mainly produced by spallation reactions in the interstellar medium, to the most abundant “metals” C, N, and O, which make up most of the 1.4% of the matter in the Sun that is not in the form of H and He (“metallicity”). Beyond them, there are “intermediate-mass” elements, such as Mg, Na, Si, and Ca mainly produced in core-collapse supernovae. The “Fe-peak” includes elements from Mn to Ni, which have relatively high abundances and are produced by nuclear statistical equilibrium in thermonuclear supernovae. Once we get to Fe, however, we have only covered about 1/4 of the total number of the elements in the cosmos: the vast majority of the atomic nuclei lie between Fe and the actinides, e.g., U. In the Sun, the abundances of the elements heavier than Fe are roughly five to six orders of magnitude lower than those of Fe (Figure 1). However, closer to us, in the Earth’s crust their abundances are only two to three order of magnitude lower than that of Fe. Most importantly, among them are found major industrial metals (Mo, Sn, Pb), precious metals (Ag, Au, Pt), and the rare earth elements (Ce, La, Nd, Sm, etc), i.e., the seeds of technology elements that make possible the high-tech world we live in today. In this paper, I will review our current knowledge of how a fraction of the cosmic abundances of the elements heavier than Fe (including some of those that are used to build for example a smartphone) is produced in giant stars.
Beyond Fe, the Coulomb barrier generated by the protons in the atomic nucleus is too large to allow captures of charged particles, and the only effective way to produce nuclei heavier the Fe are neutron captures, since neutrons do not have a charge. Traditionally, neutron-capture processes are split into two extreme cases [1]: if the neutron density \( N_n \) is very low, of the order of \( 10^8 \) n/cm\(^3\), the time that it takes for an unstable nucleus to capture a neutron is slower than the time it takes to decay. This is the case of the \emph{slow} neutron-capture process (the \( s \) process), whose path effectively proceeds along the valley of \( \beta \)-stability. At the opposite extreme, when \( N_n \) is very high, \( > 10^{20} \) n/cm\(^3\), the time that it takes for an unstable nucleus to capture a neutron is more \emph{rapid} than the time it takes to decay. This is the case of the \emph{rapid} neutron-capture process (the \( r \) process), whose path effectively proceeds on the neutron-rich side far away from the valley of \( \beta \)-stability. At the end of the neutron flux, the \( r \) process has produced only radioactive nuclei, which \( \beta \) decay towards their first stable isobar. The \( r \) process to occur needs extreme conditions, which are found in neutron star mergers and supernovae environments (see paper by K. L. Kratz, these proceedings). Instead, the \( s \) process can happen during the hydrostatic evolution of massive stars, as well as of low-mass stars, during their asymptotic giant branch (AGB) phase. This final phase of the life of low-mass stars is presented in details in the paper by M. El Eid (these proceedings), so here I will focus mostly on the \( s \) process occurring within it. First, I will summarize the nuclear physics features of the \( s \) process, which are valid independently of the stellar site where it occurs.

1.1. The three \emph{s}-process Golden Rules

To interpret models and observations of \( s \)-process patterns, to a first approximation, it is possible to rely on three simple rules.

(i) \textbf{Rule 1: Neutron magic nuclei on the \emph{s}-process path have low neutron-capture cross sections,} \( \sigma \), \textbf{relatively to the other nuclei. They act as bottlenecks, and can accumulate.} Because the \( s \)-process path runs along the valley of \( \beta \)-stability, these neutron magic nuclei are all stable. The first neutron magic number on the \( s \)-process path, which usually starts with \( ^{56}\text{Fe} \) as the seed, is 50 and the first magic nucleus is \( ^{88}\text{Sr} \), which has \( \sigma = 6.13 \) mbarn (at 30 keV, see the kadonis.org database [2]). For comparison, \( ^{87}\text{Sr} \) has \( \sigma = 97 \) mbarn. Moving forward, the second neutron magic number is 82 at \( ^{138}\text{Ba} \) (\( \sigma = 4 \) mbarn) and the third is 126 at \( ^{208}\text{Pb} \), which also has a magic number of protons (82, and \( \sigma = 0.36 \) mbarn). Because the neutron-capture cross section \( \sigma \) represents the probability that the nucleus will capture a neutron, if this probability is low, as for the neutron magic nuclei, then these nuclei are produced, but not destroyed as easily. A large number of “events”, in the form of neutrons hitting them, are required to “convince” them to capture one. After a given number of “neutron hitting events”, the magic nuclei will start capturing neutrons and the \( s \)-process flux will pass through and beyond them to produce heavier nuclei. This will happen sequentially, as the bottleneck at \( ^{87}\text{Sr} \) needs to be bypassed first, and the bottleneck at \( ^{138}\text{Ba} \) second. The bottleneck at \( ^{208}\text{Pb} \) is effectively never bypassed because all nuclei beyond it decay back so that the \( s \) process terminates here. More neutrons simply results in more \( ^{208}\text{Pb} \).

