Nucleosynthesis, mixing, and rotation

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Nucleosynthesis in stars: The Origin of the Heaviest Elements

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Abstract. The chemical evolution of the Universe is governed by the nucleosynthesis contribution from stars, which in turn is determined primarily by the initial stellar mass. The heaviest elements are primarily produced through neutron capture nucleosynthesis. Two main neutron capture processes identified are the slow and rapid neutron capture processes (*s* and *r* processes, respectively). The sites of the *r* and *s*-process are discussed, along with recent progress and their associated uncertainties. This review is mostly focused on the *s*-process which occurs in low and intermediate-mass stars which have masses up to about 8 solar masses ($M_\odot$). We also discuss the intermediate-neutron capture process (or *i*-process), which may occur in AGB stars, accreting white dwarfs, and massive stars. The contribution of the *i*-process to the chemical evolution of elements in galaxies is as yet uncertain.

Keywords. nuclear reactions, nucleosynthesis, abundances, stars: AGB and post-AGB, galaxies: abundances

1. Introduction

The story of the origin of the elements is one of the most fascinating in astronomy. Primordial element synthesis during the Big Bang 13.7 billion years ago created hydrogen, helium, and trace amounts of lithium (Li). The rest of the elements came from stars. The quest for the stellar sites that produced the elements is fundamental to modern science because this quest is linked to questions concerning the origins of planetary systems, life and astrobiology, origins of the Universe, and the process of galaxy formation.

Elements from carbon to iron are made by charged-particle nuclear reactions inside stars. By charged-particles reactions we mean those involving protons and α particles (helium atomic nuclei). These are the type of reactions that are taking place in the heart of our Sun, where hydrogen (H) is being fused or burnt into helium (He). Once a star runs out of its main source of fuel, hydrogen, the core contracts until the temperature in the centre is hot enough to fuse helium, the next most abundant element. Helium fusion reactions synthesize carbon and oxygen, and are the last central nuclear source for stars less massive than 8 times the mass of our Sun ($8M_\odot$). After core helium burning the stars enter the asymptotic giant branch (AGB) phase, where they are seen as immense red giants with distended outer envelopes. The outer layers are only tenuously held on and can be lost from the star by outflows of material (winds). Eventually, the winds drive the entire envelope into interstellar space, revealing the hot cores which light up the gas as beautiful planetary nebulae. We refer to reviews of the AGB phase by Karakas & Lattanzio (2014) and Herwig (2005) for details.

The low and intermediate-mass stars that evolve into AGB stars are fairly numerous because the initial mass function peaks at $\approx 1M_\odot$. Of importance for the chemical content of the Galaxy is the fact that the stellar winds contain matter that has been enriched by nuclear reactions deep in the star's interior, and brought to the stellar surface via mixing episodes. AGB stars are therefore crucial contributors to the chemical evolution of elements in galaxies across the Universe (Romano *et al.* 2010; Kobayashi *et al.* 2011). Furthermore, galaxies care about AGB stars because their dusty winds contribute toward the dust budgets of galaxies, and in particular are copious producers of carbon-rich dust even in metal-poor galaxies. Galaxies dominated by intermediate-age stellar populations emit much of their starlight in the infra-red, which is mostly produced by AGB stars.

Spectacular supernova explosions mark the end of stars more massive than about $10M_{\odot}$. These explosions release vast quantities of energy and α-elements (e.g., oxygen, magnesium, silicon, calcium) as well as iron into the Galaxy. Binary systems that explode as Type Ia supernovae are also responsible for producing substantial metals, mostly in the form of iron-peak elements. Nomoto, Kobayashi & Tominaga (2013) reviewed the explosive nucleosynthesis from supernovae and their contribution toward the Galactic chemical evolution of galaxies.

When considering the sources of nucleosynthesis in galaxies it is important to consider the different lifetimes of contributing sources. Massive stars have short lifetimes and explode almost instantaneously, compared to the lives of galaxies. In contrast, AGB stars span an enormous range in stellar lifetimes. The most massive stars that experience the AGB phase of about $8M_{\odot}$ have short lifetimes of 30 million years whereas the lowest masses to enter the AGB have lifetimes of 10 billion years, comparable to the age of the Milky Way Galaxy.

