The slow neutron capture process

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Origin of heavy elements

• Most heavy nuclei are formed by neutron addition onto Fe-peak elements

• Two processes:
  – *r-process* (rapid neutron capture)
  – *s-process* (slow neutron capture)

References:
• Meyer (1994), Gallino et al. (1998), Busso et al. (2001), Sneden et al. (2008), Käppeler et al. (2011)
Making heavy elements

The radioactive Tc is observed in stars!

- Slow process path
- Rapid process path
SITES OF HEAVY ELEMENT NUCLEOSYNTHESIS
Sites of heavy element nucleosynthesis

- Neutron star mergers
- Magnetic-hydrodynamically driven supernovae → unusual supernovae

Massive stars

- Asymptotic giant branch stars

The r-process
- \( \approx 50\% \)

The s-process
- \( \approx 50\% \)
The s-process: massive stars

- Rotation can significantly affect s-process production inside massive stars, e.g., from Choplin et al. (2018) for models with metallicity $= 10^{-3}$

See also Limongi & Chieffi (2018), Frischknecht et al. (2016), Pignatari et al. (2008)
Asymptotic Giant Branch stars: (upper mass limit ~6-8Msun)

- After core He-burning, the C-O core contracts and the star becomes a giant again
- Double-shell configuration
- He-burning shell is thermally unstable and flashes every ~$10^4$ years
- Rapid, episodic mass loss erodes the envelope

Review by Karakas & Lattanzio (2014)
Schematic AGB evolution

$^4\text{He}, \ ^{12}\text{C}, \text{s-process elements: Zr, Ba, ...}$

At the stellar surface: C$>$O, s-process enhancements

Envelope burning: $^{12}\text{C} \rightarrow ^{14}\text{N}$

Interpulse phase ($t \sim 10^4$ years)
Nucleosynthesis in AGB stars

- **Low-mass**: ~0.9 to $3 M_{\text{sun}}$ for $[\text{Fe/H}] \leq -1 \rightarrow \text{Ba, CEMP}$
  - Third dredge-up: helium shell mixed into the envelope (e.g., $^{12}\text{C}$, s-elements)
- **Intermediate-mass**: $M \gtrsim 3 M_{\text{sun}}$ for $[\text{Fe/H}] \leq -1 \rightarrow \text{N-rich}$
  - H-burning (e.g., $^{14}\text{N}$) plus third dredge-up $\rightarrow$ primary C and N

Models of $[\text{Fe/H}] = -0.7$ from Karakas et al. (2018)
THE S-PROCESS IN AGB STARS
The s-process depends upon

1. Mass
2. Metallicity
3. Rotational velocity
The s-process: The effect of mass

- Models of $[\text{Fe/H}] = -2.3$ from Lugaro, Karakas, et al. (2012):

![Graph showing the effect of mass on the s-process]

- $\text{Sr} = 38$
- $\text{Rb} = 37$
- $\text{Ba} = 56$
- $\text{Pb} = 82$
The s-process: The effect of mass

- Models of $[\text{Fe/H}] = -2.3$ from Lugaro, Karakas, et al. (2012):

\[ \text{Sr} = 38 \]
\[ \text{Rb} = 37 \]
\[ \text{Ba} = 56 \]
\[ \text{Pb} = 82 \]
Mixing a few protons into the top of the He-shell produces a $^{13}\text{C}$ pocket $\rightarrow$ $^{13}\text{C}$ burns \textit{radiatively}.
Neutron production: $^{22}\text{Ne}$ source

Extra burst of neutrons from the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction, which takes place during thermal pulses.
Theoretical models

Typical neutron density profile in time:

- Neutron source: $^{13}\text{C}(\alpha,n)^{16}\text{O}$, $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$

- Maximum neutron density: $10^8$ n/cm$^3$, $\sim 10^{14}$ n/cm$^3$

- Timescale: $\sim 10,000$ yr, days – 10 yr

- Neutron exposure: 0.3 mbarn$^{-1}$, 0.02 mbarn$^{-1}$

(at solar metallicity)
Theoretical models

Typical neutron density profile in time:

Neutron source

Maximum neutron density

Timescale

Neutron exposure

Low mass

$^{13}\text{C}(\alpha,n)^{16}\text{O}$

$10^8 \text{ n/cm}^3$

$\sim10,000 \text{ yr}$

$1-2 \text{ mbarn}^{-1}$

Intermediate mass

$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$

$\sim10^{14} \text{ n/cm}^3$

days – 10 yr

$\sim0.2 \text{ mbarn}^{-1}$

(at low metallicities)
Effect of stellar metallicity?