The key quantity that determines if the magic bottlenecks are bypassed, and consequently what is the final \( s \)-process distribution, is clearly the number of “events”, i.e., the number of times that the magic nucleus is hit by a neutron. This is proportional to a quantity called “neutron exposure”, or \( \tau \), which is the total neutron flux integrated over time, i.e., \( \int N_n v_{\text{thermal}} \, dt \), where \( v_{\text{thermal}} \) is the velocity of the neutrons, equal to the thermal velocity. Unsurprisingly, the distribution of the abundances in the Solar System shown in Figure 1 presents three \( s \)-process peaks corresponding to the stable nuclei with neutron magic numbers at Sr, Ba, and Pb. The three \( r \)-process peaks at Se, Xe, and Pt corresponds instead to unstable nuclei with neutron magic numbers, since the \( r \)-process path runs far away from
valley of $\beta$-stability (the element Sn also appears as a relative peak because it has a magic number of protons and some of its isotopes have relatively low $\sigma$ values).

(ii) **Rule 2:** In-between neutron magic nuclei the abundances are in equilibrium because the more they are produced, the more they are destroyed (the reaction rate is proportional to the abundance itself) until production and destruction balance each other. (This is also true for neutron magic nuclei for high neutron exposures, i.e., once their bottlenecks are completely bypassed.) It can be derived that steady-state equilibrium on the $s$-process path is given by $N_s(A) \sigma(A) \sim$ constant, where $N_s(A)$ is the $s$-process abundance of a nucleus of mass $A$ and $\sigma(A)$ its neutron-capture cross section. This means that it is very easy to calculate relative abundance as ratios of neutron-capture cross sections, e.g., $N_s(A)/N_s(A+1) \sim \sigma(A+1)/\sigma(A)$. To a first approximation, these are independent of the neutron flux, as well as of the thermodynamic conditions, however, one should keep in mind that some neutron-capture reaction rates $\sigma v_{\text{thermal}}$ may have a dependence on the temperature, in which case $\sigma$ is not proportional to $v_{\text{thermal}}$, and the abundance ratios change with the temperature.

(iii) **Rule 3:** “Branching points” can open, where the $s$-process path has the option to move slightly off the valley of $\beta$-stability, not much further than a few mass numbers. As a rule of thumb this may happen when the unstable nucleus has a half life larger than roughly a day. While the classical definition of the $s$ process involves very low neutron densities, $\sim 10^8$ n/cm$^3$, reality is that neutron captures still more or less follows the valley of $\beta$-stability for neutron densities up to $\sim 10^{13}$ n/cm$^3$. The difference is that as the neutron density progressively increases the probability of unstable nuclei to capture a neutron instead of decaying also increases, depending on their decay rate and $\sigma$ and of course the neutron density. The decay rate can also depend on the temperature, in which case the branching point act as thermometers for the $s$ process.

To apply the three Golden Rules, especially Rule 1 and Rule 3, one needs to understand the difference between the “neutron exposure” and the “neutron density”. The neutron exposure controls Rule 1 while the neutron density controls Rule 3, so it is crucial to be able to distinguish the two. A simple explanatory diagram is shown in Figure 2. The neutron exposure is proportional to the total number of neutrons integrated over time, which is represented by the area below the neutron density profile. The neutron exposure is controlled by both the neutron density and the timescale of the neutron release. It possible to have cases where the neutron density is low, but the timescale is long and the neutron exposure is large (case $a$ in the figure) and cases where the neutron density is high but the timescale is short, and the neutron exposure is small (case $b$ in the figure). In fact, these two different cases corresponds for example to the activation of the two neutron sources in AGB the $^{13}$C($\alpha$,n)$^{16}$O and the $^{22}$Ne($\alpha$,n)$^{25}$Mg reactions discussed below.