In this review I summarise the mechanism for producing elements heavier than iron in nature along with the sites of heavy element nucleosynthesis.

2. Making heavy elements

The origin of elements heavier than iron is not linked to the nuclear reactions that produce energy inside stars. Heavy elements are instead synthesized by reactions that involve *the addition of neutrons* onto Fe-peak elements. The foundations for the origin of heavy elements was laid down in the seminal review papers of Burbidge *et al.* (1957) and independently by Cameron (1957). Forty years later, Wallerstein *et al.* (1997) provided a comprehensive update, based on the latest observations, theoretical models, and nuclear physics data.

It was proposed that two processes can produce the bulk of heavy elements in our solar system (Fig. 1): The *slow* and *rapid* neutron-capture process (or s and r process, respectively). The s-process occurs when the rates of neutron addition are, in general, slower compared to the timescales for the β-decays of radioactive nuclei. This builds up nuclei along the valley of nuclear stability as shown In Fig 2, where the path of the s and r processes are shown in a section of the chart of the nuclides. We can see that the main s-process path goes through the long-lived unstable Tc isotope, ^{99}Tc, which has a half life of $\approx 2 \times 10^5$ years. Tc was first detected in the spectra of long-lived red giant stars in the early 1950's the first observational confirmation that stars can make elements heavier than iron.

During the r-process there are so many neutrons that radioactive nuclei do not have time to decay before capturing another neutron and this produces nuclei far from nuclear stability. Once the neutron flux is gone the unstable nuclei decay until stable nuclei are produced; the result is some of the rarest heaviest elements found in nature including uranium and thorium. Of interest but not part of this story is the origin of the rare proton-rich isotopes such as ^{94}Mo which are only destroyed by neutron-capture reactions. These isotopes are likely synthesized by combinations of proton captures, β-decays and/or spallation reactions occurring in high energy, explosive environments (e.g., core collapse supernovae).

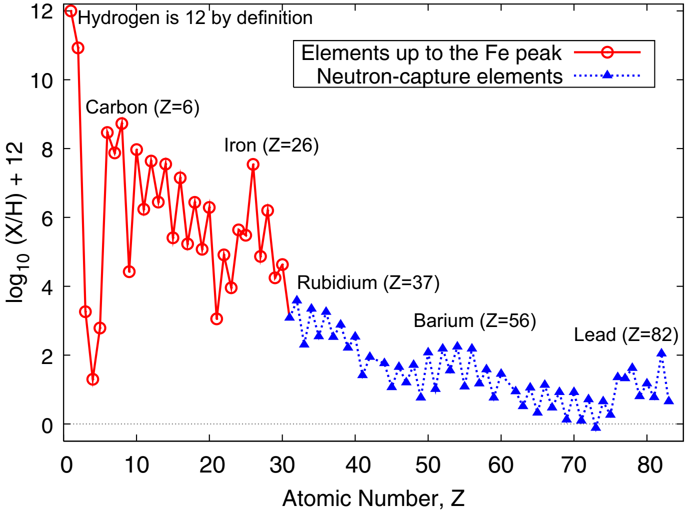

Figure 1. Solar abundance distribution using data from Asplund *et al.* (2009). The main features of the abundance distribution include the hydrogen peak ($Z = 1$) followed by helium ($Z = 2$). The gorge separating helium from carbon, the continuous decrease from carbon to scandium ($Z = 21$), followed by the iron peak, and the gentle downwards slope towards the platinum ($Z = 78$) and lead peaks, ending with the heaviest element found in nature, e.g., uranium ($Z = 92$).

