Nuclear physics and stellar MHD coupled together solve the puzzle of oxide grain composition

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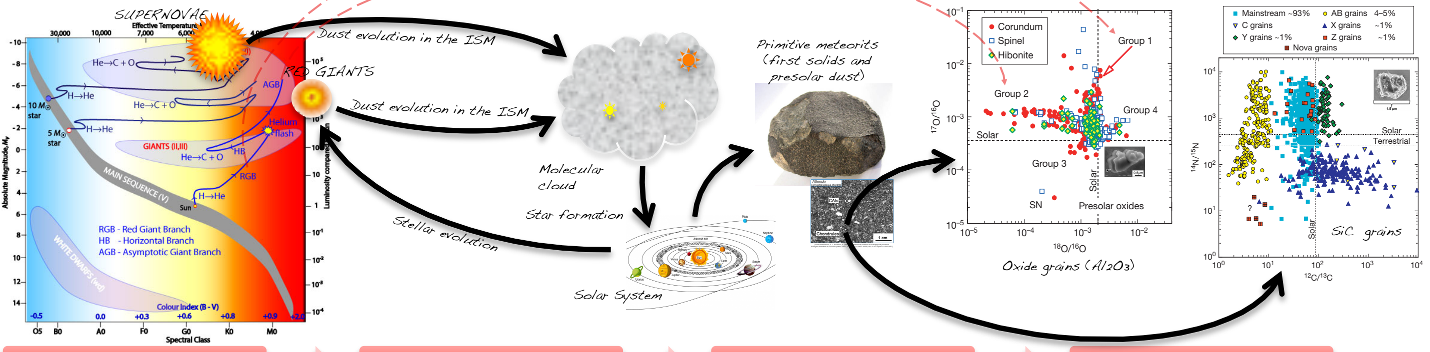
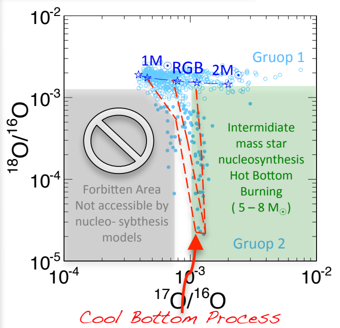


1995-2004

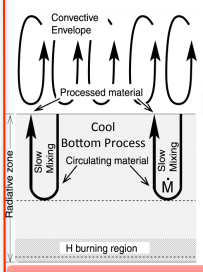


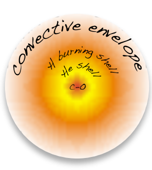
Cool Bottom Process

Wasserburg et al. (1995) suggested the presence of a deep matter circulation to account for oxygen isotopic ratios and several large excesses of ^{26}Mg found in Al_2O_3. These authors developed the model of a "*Cool Bottom Process*" model in which currents transport matter downward, from the bottom of the envelopes to the regions where H-burning occurs, and upward, in the opposite direction, enriching the stellar surface with fresh products of the CNO cycle.

Nollett et al. (2004) examined the effects of CBP by using a parametric model in which deep mixing is charcterized by the mass circulation rate and the maximum temperature/depth experienced by the circulating material.

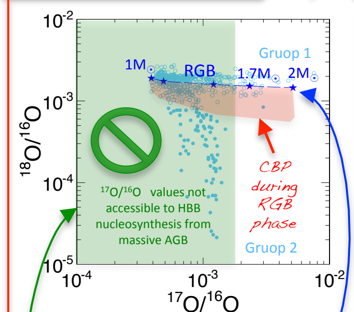
Despite the results achieved applying CBP model to low mass AGB stars, some grains belong to a "forbbiden" area not accessible by nucleosybthesis models were found and the contrinution of intermediate mass stars nucleosynthesiswas needed to account for formation of group 1 grains showing the larger value of $^{17}O/^{16}O$.





AGB star structure

2005-2011



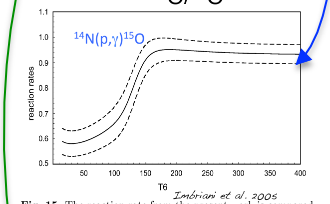


Fig. 15. The reaction rate from ~~the present work is~~ compared with that of the NACRE compilation [26]. The dashed curves represent the uncertainty of the present reaction rate.

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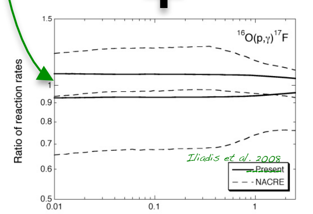

FIG. 9. Reaction rates of $^{16}O(p,\gamma)^{17}F$. For better comparison, we show the lower bound, recommended rate and upper bound on the rate normalized to the present recommended rate. Solid and dashed lines indicate the rate ratios for the present and the NACRE [9] results, respectively.