2. The $s$ process in AGB stars

Observational evidence of the occurrence of the $s$ process in AGB stars has been accumulated starting from the 1950s [3, 4, 5, 6] and includes the observation of Tc, a radioactive elements that would not be present in the envelopes of these star if it was not produced in situ in their deep layers and mixed up to the surface. The structure and evolution of AGB is covered in the paper by M. El Eid (these proceedings), here, I briefly remind the essential points. An AGB stars is made essentially of two components: a large convective envelope that extends to hundreds of solar radii and includes most of the stellar mass, and a very compact inner region, which includes 1/3 to 1/6 of the total mass concentrated on a radius just a few times that of the Earth. The inner region is separated in different layers: most of the mass is located in an electron-degenerate core made of C and O from the previous H and He burning, on top of the core are the He- and
Figure 1. Solar abundances of atomic nuclei as function of their mass, normalised to Si=10^6. The elements corresponding to the different peaks are highlighted, in particular Sr, Ba, and Pb represent the three s-process peaks corresponding to the neutron magic numbers 50, 82, and 126.

Figure 2. Schematic example of two possible temporal evolution of the neutron density during the s process, to illustrate the difference between neutron exposure and neutron density. The neutron exposure is proportional to the total number of neutrons released in time, i.e., to the area below the neutron density profile. The neutron exposure is much larger in case a than in case b, conversely, the neutron density reaches much higher values in case b then in case a.

H-burning shells separated by a region rich in He and called “intershell”. This is the location of interesting nucleosynthesis, including the s process. The schematic temporal evolution of the internal structure of an AGB star is illustrated in Figure 3. The H-burning shell is activated most of the time, while the He-burning shell becomes active episodically and drives convection over the whole intershell (“convective pulse”). After a pulse is extinguished a mixing episode (“dredge-up”) can occur between the envelope and the intershell carrying to the surface material synthesised by nuclear reactions in the intershell, e.g., C made in the pulse by partial He burning and s-process nuclei. This cycle can occur many times over the AGB lifetime, depending on the initial stellar mass and how quickly the strong stellar winds carry away the envelope material.

For the s process free neutrons are needed and the 13C(α,n)16O reaction is the main source in AGB stars because it activates already at temperatures around 90 MK. Partial mixing of protons is assumed in the models to occur in a thin region of the intershell at the deepest extent of each dredge-up episode where a sharp discontinuity arises between the intershell and the convective envelope. The protons react with 12C and, under the basic assumption that the number of mixed protons declines with the mass depth, a “pocket” is produced, rich in 13C in the bottom layers - where the mixed number of protons is lower - and rich in 14N in the top layers - where the mixed number of protons is higher and CNO cycle equilibrium is achieved. The 13C(α,n)16O is activated usually before the onset of the next convective pulse, hence in radiative conditions creating a thin layer extremely s-process rich (Figure 3) [7, 8, 9, 10]. The initial stellar mass at which this sequence of events is believed to occur is between roughly 1.5 and 4 M⊙. Below this mass range no dredge-up episodes are found, which are the premise for the assumed mixing of protons. Above this mass range, two effects play a role to remove the 13C-rich pocket: (i) the mass of the intershell becomes progressively smaller, e.g., for a 2 M⊙ star it is of the order of 0.02 M⊙, while for a 5 M⊙ star it is of the order of 0.001 M⊙, so the
mass affected by the mixing of protons also shrinks [10]; (ii) the base of the envelope is so hot that the protons burn while they are mixed, and it is not possible to build a proton profile with a low abundance of protons in the layer deepest in mass leads to the production of $^{13}$C [11]. This theoretical scenario is also confirmed by observations [12].

Currently, one of the most debated effects on the neutrons released in the $^{13}$C pocket is that of stellar rotation. Initially, a star like the Sun can be assumed to rotate more or less like a rigid body, however, when it becomes a giant the envelope expands and slows down (like the ice skater opening his arms) and the core contracts and speeds up (like the ice skater closing his arms). The pocket is located at the border between these two different components, i.e., right on a discontinuity of the rotational velocity. This discontinuity generates mixing inside the otherwise radiative pocket, which carry $^{14}$N from the top layers into the $^{13}$C-rich bottom layers. $^{14}$N is the main “neutron poison” for the s process, i.e., it steals neutrons from $^{56}$Fe and the heavier nuclei because its $^{14}$N(n,p)$^{14}$C cross section is relatively high, 1.83 mbarn - by comparison the neutron-capture cross sections of the C, N, O isotopes are of the order of $10^{-2}$ mbarn. In this situation the amount of free neutrons (and hence the neutron exposure) inside the $^{13}$C pocket can decrease dramatically and the overall s-process distribution shifts towards lighter elements (Golden Rule 1) [13, 14, 15]. On the other hand, physical mechanisms exist that can couple the core to the envelope, make it rotate slower, and decrease the rotational velocity discontinuity and the effect of rotation on the s process. These are, for example, magnetic fields (both fossil and generated by rotation itself [16]) and gravity waves. We do not have yet an accurate description of their impact on the evolution of angular momentum in stars, but we do have observations of the rotational velocities of giant stars and of white dwarfs from stellar seismology [17, 18]. From trying to match these observations Cantiello et al. [19] derived that the AGB evolution should occur at nearly constant core angular momentum. It will be of much

**Figure 3.** Schematic illustration of the evolution of the internal structure of an AGB star with indicated the locations in time and space where neutrons are released for the s process.
interest to investigate what is the effect of these results on the s process.