1. All $^{13}\text{C}$ nuclei are converted into neutrons and the main neutron absorber is $^{56}\text{Fe}$:

$$\text{Neutron density} \approx \frac{^{13}\text{C}}{^{56}\text{Fe}}$$

2. $^{13}\text{C}$ in the pocket is produced by proton captures on primary $^{12}\text{C}$, from triple-$\alpha$ in the He shell:

$^{13}\text{C}$ is a primary neutron source!

Clayton (1988)
What are the implications?

3. The neutron density scales with the inverse of $^{56}\text{Fe}$, i.e., with the metallicity. 

This means that lower metallicity stars produce more neutrons and more heavier elements. 

$[\text{Ba/Sr}]$ (or $[\text{Ce/Y}]$) should increase with decreasing metallicity.

Is this true?
From theoretical models

From the FRUITY database: From Cristallo et al. (2015)

\[ \frac{[X_i]}{[Fe]} \]

\[ Z = \text{proton number} \]

[Fe/H] = -0.15

Sr (Z= 38)  Ba (Z= 56)

Pb (Z= 82)

M=2  M\odot
M=3  M\odot
M=4  M\odot
M=5  M\odot
M=6  M\odot
From observations of Barium stars

Cseh et al. (2018) compared the data with model predictions:

![Graph showing [Ce/Y] vs [Fe/H] for different stellar models](image_url)
The effect of stellar rotation?


**Fig. 6.** Comparison between Ba star observations and the predicted final surface composition for the same selection of FRUITY and Monash models as in Fig. 5. We show also 3 M\(_\odot\) type He07 models from Battino et al. (2016) for comparison. We consider all the four combinations of the ls (Y, Zr) and the hs (Ce, and Nd) elements. The dots without error bars represent stars for which there are less than 3 lines for one of the elements.

**Fig. 7.** Comparison for [Ce/Y] between the Ba stars and the 1.5\(\,M\odot\) rotating and non-rotating (IRV = initial rotational velocity) FRUITY models that achieve [s/Fe] > 0.25. The dots without error bars represent stars for which there are less than 3 lines for one of the elements.

Regarding the s-process, stellar rotation and the ensuing difference in the angular momentum between the core and the envelope when the star becomes a giant has been demonstrated to drive mixing inside the 13\(^{\text{C}}\) pocket during the neutron flux on the AGB phase and effectively diminish the neutron exposure (Herwig et al. 2003; Siess et al. 2004; Piersanti et al. 2013). This is because the partial mixing of protons from the envelope that results in the formation of the 13\(^{\text{C}}\) pocket also produces an adjacent 14\(^{\text{N}}\)-rich pocket (Goriely and Mowlavi 2000; Lugaro et al. 2003b; Cristallo et al. 2009; Buntain et al. 2017). Rotational mixing, if it occurs, carries 14\(^{\text{N}}\) into the 13\(^{\text{C}}\) pocket, and the 14\(^{\text{N}}\)(n,p)\(^{14}\text{C}\) reaction (Wallner et al. 2016) effectively captures the free neutrons. Rotation could thus represent a second parameter that varies the s-process distribution at any given metallicity.
AGB chemical yields

Example: $[\text{Fe/H}] = 0$ (solar) from Karakas & Lugaro (2016)

Yield = amount of an isotope ejected into the ISM over the star’s lifetime

Initial stellar mass ($M_{\odot}$)

Black dots = weighted by an IMF
AGB yields with s-process elements

- **Our group**: Fishlock et al. (2014), Karakas & Lugaro (2016), Karakas et al. (2018); yields of 1 to ~8Msun (-2.3 ≤ [Fe/H] ≤ +0.3)
- **FRUITY database**: Cristallo et al. (2015); includes a few models with rotation (-2.15 ≤ [Fe/H] ≤ +0.15)
- **NuGrid/MESA**: Pignatari et al. (2016), Ritter et al. (2018); for Z = 0.001, 0.006, 0.01 and 0.02

What is lacking? Yields for low metallicity for all masses. Super-AGB yields (Q: are they even needed?)
Very low-metallicities

Here $[\text{Fe/H}] < -2.5$

Model mass ranges studied:

- $M = 4$ to $9\text{M}_{\odot}$
- Metallicities: $[\text{Fe/H}] = -3.2$

What is lacking?

