Effects of Rotation on the s-process Nucleosynthesis in low-mass AGB Stars

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## F.R.U.I.T.Y.

**FULL-Network Repository of Updated Isotopic Tables & Yields**

**Select Data:**

<table>
<thead>
<tr>
<th>Mass ($M_\odot$)</th>
<th>Metallicity $(Z)$</th>
<th>Nuclides Properties</th>
<th>Multiple Table format</th>
<th>Single Table format</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$</td>
<td>$Z$</td>
<td>$Z$</td>
<td>All TDUs</td>
<td>Final Composition</td>
</tr>
<tr>
<td>$Z_{\text{sun}}$</td>
<td>$A$: All</td>
<td>$Z$: All</td>
<td>Final</td>
<td>Final</td>
</tr>
</tbody>
</table>

**NOTES ON THE MODELS** (pdf file)

- **$10^{-4} \leq Z \leq Z_{\text{sun}}$**
- **$1.3 \leq M/M_{\text{sun}} \leq 3.0$**

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**EuroGENESIS Workshop** - Barcelona, April 18-19, 2013
Origin of the elements

Massive Stars

AGB Stars

Weak Component: $A < 90$

Main Component: $90 < A < 204$

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A bit of history …

1868: Father A. Secchi observed “Red Carbon Stars” in the Galactic Disk

* C stars have $C/O > 1$
* Evolved low mass giant stars (AGB Stars)
* They go through the M, MS, S, C(N) stage
* Enhancement of s-elements (both light-s and heavy-s)

Detection of $^{99}\text{Tc}$ $\tau_{\text{hl}} \sim 10^5$ yr

The enrichment in s-elements and carbon has to occur during the AGB phase!

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The neutrons source

In principles all reactions producing neutrons $(p,n), (\alpha,n), (\gamma,n), \ldots$

- Actually, there are only two efficient reactions:

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

$^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^-\nu)^{18}\text{O} (\alpha,\gamma)^{22}\text{Ne}$

It works for $T \sim 9 \cdot 10^7$ K

It works for $T > 3 \cdot 10^8$ K

This occurs in AGBs with $M > 3M_{\text{sun}}$

Lack of C-enhancement
The formation of $^{13}C$ pocket

A bit of history

Iben 1982
Atomic diffusion driven by the sharp chemical discontinuity.

Herwig et al. 1997
Convective overshoot.

Langer et al. 1999
Rotation-induced mixing.

Denissenkov & Tout 2003
Gravity waves.

Busso et al. 2004
Circulation induced by magnetic field.
The formation of $^{13}\text{C}$ pocket

Becker & Iben 1979

The inner border of CE is unstable!

Straniero et al. 2006

$$X_i = X_i^0 + \frac{1}{M_{\text{conv}}} \sum_k (X_k^0 - X_i^0) f_{i,k} \Delta M_k$$

$$f_{i,k} = \Delta t \left[ \int_{r_i}^{r_k} \frac{dr}{\nu(r)} \right]^{-1}$$

$$\nu = \nu_{\text{BCE}} e^{-\frac{d}{\beta H_p}}$$

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The formation of $^{13}C$ pocket

![Graphs showing the formation of $^{13}C$ pocket]
The formation of $^{13}\text{C}$ pocket

$\Delta M \sim 10^{-3} M_{\odot}$

$M = 2M_{\odot}$

$Z = Z_{\odot}$
The effects of rotation: I

Lifting + cylindrical symmetry

\[
\frac{dm}{dr} = 4\pi r^2 \rho
\]

\[
\frac{dL}{dm} = \varepsilon_{\text{nuc}} - \varepsilon_v + \varepsilon_g
\]

\[
\frac{dP}{dm} = -\frac{G m_r}{4\pi r^4} \cdot f_P
\]

\[
\frac{d\ln T}{d\ln P} = \min \left[ \nabla_{\text{ad}}, \nabla_{\text{rad}} \cdot \frac{f_T}{f_P} \right]
\]

\[
f_P = \frac{4\pi r^4}{m_\psi S_\psi} (g^{-1})^{-1}
\]

\[
f_T = \left( \frac{4\pi r^2}{S_\psi} \right)^2 \left( \langle g \rangle \langle g^{-1} \rangle \right)^{-1}
\]
The effects of rotation: II
Transport of angular momentum & mixing

\[
\frac{\partial \omega}{\partial t} = \frac{1}{i} \frac{\partial}{\partial m} \left[ (4\pi r^2 \rho)^2 iD_J \left( \frac{\partial \omega}{\partial m} \right) \right]
\]

\[
D_J = D_{\text{conv}} + f_\omega (D_{ES} + D_{GSF} + D_{SS} + D_{DS} + D_{SH})
\]

\[
\frac{\partial X_k}{\partial t} = \frac{\partial}{\partial m} \left[ (4\pi r^2 \rho)^2 iD_C \left( \frac{\partial X_k}{\partial m} \right) \right]
\]

\[
D_J = D_{\text{conv}} + f_\omega f_c (D_{ES} + D_{GSF} + D_{SS} + D_{DS} + D_{SH})
\]
## The models