In summary, rotation can alter the neutron flux by generating mixing inside $^{13}\text{C}$ pockets, which would otherwise behave radiatively, and potentially producing a lower neutron exposure. Another situation where $^{13}\text{C}$ burns while mixed with $^{14}\text{N}$ occurs in stars of low masses and relatively high metallicity. In these stars the temperature in the $^{13}\text{C}$ pocket may not reach the 90 MK required to burn $^{13}\text{C}$ before the onset of the next convective pulse and the $^{13}\text{C}$ nuclei burn completely or partially as they are ingested in the convective thermal pulse (Figure 3) [10, 20]. With respect to the case where all the $^{13}\text{C}$ nuclei burn radiatively, the result is a lower neutron exposure - similarly to the rotation case, because the $^{13}\text{C}$ nuclei are mixed with $^{14}\text{N}$ nuclei, which in the case of the ingestion are also present in the H-burning ashes - but a higher neutron density - because the temperature is higher in the pulse and the burning timescale is a few tens of years rather than a few tens of thousands of years. The neutron profile looks more like case $b$ in Figure 2, while in the radiative case it looks more like case $a$. Both the overall distribution (Golden Rule 1) and the effect of branching points (Golden Rule 3) are affected, with the overall distribution weighted towards the first s process peak and the branching points being more open.

2.1. Uncertainties in the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction and the impact on s-process results

A number of estimates are available for the rate of the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction and are shown in Figure 4 for the narrow range of temperature where the reaction is activated in the $^{13}\text{C}$ pocket of AGB stars. Direct measurements of the rate have not yet been possible since the Gamow window is at 140–230 keV. Some studies [23] have extrapolated direct measurements performed at energies above 270 keV. Most other studies have employed indirect methods to evaluate the fundamental contribution of the sub-threshold resonance due to the 6.356 MeV state in $^{17}\text{O}$. For clarity, I do not show the error bars in Figure 4, however, note that the last two estimates of the rate [24, 22] are outside of each other error bars (see Table 1 of [30]).

Most important is the question if these different rates and their disagreement have an impact on the s-process results. In the framework of the radiative $^{13}\text{C}$ pocket (i.e., for initial stellar masses $> 2 \text{M}_\odot$) there are no changes in the model results using any of the rates [24, 22, 30]. This is because if all the $^{13}\text{C}$ burns radiatively the neutron density profile is of type $a$, as shown in Figure 2. In this case, if the $^{13}\text{C}$ burns faster or slower the neutron density may somewhat increase or decrease, as the timescale of burning decreases or increases, respectively. However, the area below the curve, proportional to the neutron exposure, does not change. It should be
warned that the different rates have not been tested yet in models that include rotation. My expectation is that the value of the rate would have a much bigger impact in these models because of the competition of the timescales between the burning and the mixing.

On the other hand, the different $^{13}\text{C}(\alpha,n)^{16}\text{O}$ rates have an impact when the $^{13}\text{C}$ is ingested in the convective pulse (i.e., for initial stellar masses $< 2\, M_\odot$) [24]. This is because if the rate is faster more $^{13}\text{C}$ burns radiatively and less is ingested in the convective region, keeping the overall neutron exposure higher. Also, if the rate is faster, the $^{13}\text{C}$ that gets ingested in the convective pulse burns somewhat quicker than it takes for the convective region to engulf $^{14}\text{N}$, and the neutron exposure and the neutron density in the pulse increase. The branching point at $^{85}\text{Kr}$ is very sensitive to changes in the neutron density and can be used to test the different burning conditions. This is because it is activated already at relatively low $N_n \sim 10^8$ n/cm$^{-3}$ given the long half life of $^{85}\text{Kr}$ (11 yr). This branching point produces the neutron magic nucleus $^{86}\text{Kr}$, whose abundance relative to $^{82}\text{Kr}$ is measured in meteoritic stardust grains. Interestingly, the observed $^{86}\text{Kr}/^{82}\text{Kr}$ ratio increases with grain size, which gives us the opportunity to directly link the neutron density experienced by the material inside the deepest layers of the stars to the conditions experienced during the dust formation process in the outer layers of the star. It appears that the high $^{86}\text{Kr}/^{82}\text{Kr}$ ratio observed in the large (a few $\mu$m) grains can be produced in the low-mass AGB models where the $^{13}\text{C}$ burns convectively [31]. However, using the highest or the lowest rate for the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction results in a difference of 30% in the $^{86}\text{Kr}/^{82}\text{Kr}$ ratio, which does not allow us to reach firm conclusions. Future, planned measurements of this reaction at underground laboratories like LUNA and JUNA will allow us to settle this problem.