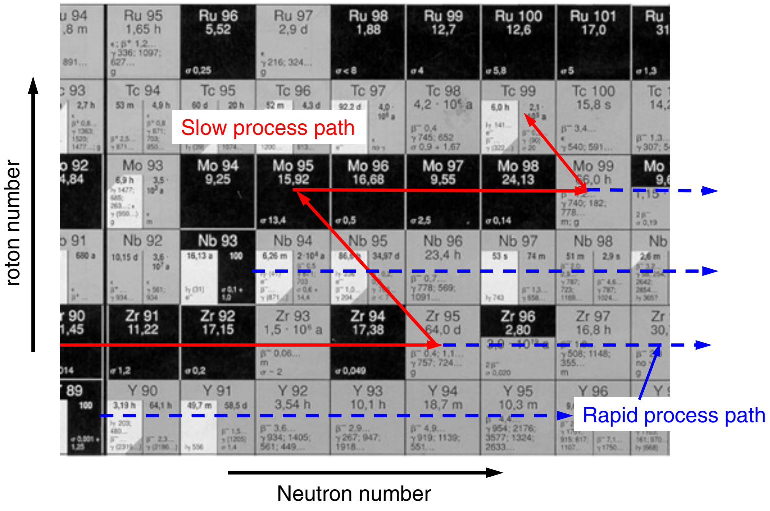

Figure 2. A section of the chart of the nuclides. Neutrons increase on the x-axis and protons on the y-axis. Here we can see isotopes around the Sr to Tc region, where stable isotopes are shown in black, with the solar system fraction provided (e.g., 17.38% for ^{94}Zr). Gray squares show unstable radioactive isotopes, where the half-life is given (e.g., 1.5×10^6 years for ^{93}Zr). The path of the s-process is highlighted by the solid red line, with the r-process path by the dashed blue line.

3. Sites of heavy element nucleosynthesis

The astrophysical site of the s-process in nature is well constrained by observational evidence and theoretical models to occur inside AGB stars. Massive stars may also produce heavy elements via the s-process in hydrostatic evolutionary phases leading up to core collapse. The origin of the r-process was for many years a complete mystery. Owing to recent discoveries coming from the gravitational wave community we have now confirmed merging neutron stars as a site of the r-process.

Here we summarize the sites of heavy element nucleosynthesis in more detail, starting with the r-process.

3.1. *The site(s) of the r-process*

The rapid neutron capture process releases a huge number of neutrons over a few seconds where typical densities are on the order of $N_{\mathrm{n}} > 10^{20}$ n cm^{-3}. Such conditions suggest an explosive site and for a long time core collapse supernovae were the favoured mechanism for producing the r-process. Calculations have so far failed to produce the necessary neutron rich environments (Thielemann *et al.* 2018). Other rarer sites were also proposed including electron-capture supernovae (Wanajo *et al.* 2011), merging neutron stars (Lattimer & Schramm 1976), and magneto-rotationally induced supernova (Winteler *et al.* 2012). Up until 2016 it was unclear what site(s) were responsible (Sneden *et al.* 2008).

In 2016 measurements of Ba and Eu in the ultra-faint dwarf galaxy Reticulum II by Ji *et al.* (2016) provided some hints. The high abundances of these two elements, higher than in other dwarf galaxies, suggested that a single rare r-process event took place that produced the heavy elements. The study ruled out core collapse supernovae; too many of them were needed, which would have blown the already fragile galaxy apart. A complementary study by Wallner *et al.* (2015) of the heavy ^{244}Pu isotope in ocean floor sediments also ruled out core collapse supernovae. Again, a rare source such as merging neutron stars was suggested in order to account for the low abundance of the ^{244}Pu detected.

In 2017 the discovery of gravitational waves by the source GW170817 settled at least part of the mystery. The source of the gravitational waves was determined to originate from a pair of merging neutron stars (Abbot *et al.* 2017). The electro-magnetic counterpart was also discovered to be a red kilonova where the spectral energy distribution was best fit by the decay of radioactive isotopes produced by the r-process (Kilpatrick *et al.* 2017). It has been estimated that $\sim 0.05 M_{\odot}$ of pure r-process elements were expelled (Drout *et al.* 2017).

It is still not clear if merging neutron stars is the *only* site of the r-process in nature. The element Eu is primarily made by the r-process ($\sim$ 98% in the solar system is attributed to the rapid process). Spectroscopic observations of Eu in old, metal-poor halo stars show high levels of Eu and significant scatter (Sneden *et al.* 2008). Can neutron star mergers occur early enough and frequently enough in the Galaxy to account for the abundances of Eu observed in the halo and disk?