- **No s-process**
- No non-standard stellar physics (e.g., rotation)

From Gil-Pons et al. (2013) – tabulated yields

See also studies by Siess et al. (2002), Iwamoto et al. (2004), Iwamoto (2009), Campbell & Lattanzio (2008), Suda & Fujimoto (2010), Cruz et al. (2013)
PUZZLES
Challenges and puzzles

1. The Sr, Y, Zr abundances in metal-poor stars $\rightarrow$ points to another source of heavy elements (light $r$-process?)

2. The CEMP r/s stars $\rightarrow$ CEMP $i$? Site? (e.g., Hampel et al. 2016, Denissenkov et al. 2018)

3. Origin of neutron-capture elements in post-AGB stars. Also $i$-process?

4. Did pre-solar SiC grains originate in a *metal-rich* AGB population?
Puzzles: CEMP r/s stars

• About 50% of CEMP stars with an s-process signature also show an enrichment in r-process elements

→ *Is this the i-process? E.g.,*  
→ Dardelet et al. (2015), 
→ Hampel et al. (2016)

**Definition of CEMP s/r:**
• \([\text{Eu/Fe}] > 1\)
• \([\text{Ba/Eu}] > 0\) but lower than for CEMP-s
• Appear distinct from CEMP-s (e.g., Lugaro et al. 2012; Cohen et al. 2005)
Puzzles: metal-poor post-AGB stars

- In the Small and Large Magellanic Cloud, a population of very s-process enriched post-AGB stars have been discovered

- The stars only have *upper limits* for Pb

The abundance pattern of the post-AGB star J004441.04 ([Fe/H] = -1.4) in comparison with model predictions from various groups

From De Smedt et al. (2012)
Metal-poor post-AGB stars

Where are they on the Ba/La-Eu diagram?

SMC post-AGB star J004441 sits all the way up here!!

[C/Fe] = 1.67, [O/Fe] = 1.14 (!), [Mg/Fe] = 1.16 (!), [La/Fe] = 2.84, [Eu/Fe] = 1.93, [W/Fe] = 2.72 …

This is a self-enriched star…
Neutrons are released in $^{13}$C pockets – we don’t know how these form!

What is the effect of the sudden mixing of protons?

See Tripella et al. (2016), Buntain et al. (2017), Piersanti et al. (2013)
The intermediate-neutron capture process

- Observations have presented us with abundances that are not easily explained with s-process models
- Could they be better fit by an “intermediate” process?

- Burst of neutron production above what we find in s-process models
- The intermediate or “i-process” (Cowan & Rose 1977)
The i-process in post-AGB stars

- Neutron densities on the order of $\sim 10^{11}$ n/cm$^3$ operating not in equilibrium can produce a pattern that matches
- Plot by Melanie Hampel (PhD student, Monash Uni)
CEMP-\(r/s\) should be CEMP-\(i\)

- Best-fitting model for CEMP-\(s/r\) star LP625-44
- Hampel et al. (2018, in prep) now including Pb
What are the site(s) of the $i$-process?

- Low-mass, low-metallicity post-AGB stars (Lugaro et al. 2015)?
- Low-metallicity intermediate-mass AGB stars (Jones et al. 2016)?
- Rapidly accreting white dwarfs (e.g., Hillebrandt et al. 1986, Denissenkov et al. 2017, 2018)
  - There are issues with the Denissenkov et al. models but the idea as a site for GCE is interesting
Chemical evolution with heavy elements

Kobayashi, Karakas & Lugaro (2018, in prep)
Chemical evolution with heavy elements

Kobayashi, Karakas & Lugaro (2018, in prep) – see her talk on Friday!

See also Prantzos et al. (2018)
Summary

- With available s-process yields, we can now make quantitative chemical evolution predictions including heavy elements.
- The new yields are timely, given the release of stellar abundance data from surveys for 100,000+ stars (e.g., GAIA-ESO survey; Galah in Australia, Buder et al. 2018; K2 mission, e.g. Huber et al. 2016).
- We are still missing predictions for the lowest metallicities.
- Puzzles related to post-AGB and CEMP r/s may be related to the i-process.