### 2.2. Post-AGB stars in the Large and Small Magellanic Clouds

De Smedt et al. [32, 33, 34] and van Aarle et al. [35] derived the abundances of many neutron-capture elements from the spectra of six post-AGB stars, the direct progeny of AGB stars, in the Large and Small Magellanic Clouds. Because we know the distances of these galaxies we can derive the absolute luminosity of these stars and comparing to evolutionary models we can infer that their initial masses were between 1 to 1.5 $M_\odot$. The metallicity is also observed to be roughly 1/10th of solar. At this low metallicity the $^{13}\text{C}$-pocket models predict large abundances of Pb, because there are less Fe seed nuclei to capture the neutrons, the neutron exposure is high and the overall s-process pattern shifts towards the third peak at Pb [7, 36]. The expected high abundances of Pb, however, are not observed in these post-AGB stars. Lugaro et al. [37] have tried to resolve this discrepancy by changing the $^{13}\text{C}$-pocket profile to simulate in a simple way the possible effect of rotation, or by artificially keeping the temperature low in the $^{13}\text{C}$ pocket so that the $^{13}\text{C}$ burns in convective conditions. As described above, both cases lead to a reduction of the neutron exposure. This, in turn, leads to less of the s-process abundance flux to bypass the second neutron magic number at $^{138}\text{Ba}$, resulting in a lower Pb abundance, as observed. However, also the abundances of all the elements between Ba and Pb, e.g., Gd, Hf, and W, are necessarily lowered, since the bottleneck at Ba is more narrow. The conclusion is that when the Pb abundance is matched, the abundances of these elements are all underpredicted. The solution to this problem may be found outside the s-process framework, by moving into a neutron-capture regime where the neutron density is in-between those of the s and the r processes. If the neutron-capture flux substantially moves away from the valley of $\beta$-stability, the elemental distributions can be affected in ways that are otherwise impossible for the s-process due to the constraints imposed by the stable magic nuclei acting as bottlenecks on its path. The existence of this intermediate process was first suggested by Cowan & Rose [38] and recently modelled by Herwig et al. [39]. More details can be found in the paper by M. Pignatari (these proceedings). From the observations of the six post-AGB stars in the Magellanic Clouds we derive that this process must be relatively common in AGB stars of low mass. Proton-ingestion episodes directly inside convective pulses may drive it, however, multi-dimensional, hydrodynamical models are required.
to address this possibility.

2.3. The other neutron source in AGB stars: $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$

![Figure 5](image_url)

The $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction becomes an important neutron source only for AGB stars of masses $> 3 \, M_\odot$ because it requires temperatures higher than 300 MK to be activated, which are reached only in the convective pulses of these stars (Figure 3). The lowest well studied resonance at 832 keV dominates the rate [43] and lies above the relevant astrophysical energies. The influence of a possible resonance at 635 keV was included in the calculation of the upper limit of the NACRE rate (Figure 5) but then ruled out based on parity [42]. Currently, the different estimates agree with each other within the error bars (see also Table 2 of [30]), however, these theoretical extrapolations may be affected by other unknown low-energy resonances so it is not easy to estimate the true current uncertainty. The activation of the $^{22}\text{Ne}$ neutron source occurs on short timescales (order of years) and results in neutron density profiles similar to case $b$ of Figure 2. This means that neutron exposures are usually relatively low, favouring production of the first $s$-process peak, but neutron densities are high, even up to $10^{13} \, n/cm^3$, so many branching points are open in these conditions. For example, the branching point at $^{86}\text{Rb}$ (half life 19 days) is activated by the $^{22}\text{Ne}$ neutron source resulting in the high Rb abundances [44] observed in massive AGB stars [45, 46]. However, the model results are not able to quantitatively match the observations. As for most branching points, they are very sensitive to the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ rate. Only future, planned underground experiments will allow us to provide more accurate and precise model predictions.

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