The probability of neutron star mergers as a function of time in galaxies is not well constrained – we only have one confirmed event. Recent studies suggest that the rate of neutron-star mergers determined from theory and observations cannot account for the chemical evolution of Eu in Galactic disk stars (e.g., Hotokezaka *et al.* 2018). This suggests that at least one other, rapid source, of r-process elements may be needed to enrich the Galaxy. Future gravitational wave discoveries from merging neutron stars may help solve this problem, and provide some indication of how normal or unusual GW170817 is.

One issue is that we cannot directly observe the elemental abundances produced in the kilonova. For this reason the best way to constrain models of the r-process is to remove the s-process contribution from the solar system abundances. This technique allows us to obtain an “observational” r-process distribution. This is still the most accurate observational test for comparison to the r-process models, which are extremely uncertain both in the stellar and the nuclear physics.

3.2. *The s-process*

In low and intermediate-mass stars, the s-process can occur during hydrostatic burning of helium in the core or shell, where unstable helium shell burning is characteristic of the AGB phase of evolution. In massive stars the s-process occurs also during hydrostatic burning in the carbon and helium burning shells.

During the s-process neutron densities are typically on the order of $N_{\rm n} \lesssim 10^{13}$ n cm^{-3}, depending on the source of neutrons. In massive stars neutrons are released by the ^{22}Ne(α,n) ^{25}Mg reaction, which operates at temperatures over about 300×10^6 K. The efficiency of the ^{22}Ne neutron source relies on the concentration of ^{22}Ne, which is produced by α-captures onto ^{14}N during He-burning. Normally this is a secondary process and dependent on the initial abundance of CNO nuclei that the star was born with.

However in rapidly rotating massive stars, primary ^{14}N can be produced which in turn leads to an enhanced concentration of ^{22}Ne in the He-shell. We refer to the review by Maeder & Meynet (2012) for details. Rotation means that even low-metallicity massive stars can produce significant s-process elements. Nucleosynthesis calculations include those by Pignatari *et al.* (2008), Frischknecht *et al.* (2016), Choplin *et al.* (2018), and Limongi & Chieffi (2018). The contribution of massive stars toward the s-process is important for elements between Zn and Sr.

3.3. *The s-process: AGB stars*

Theoretical and observational studies of the s-process have a long history. We do not attempt to review the full history here but refer to Busso *et al.* (1999), Herwig (2005), Sneden *et al.* (2008), Käppeler *et al.* (2011), and Karakas & Lattanzio (2014) for references. Below we summarize the operation of the s-process in AGB stars. In Section 4 we review the latest AGB s-process yields predictions.

The first neutron source postulated to occur in AGB stars was also the ^{22}Ne(α,n)^{25}Mg reaction. However because this reaction occurs at temperatures over 300×10^6 K it is only efficient in intermediate-mass AGB stars over about $4M_\odot$. It may also produce a brief burst of neutrons in lower mass AGB stars during their final few thermal pulses. In low-mass AGB stars, neutrons are produced predominantly by the ^{13}C(α,n)^{16}O reaction (e.g., Abia *et al.* 2001). The difficulty with the ^{13}C neutron source is that ^{13}C is absent in the He-shells of AGB stars, unlike ^{22}Ne it is not produced by He-burning reactions. For this reason it has been hypothesised that some mixing of protons from the surrounding envelope occurs into the top layers of the He-shell. These protons are captured by the abundant ^{12}C to form ^{13}C via ^{12}C(p,γ)^{13}N(β^+)^{13}C. Straniero *et al.* (1995) found that the ^{13}C nuclei burn radiatively between pulses, allowing for the release of neutrons and neutron-capture reactions relatively slowly. In AGB stars, typical timescales for neutron captures are on the order of 10^4 years with neutron densities $N_{\rm n} \lesssim 10^8$ n cm^{-3}. AGB stars are particulary important for the production of elements between Sr and Pb.

