Neutron captures in stellar nucleosynthesis

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Abstract. Apart from cosmological hydrogen and helium, chemical elements in the Universe are produced in stars, during both quiescent and explosive phases. The Sun chemical distribution witnesses the pollution from already extinct stellar generations at different epochs before the Solar System formation. The two major nucleosynthesis processes responsible for the formation of elements heavier than iron are the slow neutron capture process (the s-process) and the rapid neutron capture process (the r-process). A third, less common, nucleosynthesis channel is related to the intermediate neutron capture process (the i-process), whose existence is not ascertained yet. Finally, a few proton-rich isotopes are created by the p-process. I will show their characteristics and the stellar sites where they are at work.

1 Introduction

The chemical history of the Universe experienced a progressive enrichment of metals (i.e. elements with A≥12) at the expense of the cosmological hydrogen. The distribution of heavy elements (A>56) in the solar system shows an exponential decline, superimposed to a series of double-peaks, related to the s (slow) and the r (rapid) processes [1]. Elements heavier than iron can be synthesized mainly via neutron capture processes, whose occurrence is not hampered by the Coulomb barrier. This kind of nucleosynthesis may easily work at low energies, because neutron capture cross sections generally increase with decreasing energy.
The most common neutron fluxes in stars are either quite small (s-process: $n_n \sim 10^7$ cm^{-3}) or quite large (r-process: $n_n > 10^{20}$ cm^{-3}). In principle one might expect to encounter astrophysical neutron fluxes in the large region between these two densities. Although not universally recognized, those events are apparently not common, even if in the last 10 years there has been a growing evidence for the need of such intermediate neutron capture process (i-process; [2–4]). For the s-process, two stellar sites have been unequivocally identified: low mass Asymptotic Giant Branch (AGB) stars [5–7] and quiescent phases of massive star evolution [8]. On the other hand, r process is believed to occur during late evolutionary stages of massive stars (single or binary), the exact site being still matter of debate (Magneto-rotational SuperNovae [9], Neutron stars mergers (NSMs) [10], Collapsars [11]). In the following Sections, I will review the three aforementioned neutron capture processes.

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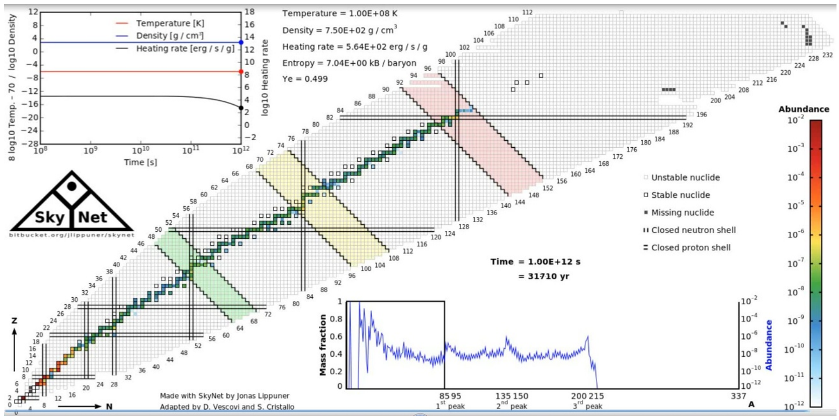

Figure 1. Typical pattern of the s-process. The plot has been produced with the PYTHON graphical interface of the SKYNET code [14].

