Does the main component of the \( s \)-process in AGB stars constrain the neutron source in the \( ^{13}\text{C} \)-pocket?
Introduction: s-process in AGB-LMS.

Thermally Pulsing (TP)
Asymptotic Giant Branch (AGB)
low mass stars (LMS)

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

Old Nuclear Physics classifications:
- Weak component
  A<90 - massive stars
- Main component
  from Sr to Bi
- Strong component
  for $^{208}\text{Pb}$ - unnecessary

$^{13}\text{C}(\alpha, n)^{16}\text{O}$
13C-pocket formation: the standard idea.

- An amount of protons is injected into the He-rich region below the envelope at each dredge-up phenomenon and the $^{13}$C reservoir is formed by:

$$^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta^+ + \nu)^{13}\text{C}$$

- **DANGER:** Too efficient proton captures produce $^{14}$N that is an efficient absorber for most of the neutrons, inhibiting the captures on heavier nuclei.

- Gallino et al.(1998) and Bisterzo et al.(2014) suggested a proton-mixing typically of about $(0.5-2) \times 10^{-3}$ $M_\odot$ and showed how this choice allows the buildup of the s-process main component.

- Cristallo et al.(2009-2011) provided a more quantitative approach, assuming that convective velocities at the envelope border do not drop abruptly to zero, but decrease exponentially.
Open issues of the standard scenario.

- Spectroscopic measurements (D’Orazi et al., 2009; Maiorca et al., 2011; Jacobson et al., 2013) in open clusters younger than the Sun showed that the abundances of neutron-rich elements have continued to increase.

- Other indications of an increasing $s$-process production came from McWilliams et al. (2013) in the Sagittarius Dwarf Galaxy and for Ba by Mishenina et al. (2013). (See also Karakas's talk)

- Theoretically speaking, Piersanti et al. (2013) showed that in models with stellar rotation, instabilities at the shear layer induce more effective mixing, leading mainly to $^{14}$N. (See also Hirschi's talk!!!)
13C-pocket formation: a forced mechanism.

Magnetic buoyancy

Convective envelope

During TDU

Turbulent regime

Helium Shell

Differential rotation

1. Rotational shears can promote magnetic fields

2. Magnetic structures can reach the envelope

3. An amount of protons can be injected into the He-rich region.

C-O degenerate core

Rigid body rotation

- P/P₀ = (r/r₀)⁷
- ρ/ρ₀ = (r/r₀)⁶
- T/T₀ = (r/r₀)⁻¹

Parker' mechanism

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Nuclei in the Cosmos – Debrecen – Hungary – 07/07/2014
The extended $^{13}\text{C}$-pocket.

- The $^{13}\text{C}$-pocket is more extended than in the common assumptions made so far. The average value is $4-6 \times 10^{-3}$ solar masses, covering a large part of the intershell region.
- The profile of proton penetration is roughly EXPONENTIAL.
- The $^{13}\text{C}$-pocket is where the green line overcomes the red one.
- There is only a limited neutron production in the $^{14}\text{N}$-rich region, because $^{14}\text{N}$ is the main neutron absorber.
MHD model by Nucci & Busso (2014)

- No numerical approximations (exact analytic solution).
- Simple geometry: toroidal magnetic flux tubes.

Equations:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \frac{1}{\rho} \nabla p - \mathbf{F} + \frac{1}{4\pi \rho} \mathbf{B} \times (\nabla \times \mathbf{B}) - \eta \Delta \mathbf{v} = 0 \]

\[ \frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) - \nu_m \Delta \mathbf{B} = 0 \]

Solutions:

\[ v_r = a_1 r^{-(k+1)} \]

\[ v_\theta = a_2 r^{-1} + a_3 r + a_4 r^a_{10}/r^{a+1} \]

\[ B_\theta = r^{k+1} F(\xi), \quad [\xi = r^{k+2} - a_1 (k + 2) t] \]

where \( k \) is the exponent of the density distribution:

\[ \rho = \rho_0 (r/r_P)^k \]
Code improvements: nuclear inputs.