During the interpulse the neutrons are captured by iron-peak nuclei and converted into heavy elements. The next thermal pulse engulfs the pocket of heavy elements and subsequent third dredge-up mixes some of these heavy elements to the surface (along with C, F etc) where they can be observed. In low-mass AGB stars elements between Sr and Pb can be made in large quantities, where observed $[s/\text{Fe}] \sim 1$ in AGB stars. The exact distribution of heavy elements is dependent on the thermodynamic quantities in the stellar models and depends on the initial mass and metallicity. In Fig 3 we show the final surface composition of low-mass AGB models of $[\text{Fe/H}] = -0.7$. In particular the

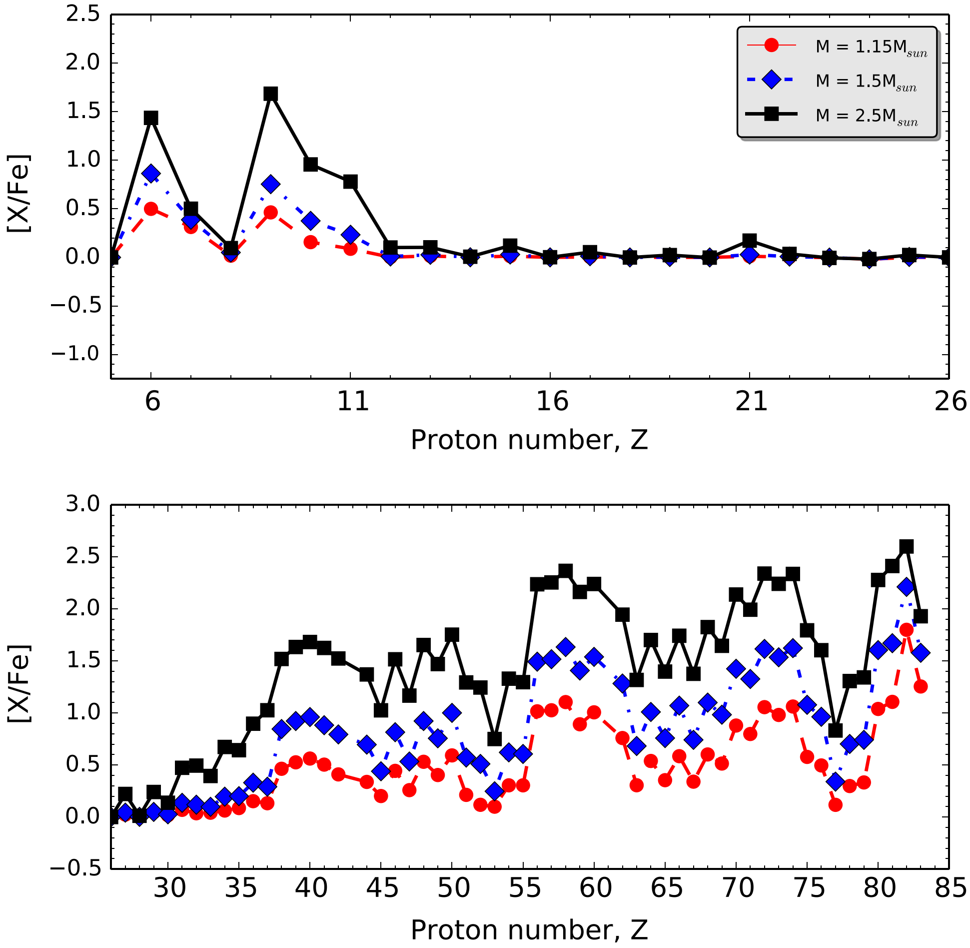

Figure 3. The final surface composition for a selection of low-mass AGB models of [Fe/H] = −0.7. The top panel shows elements lighter than iron while the bottom panel shows elements heavier than iron. Using model predictions from Karakas *et al.* (2018).

bottom panel shows the results for *s*-process elements where large enhancements in Sr ($Z = 38$), Ba ($Z = 56$) and Pb ($Z = 82$) are noticeable. The ratio of Sr/Pb and Ba/Pb in particular depends on the initial metallicity. This is because the amount of ^{13}C made in the He-intershell is primary which means that the ratio of neutrons/Fe increases with decreasing metallicity. This leads to a build up of Pb in low-metallicity AGB models as noticed first by Gallino *et al.* (1998) and later confirmed by observations by van Eck *et al.* (2001).

4. Yields from AGB stars

Stellar yields are an essential ingredient of chemical evolution models. While there are many studies of the *s*-process in AGB stars, it has only been in the last 10 years that tabulated stellar yields including *s*-process elements have been available. For this reason we limit our discussion here to these predictions, noting that other yield sets exist that focus on elements lighter than Fe (e.g., Ventura *et al.* 2013). We also do not discuss the many studies of AGB nucleosynthesis where only surface abundance predictions are given. Bisterzo *et al.* (2010) for example only published surface abundance predictions

Table 1. *s*-process yields: We only show predictions that include *s*-process elements as well as yield tables, not just surface abundance predictions.