2 The s-process

A typical s-process pattern is reported in Figure 1. The main s-process flow proceeds closely stick to the β stability valley (empty squares in the plot represent stable isotopes). Interestingly, there are isotope which are shielded by an r-process contribution by their stable isobars, named s-only, whose production is of paramount importance to calibrate s-process calculations (see [12] and references therein; see also [13] for a recent exploration of this subject). the main seed for the s-process is ^{56}Fe: this is due to its rather large abundance and neutron capture cross section. In Figure 1 mass fractions at the end of a typical s-process neutron exposure are reported. Three peaks clearly emerge from the distribution, corresponding to nuclei with neutron magic nuclei (N=50, N=82 and N=126). Those isotopes, characterized by closed shells configurations, are more stable with respect to their neighbors and, therefore, act as bottlenecks of the s-process fluency. The isotopes with the slowest neutron capture cross sections are ^{88}Sr, ^{138}Ba and ^{208}Pb, which marks the three s-process peaks. Another important quantity in s-process calculations is the neutron-to-seed ratio, defined as the ratio between the local neutron abundance and the local seed (mostly ^{56}Fe) abundance. The larger this ratio is, the more heaviest isotopes (as ^{208}Pb) are produced.
The two major neutron sources for the s-process are the ^{13}C(α,n)^{16}O and the ^{22}Ne(α,n)^{25}Mg reactions. The first reaction dominates in Thermally Pulsing low mass AGB stars ($1 < M / M_\odot < 4$; [15, 16]) and it is responsible for the *main* component of the s-process ($88 \leq A \leq 208$). The AGB phase is attained by low and intermediate mass stars which are unable to activate advanced burnings in their core. During this phase, the stars consist of a partially degenerate C-O core, a radiative layers between an He-shell and an H-shell (where the s-process takes place) and by an expanded cool H-rich envelope. The products synthesized in the internal layers are carried to the surface by mixing episodes known as Third Dredge Ups (see [17] and references therein). Interested readers may download AGB surface abundances and yields from the FRUITY database[1] [6].
The other neutron source, the ^{22}Ne(α,n)^{25}Mg, is the main neutron producer in massive stars, accounting for the *weak* component of the s-process ($A<88$). As a matter of fact, elements between iron and the first s-process peak are efficiently synthesized by the weak s-process [8],

[1] http://fruity.oa-teramo.inaf.it/

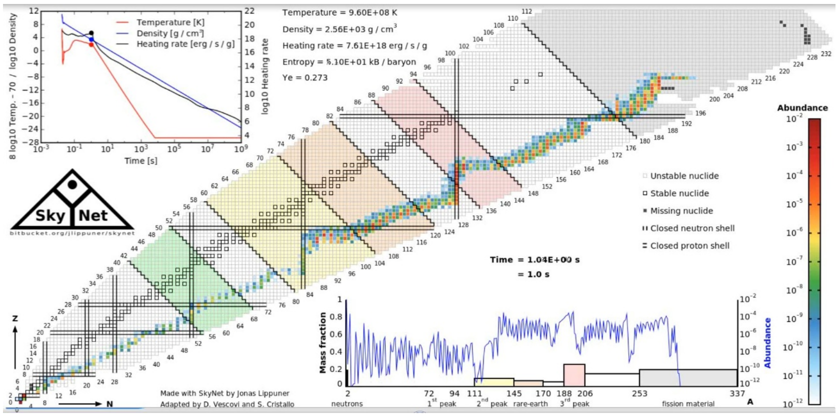

Figure 2. Typical pattern of the r-process. The plot has been produced with the PYTHON graphical interface of the SKYNET code [14].

which is at work during the core He-burning (n$\sim 10^6$ cm^{-3}) and the C-shell burning (n$\sim 10^{12}$ cm^{-3}) phases of massive (M> 9 M$_\odot$) stars evolution.