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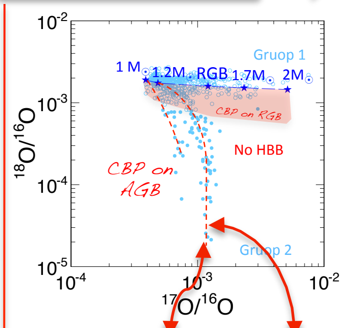
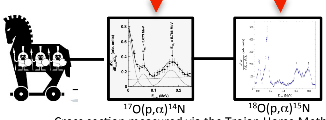
Group 1 oxide grains formed in RGB stars with M>2M⊙

CBP during the RGB phase of stars with mass < 2M⊙ accounts for by smaller values of $^{18}O/^{17}O$ recorded in group 1 grains (Palmerini et al. 2011).

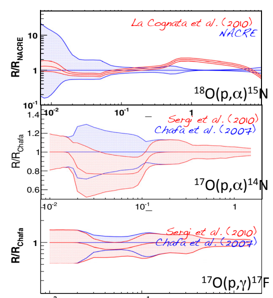
2011-2013





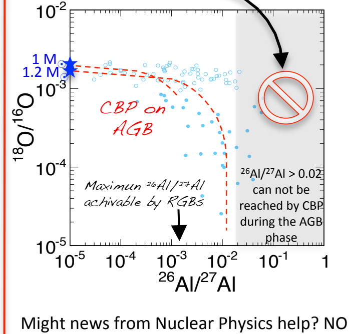
Cross section measured via the Trojan Horse Method

Sergi et. (2010) La Cognata et al. (2010)



Oxygen isotopic mix of group 2 oxide grains suggests that they formed in low mass AGB (1-1.5M⊙) experienced CBP (Palmerini et al 2011, 2013)

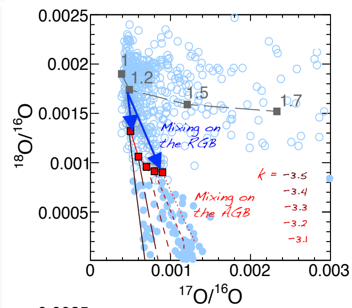
BUT

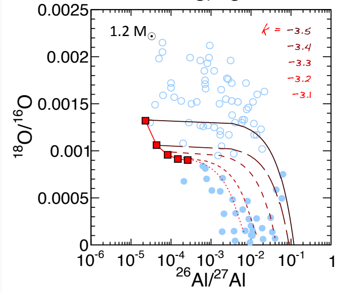


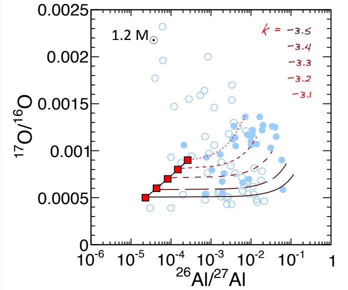
Might news from Nuclear Physics help? NO

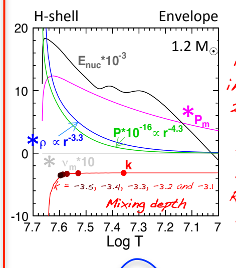
($^{25}Mg(p,\gamma)^{26}Al$ measurement by Straniero et al 2013 and $^{26}Al(p,\gamma)$ by Pain et al 2015)

2013-2016









The puzzle of O and Al isotopic mix in group 1 and 2 oxide grains is solved: they formed in low mass RGB and AGB stars where MHD mixing was at play.

Mixing rate $\dot{M} = 4\pi\rho_r r^2 v_r f$

Mixing velocity: $v_r = v_p\left(\frac{r_p}{r}\right)^{-(k+1)}$

A field of a few 10^5 Gauss is sufficent to obtein the values suggested by the paramentric CBP models.

fractional area occupied by flux tubes

*the simplest solution satisfying the boundary conditions**

Magnetic structures filling factor (1-2%)

2007-2014

The full MHD equations*

$$\begin{cases} \frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\cdot\vec{v}) = 0 \\ \frac{\partial\varepsilon}{\partial t} + \vec{v}\cdot\nabla + \frac{P}{\rho}\nabla\cdot\vec{v} - \frac{1}{\rho}\nabla\cdot(K\nabla T) + \frac{j^2}{\rho\sigma} = 0 \\ \frac{\partial\vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} + \frac{1}{\rho}\nabla P - \vec{F} - \frac{1}{\rho c}\vec{j}\times\vec{B} - \nu\nabla^2\vec{v} = 0 \\ \frac{\partial\vec{B}}{\partial t} - \nabla\times(\vec{v}\times\vec{B}) - \lambda\nabla^2\vec{B} = 0 \end{cases}$$

can be solved analytically in an exact way when:

* the plasma density distribution has the form $\rho \propto r^k$, where $k < -1$;

* Magnetic Prandtl number $P_m > 1$;

* The magnetic diffusivity ν_m is small.

Stellar magnetic field might promote the mixing between the H-burning shell and the base of the convective envelope (Busso et al. 2007; Nucci and Busso 2014)

The solution implies a natural expansion of magnetized zones, carrying matter from near the H-burning shell to the envelope and then pushing down envelope matter to the radiative zone for mass conservation. In other words the solution proves that stellar MHD might promote deep mixing mechanisms, or CBP, in evolved low mass stars.

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