Reference	**Mass Range (in $M_\odot$)**	**Metallicity Range (in mass fraction, Z)**	**Downloadable tables?**
FRUITY database$^{(a)}$	1.3–6.0	2×10^{-5} to 0.02	Yes
Monash models$^{(b)}$	1.0–8.0	1×10^{-4} to 0.03	Yes
NuGrid/MESA$^{(c)}$	1.5–5.0	0.01, 0.02	Yes

(a) Website: http://fruity.oa-abruzzo.inaf.it/
(b) Data tables available for download from associated papers.
(c) Website: http://www.astro.keele.ac.uk/nugrid/data-and-software/yields/

although the yields from their updated models have been subsequently used in chemical evolution studies (e.g., Bisterzo *et al.* 2017). For a more detailed set of references we refer to Karakas & Lattanzio (2014) noting that this is already 4 years out of date!

In Table 1 we provide a brief summary of the AGB yields available that include *s*-process elements. The three main groups are the FRUITY models, the Monash/Stromlo calculations and the NuGrid/MESA models. The FRUITY models are described in a series of papers starting with Cristallo *et al.* (2009) and detailed in Cristallo *et al.* (2015). We refer to references given on the FRUITY website (see Table 1) for details of the models. These are currently the only AGB yields of the *s*-process that include stellar rotation.

The yield tables from the Monash/Stromlo models are available for download from the papers associated with these studies. The main papers are Fishlock *et al.* (2014), Karakas & Lugaro (2016) and Karakas *et al.* (2018). These calculations include the full range of AGB masses up to the CO-core limit of $8M_\odot$ for solar metallicity. Fishlock *et al.* (2014) and Shingles *et al.* (2015) also include a few models of heavy-element yields from super-AGB stars; and the latter paper also includes the effect of helium enrichment on stellar yields.

NuGrid/MESA yields are described in Pignatari *et al.* (2016) although there is an extended set published by Ritter *et al.* (2018). The novelty of the NuGrid/MESA yields is that they also include yields of massive stars calculated using the same codes, which means the same initial abundances and reaction rates. The second set covers a larger range of masses from $1-25M_\odot$ and larger range of metallicity, from $Z=0.02$ to 0.0001, with α-enhancement for lower metallicities. We note that on the NuGrid website given in Table 1 only the first set from Pignatari *et al.* (2016) is currently available.

There are currently considerable gaps in the yields available. These are the most significant at low metallicities, where there are no tabulated yields below $Z \leqslant \text{few} \times 10^{-5}$. Very low metallicity models may experience proton-ingestion episodes at various phases of stellar evolution. Current studies are limited to Cruz *et al.* (2013) and Campbell *et al.* (2010). Furthermore, there are few yields of super-AGB stars that include full *s*-process calculations, beyond one or two masses discussed already (e.g., the $7M_\odot$, $Z=0.001$ model in Fishlock *et al.* 2014). The AGB yields also do not consider the effect of a binary companion.

5. Beyond the standard model of nucleosynthesis

We have made considerable progress in understanding the *s*-process in spite of considerable modelling uncertainties. This is mostly owing to excellent nuclear physics data. The major uncertainty for the *s*-process is the mechanism for the formation of a ^{13}C-rich region in the He-intershell of AGB stars (Buntain *et al.* 2017). Convective overshoot may be responsible (Herwig *et al.* 1997; Cristallo *et al.* 2009), perhaps helped by magnetic fields (Trippella *et al.* 2016). How stellar rotation affects the *s*-process is still an open question. Models have found that rotation may inhibit the *s*-process completely (Herwig *et al.* 2003) or simply modulate the abundances (Piersanti *et al.* 2013).