### $M=2$ $M_{\text{sun}}$ - $[\text{Fe/H}]=0$

<table>
<thead>
<tr>
<th>$V_{\text{ini}}$ [km/s]</th>
<th>$\tau_{\text{MS}}$ [10$^8$ yr]</th>
<th>$M_{\text{H}}^{\text{Tip}}$ [M$_{\text{sun}}$]</th>
<th>$\tau_{\text{He}}$ [10$^8$ yr]</th>
<th>C/O</th>
<th>$M_{\text{CO AGB}}$ [M$_{\text{sun}}$]</th>
<th>$M_{\text{H AGB}}$ [M$_{\text{sun}}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.693</td>
<td>0.4628</td>
<td>1.212</td>
<td>0.253</td>
<td>0.512</td>
<td>0.545</td>
</tr>
<tr>
<td>10</td>
<td>9.702</td>
<td>0.4651</td>
<td>1.196</td>
<td>0.255</td>
<td>0.513</td>
<td>0.545</td>
</tr>
<tr>
<td>30</td>
<td>9.706</td>
<td>0.4653</td>
<td>1.194</td>
<td>0.257</td>
<td>0.517</td>
<td>0.550</td>
</tr>
<tr>
<td>60</td>
<td>9.714</td>
<td>0.4659</td>
<td>1.190</td>
<td>0.257</td>
<td>0.519</td>
<td>0.550</td>
</tr>
<tr>
<td>120</td>
<td>9.783</td>
<td>0.4686</td>
<td>1.147</td>
<td>0.267</td>
<td>0.532</td>
<td>0.561</td>
</tr>
</tbody>
</table>

### $M=1.5$ $M_{\text{sun}}$ - $[\text{Fe/H}]=-1.7$ - $[\alpha/\text{Fe}]=0.5$

<table>
<thead>
<tr>
<th>$V_{\text{ini}}$ [km/s]</th>
<th>$M_{\text{H}}^{\text{Tip}}$ [M$_{\text{sun}}$]</th>
<th>$\tau_{\text{He}}$ [10$^8$ yr]</th>
<th>C/O</th>
<th>$M_{\text{CO AGB}}$ [M$_{\text{sun}}$]</th>
<th>$M_{\text{H AGB}}$ [M$_{\text{sun}}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.470</td>
<td>0.4794</td>
<td>0.913</td>
<td>0.394</td>
<td>0.548</td>
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<tr>
<td>10</td>
<td>16.468</td>
<td>0.4795</td>
<td>0.913</td>
<td>0.395</td>
<td>0.545</td>
</tr>
<tr>
<td>30</td>
<td>16.493</td>
<td>0.4797</td>
<td>0.908</td>
<td>0.399</td>
<td>0.548</td>
</tr>
<tr>
<td>60</td>
<td>16.542</td>
<td>0.4799</td>
<td>0.900</td>
<td>0.404</td>
<td>0.552</td>
</tr>
<tr>
<td>120</td>
<td>16.905</td>
<td>0.4811</td>
<td>0.885</td>
<td>0.406</td>
<td>0.561</td>
</tr>
</tbody>
</table>
The AGB phase: the [Fe/H]=0 case
The ES circulation velocity

\[ \nu_{ES} = \frac{\nu}{E} \]

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The AGB phase: the [Fe/H]=0 case
The AGB phase: the $[\text{Fe}/\text{H}]=0$ case
The AGB phase: the [Fe/H]=0 case

\[ \frac{v_{\text{hs}}}{v_{\text{ls}}} \]

\[ v_{\text{rot}} = \{0, 10, 30, 60, 120\} \text{ km/s} \]

\[ M_H \ [M_{\odot}] \]

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The AGB phase: the [Fe/H]=-1.7 case
The AGB phase: the [Fe/H]=-1.7 case

Without rotation ...

The Fe abundance is low

The neutrons-to-seeds ratio is very high

The s-process produces large amount of Pb

Rotation reduces neutrons-to-seeds ratio

The Pb production is reduced

The abundances of hs and ls increase!!!
The AGB phase: the [Fe/H]=-1.7 case
The AGB phase: the $[\text{Fe/H}]=-1.7$ case
What are the uncertainties? (I)
What are the uncertainties? (II)
Rotation-induced mixing...

Modify the mass extension of $^{13}\text{C}$ and $^{14}\text{N}$ pocket and their relative overlap.

Reduce the average neutrons-to-seeds ratio

- the total amount of heavy elements is lower
- $^{1\text{st}}$ production is favoured with respect to $^{2\text{nd}}$

Increasing $v_{\text{rot}}^{\text{ini}}$, both $[\text{hs}/\text{ls}]$ and $[\text{Pb}/\text{hs}]$ decrease

Some CEMP have low $[\text{Pb}/\text{hs}]$...
(Bisterzo et al. 2011)
Rotating Models vs Observations

--- M=1.5M_☉ --- M=2.0M_☉ --- M=2.5M_☉ --- M=3.0M_☉

Ba & CH stars
Post-AGB
Intrinsic C-rich
Intrinsic O-rich