Recent n-captures cross sections.
Recent beta-decays.

See La Cognata's talk!!!
Results for the chemical evolution of the Galaxy with the new $^{13}\text{C}$-pocket.

### Percentage of Contribution to Solar s-only Nuclei

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Case A</th>
<th>Case B</th>
<th>Arlandini et al. (1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}\text{Ru}$</td>
<td>95</td>
<td>93</td>
<td>95</td>
</tr>
<tr>
<td>$^{110}\text{Cd}$</td>
<td>97</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>$^{120}\text{Te}$</td>
<td>94</td>
<td>92</td>
<td>91</td>
</tr>
</tbody>
</table>

### Percentage of Contributions to Solar Heavy Elements from LMS

<table>
<thead>
<tr>
<th>Element</th>
<th>This Work (A)</th>
<th>This Work (B)</th>
<th>This Work (C)</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strontium</td>
<td>90</td>
<td>89</td>
<td>86</td>
<td>55(1)</td>
</tr>
<tr>
<td>Yttrium</td>
<td>81</td>
<td>80</td>
<td>84</td>
<td>62(1)</td>
</tr>
<tr>
<td>Zirconium</td>
<td>80</td>
<td>78</td>
<td>80</td>
<td>55(2)</td>
</tr>
<tr>
<td>Barium</td>
<td>89</td>
<td>86</td>
<td>85</td>
<td>84(2)</td>
</tr>
<tr>
<td>Lanthanum</td>
<td>72</td>
<td>70</td>
<td>70</td>
<td>70(2)</td>
</tr>
<tr>
<td>Cerium</td>
<td>79</td>
<td>78</td>
<td>76</td>
<td>81(2)</td>
</tr>
</tbody>
</table>
The $s$-process main component: case A.

Production factors normalized to unity

- **Case A**

- **M=M**  

- **[Fe/H]=-0.5**  

- **Standard $^{13}$C pocket**  
  \[ 1 \times 10^{-3} \]

- **Low metallicity**  
  \[ [Fe/H]=-0.5 \]

- **Main component starting from A=90**  
  (BUT: Problems in chemical evolution.

  Need of an extra unknown process in the range $A = 90 - 130$)

- **High number of Thermal Pulses**
The s-process main component: case B.

Production factors normalized to unity

Extended $^{13}\text{C}$ pocket $6 \times 10^{-3}$

Higher metallicity $[\text{Fe/H}]=-0.15$

Main component starting from $A=86$

Small number of Thermal Pulses → C-star Luminosity Function respected
The ratio among s-only nuclei in the 2 cases.

Similar results for $A>90$ → Using simply an unique stellar generation at a suitable metallicity it is not possible to distinguish between the two cases.

In our model with a large pocket: Larger contributions to the weak-s elements

$^{86}\text{Sr},^{87}\text{Sr}$ are full members of main component

In standard scenario the solar LEEP (Light Element Primary production) must be invoked to explain Galactic (and even solar) enrichment of s-process elements in the range $90<A<130$
Case A – Standard pocket

- Short time interval
- Small contribution to the Galaxy
- Solar LEPP integration

Case B – Extended pocket

- Long time interval
- Main contribution to the Galaxy
- Solar LEPP isn't necessary
Conclusions.

• A summary:
  – recent observational and theoretical issues on the s-process;
  – an extended $^{13}$C pocket as a consequence of magnetic buoyancy;
  – the main component for $A>90$ can be reproduced in both cases by single-population models, but at rather different metallicities;
  – nuclei for $A<90$ are fed more efficiently in the case of an extended pocket;
  – no solar LEPP contribution is needed using a deeper $^{13}$C pocket.

• Several tests could be performed to discriminate between the two cases:
  – $s/C$ ratio of post-AGB stars;
  – SiC grains and meteorites;
  – chemical evolution of the Galaxy;
  – a quantitative model for the $^{13}$C pocket.

Thanks for your attention !!!