3 The r-process

The remaining half of the heavy elements in the Universe are synthesized via the r-process. The latter has been proved to be at work during NSMs, by observing and interpreting the electromagnetic transient (the so-called kilonova) following the gravitational event GW170817. Since then, an exponentially growing number of studies on this subject have become available, making the last years an exciting period for the investigation of the r-process nucleosynthesis. The electromagnetic counterpart (AT2017gfo) of the gravitational wave detection GW170817 provided the first record of the in-situ operation of the r-process. During this nucleosynthesis process, extremely large neutron densities allow the production of neutron-rich isotopes far from the β-stability valley. The physics of the r-process is by far more complex with respect to the s-process. As a matter of fact, due to the difficulties in modelling explosions and because of the large uncertainties in nuclear inputs, the r-process contribution to the solar distribution is estimated by subtracting that coming from the s-process, i.e. r=1-s [13, 18].
In Figure 2 we report the typical r-process path attained in a NSM 1 second after the merger. For many key quantities only theoretical estimates are currently available, making predictions for the r-process less robust than the corresponding ones related to the s-process. The r-process is normally characterized by a huge amount of free neutrons. Thus, due to the large neutron-to-seed ratios (up to several 1000), the nucleosynthesis becomes insensitive to the initial composition and the material loses memory of the exact thermodynamic conditions at ejection. However, there is a late phase, in which neutron captures and decays operate on very similar time scales (r-process freeze-out). During this phase, neutron captures may shape the final r-process distribution. Improvements are expected from an in-depth knowledge of properties of the nuclei far from stability, from both the theoretical and experimental point of view. To that purpose, sensitivity studies aiming at identifying the most important nuclear properties to be measured in order to reduce the uncertainty related to the r-process are particularly helpful (see e.g. [19]). Sensitivity studies play a key role in facilitating state-of-the-art measurements as they provide crucial astrophysical motivation to focus experimental campaigns

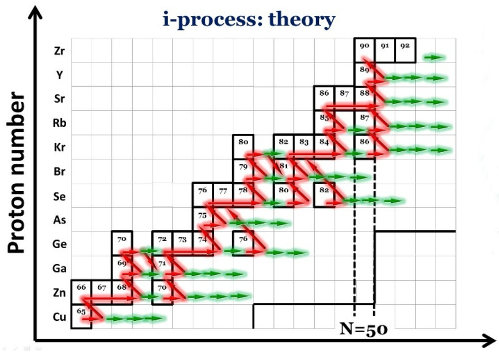

Figure 3. Typical pattern of the i-process. Green arrows mark the departure from the β stability valley. Red arrows indicate the main s-process path.

on the most impactful nuclei. However, the results of any sensitivity study have to be taken with a grain of salt, because even considering just one stellar site (as NMSs), the physical characteristics of various tracers at different angles can lead to completely different chemical patterns. The latter are mainly regulated by the neutronization level (Y_e, or electron fraction). Finally, details about interactions with neutrinos are fundamental. In fact, the neutrino transport determines the local Y_e, shaping the final r-process distribution. Besides the many stellar sites proposed to host the r-process, three are the major candidates:

- Neutron Star Mergers: these events are the only stellar site in which r-process has been demonstrated to be at work (see e.g. [20]). A rich nucleosynthesis is expected, involving also elements lighter than lantanides (as Sr, see [21]), but not H or He (see [22]);
- Magneto-rotational Supernovae: while standard supernovae are not able to develop a full r-process (but may instead be responsible for the weak component of the r-process, [23]), if the effects of strong magnetic fields are included, a complete r-process takes places [9]
- Collapsars: accretion disks around Black holes are the third candidate to host the r-process [11]. In such a case, also lighter isotopes (i.f. those belonging to the iron peak) can be produced.

To date is extremely challenging to disentangle among these three scenarios. For this reason Galactic Chemical Evolution models are required to weight their contributions and eventually identify the most probable candidates to host the r-process [24].

4 The i-process

The intermediate neutron capture process (i-process) was first theorized by [25]. It develops whenever protons are mixed in regions with typical He-burning temperatures (T $\sim$ 200-300 MK). In this situation, hydrogen burns on-fly producing ^{13}N and/or ^{13}C, on a timescale of the order of hours (thus intermediate between tens of thousands year of the s-process and 1 s of the r-process). In such a situation, a few (from 4 to 6-7) neutron captures may occur on stable isotopes (see Figure 3). Then, when the neutron exposure comes to an end, unstable isotopes decay back to their stable isobars. It is still a matter of debate if such an i-process has sizable effects or not on the Galactic Chemical Evolution history. There are examples whose chemical patterns can be fitted very well by this process. The best known example are the so-called Carbon Enhanced Metal Poor (CEMP) s/r stars, named in such a way due to their peculiar chemical surface distributions. To date, two are the major candidates to host the i-process: Low-Metallicity Low-Mass AGB stars [2, 4, 5] and Rapidly Accreting White Dwarfs [3].

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