There are some observations of post-AGB stars that do not appear to fit within the classical *s*-process scenario in AGB stars, even considering uncertainties associated with modelling and nuclear physics. These include Sakurai's Object, which appears to be best fit by a proton-ingestion episode following a late thermal pulse (Herwig *et al.* 2011). Sakurai's Object was for a long time seen as an anomaly (and it still may be!) and other post-AGB stars were seen as exquisite tracers of nucleosynthesis during the AGB phase (Van Winckel 2003).

The Magellanic Cloud post-AGB stars are some of the most *s*-process enriched objects known and overall seem to be fit well by *s*-process AGB nucleosynthesis except for the element Pb (De Smedt *et al.* 2012). There are suggestions that the abundances observed in these post-AGB stars are not made by a typical *s*-process but would be better fit by an *intermediate* neutron capture process (e.g., Lugaro *et al.* 2015), operating at higher neutron densities and resulting from a proton ingestion episode.

That there may be neutron captures occurring at intermediate neutron densities is not a new idea (Cowan & Rose 1977). Carbon enhanced metal-poor stars with an *s* and *r* process enrichment may be better fit by an *i*-process (Dardelet *et al.* 2015; Hampel *et al.* 2016). Furthermore, accreting white dwarfs may also produce *i*-process elements, which may be important for chemical evolution (Denissenkov *et al.* 2017). The contribution of the *i*-process to the Galactic inventory is as yet unknown. Côté *et al.* (2018) suggest the *i*-process may be important for the elements Sr, Y and Z. Note that Galactic chemical evolution calculations by Prantzos *et al.* (2018) using the yields from the FRUITY database and Limongi & Chieffi (2018) find no need for an extra contribution for the elements Sr, Y and Zr.

6. Summary

In this review we have summarised the sites of heavy element nucleosynthesis in the Galaxy. We have discussed the latest results for the rapid and slow neutron capture processes. While we have a site for the *r*-process we still require accurate yields of *s*-process nucleosynthesis in order to better constrain uncertain *r*-process models. While yields of AGB stars are available, there are still considerable gaps in the parameter space, particularly at low metallicities and at higher masses (e.g., for super-AGB stars). There is evidence for an intermediate-neutron capture process although the site is not well constrained at present. For this reason the contribution of the *i*-process to the Galactic inventory of heavy elements is currently uncertain.

There is currently an explosion of new stellar abundance data from various large-scale spectroscopic surveys (e.g., the Galah survey, the GAIA-ESO survey, LAMOST, APOGEE etc.). These data will help answer big questions related to the formation and evolution of galaxies but will also provide new data to help constrain stellar physics problems, such as those related to the origin of the elements and chemical evolution in galaxies.

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Discussion

Question: It’s worth noting that there is currently still no spectroscopic identification of individual elements in the kilonova associated with GW170817.

Karakas: I agree. This is an important point.

Wijers: *Comment:* Lathmer & Schramm perhaps deserve some credit for having predicted mergers as the site of the r-process. *Question:* Do the low- or high-metallicity dominate the total s-process production?

Karakas: The low-metallicity stars dominate, for various stellar physics reasons, a.o. because they mix more burnt material into their envelopes.

Zinnecker: Can you comment on the binary nature of AGB stars and their influence on nucleosynthesis? I recall that SNIa, the nucleosynthetic source of iron, requires binary star evolution. Without binaries, no iron!

Karakas: The binary nature of AGB stars is unclear. If a star reaches the AGB with a companion, the orbit will be wide. Hence, mass transfer may occur or even a truncation of the AGB phase. Binaries are likely important for ending the AGB and shaping planetary nebulae. There is still much work to be done on this topic.

Hrivnak: Regarding i-process and post-AGB stars, are you saying that this formation occurs in the post-AGB phase or that in this phase, with envelope removed, we see these results?

Karakas: The i-process occurs when protons are ingested into the convectively burning He-shell. This is more likely to occur in post-AGB stars, which have small envelopes, than in the AGB phase (for metallicities above [Fe/H] ~ -2 dex or so).

D’Antona: Again about the i-process. If it occurs only in post-AGB or at the He-core flash, it is important only to explain a few observations, but if it occurs in accreting white dwarfs, it may make an important contribution to abundances evolution. Do we have any observational evidence from observations, say of symbiotic novae or nova ejecta?

Karakas: There is no observational evidence for the i-process in novae or symbiotic stars, but observers haven’t really looked for this signature.