PROCEEDINGS OF SCIENCE

Slow and Fast Extramixing in Evolved Stars from Magnetic Buoyancy

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We present the results of nucleosynthesis computations in mass transport phenomena affecting the final evolutionary stages of a low mass star. We assume that the process starts near the H-burning shell, and is driven by magnetic mechanisms, according to recent suggestions [1]. This is due to the fact that magnetized bubbles are subject to a fast buoyancy, accompanied by a downward flow induced by the settling of the heavier non-magnetized envelope material. During its downward journey toward the H shell this envelope material can undergo further proton captures, so that the mixing process ultimately induces changes in the envelope isotopic ratios $^{12}C/^{13}C$,$^{17}O/^{16}O$,$^{18}O/^{16}O$,$^{26}Al/^{27}Al$. In most conditions the circulation is such that ^{7}Li is destroyed. Production of this nucleus can however occur in a region of the parameter space, if the fast-rising magnetic structures provide a rapid upward transport of the Be abundance, as present near the H shell or produced in the downflow. In normal low mass red giants (i.e. excluding the anomalous CJ stars and the super-Li rich objects) Li seems to be created only on the RGB, and then to undergo a slow destruction through extra-mixing processes

10th Symposium on Nuclei in the Cosmos
July 27 - August 1 2008
Mackinac Island, Michigan, USA

PoS(NIC X)074

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1. Extended mixing and magnetic buoyancy in red giants

Many red giants and asymptotic giant branch (AGB) stars (evolved low-mass red giant stars) show a photospheric composition characterized by isotopic admixtures of CNO and of other species that cannot be reproduced by canonical evolutionary codes. In the works by [2],[3] and [4] it was suggested that the chemical anomalies derive from additional transport mechanisms in which some envelope material is exposed to partial H-burning. Such phenomena have been called in various ways (extended mixing, deep mixing, and cool bottom processes, or CBP).

In a previous paper [4] a parametric study of such mixing episodes was presented, suitable to account for the isotopic mix measured in presolar oxide grains of AGB origin. The adopted formalism included two free parameters, namely the mass circulation rate ($\dot{M}$) and the maximum temperature (T_P) experienced by the moving material. In that paper it was also demonstrated how important composition changes due to CBP could occur without introducing any significant feedback on the stellar luminosity, provided T_P was kept low enough (typically 0.1 dex below the H shell temperature T_H, this last parameter being defined as the temperature at which the energy produced by p-captures is maximum).

Concerning the physical origin of extended mixing, it was often attributed to rotationally-induced phenomena; these attempts were however frustrated by the subsequent demonstration that rotationally-induced mixing would not be sufficient to account for the observed isotopic shifts [5]. More recently, it was noticed [6] that important mixing processes should be induced in stars by the molecular weight inversion generated by the reaction $^3\mathrm{He} + ^3\mathrm{He} \rightarrow ^4\mathrm{He} + 2p$. This was later recognized as being a form of *thermohaline* mixing [7]. However, extra-mixing on the AGB has to account for the presence of nuclei (like ^{26}Al), which are synthesized well below the layers where ^{3}He burns, so that thermohaline mixing is not sufficient for explaining them [8]. One has also to notice that the ^{3}He abundance in the envelope of an AGB star is very small, as it has been reduced by the previous occurrence of extra-mixing phenomena on the RGB [7]. The total available ^{3}He inventory is therefore essentially limited to the small amount that can be reproduced in the H shell and this has been recently recognized to be insufficient to drive the mixing [9]

One has to notice that a situation somehow similar to that driving thermohaline mixing can be obtained in another way. In a perfect gas, for a given value of T, the density ρ linearly depends not only on the molecular weight μ, but also on the pressure P. We can create an unbalance in ρ also by creating an unbalance in P. This is known to occur whenever the star contains magnetic fields, as the magnetized matter establishes a pressure equilibrium with the environment, making use of an extra pressure, $B^2/8\pi$, due to the magnetic field itself. Therefore the *gas* pressure in a magnetized zone is smaller, and its matter is lighter, than in the environment. This generates the well-known phenomenon of magnetic buoyancy [10]. Recently, [1] suggested that this buoyancy mechanism might account for extra-mixing in RGB and AGB stars. Maintaining magnetic fields of the proper geomentry (toroidal flux tubes), however, requires the action of a stable stellar dynamo. The possibility of generating such a dynamo in a radiative (not convective) layer has been recently the subject of some debate. MHD instabilities studied by [12] and by [13] were shown to sustain a dynamo. Subsequently Spruit [14] re-discussed the case of MHD modes in layers containing gradients of molecular weight and showed that there is a very complex interaction between the rotation, the layered structure of the zone considered, and the instabilities themselves. A reanalysis of the work by [13] with a 3D numerical simulation did not confirm the generation of a stable dynamo [11].

We notice however that the evolutionary phases and the stellar zones we are dealing with, where the occurrence of extra-mixing is needed (the RGB and AGB radiative layers below the envelope, after the occurrence of dredge up), are characterized by a homogeneous composition, and are therefore unstable to any mixing perturbation [15]. For those zones, it was noticed [16] that a dynamo can exist if a differential rotation is maintained against the action of the magnetic field that carries out the angular momentum. In the Sun this effect actually exists and is called the λ effect. Nordhaus et al. [16] proved that also in the relevant regions of red giants and AGB stars only a small energy supply from the convective envelope is sufficient to maintain the differential rotation and hence the dynamo, and that this can occur for magnetic field values similar to those suggested by [1]. On this basis, we shall therefore assume that a dynamo mechanism does exist below the convective border of the envelope in the studied evolutionary stages. For them, detailed nucleosynthesis results were not presented in the original papers where magnetically-induced mixing was suggested [1, 16]. We therefore start here to undertake this task.

As clarified by [9], thermal exchanges with the environment, proportional to the surface of the magnetized bubbles, would strongly reduce the upward velocity estimated by [1]. Fast buoyant structures must therefore be small. One can therefore think of magnetically-induced mixing as a phenomenon that can occur at very different speeds, depending on the size of the unstable magnetized regions. This feature appears as a characteristic property of magnetic mixing and, as we shall see, may be important for Li production/destruction.

In what follows we assume that the velocity profile of the upward magnetized flow is the same as given in [1]:

$$v(r) = \frac{1}{2} \cdot (\frac{\rho(r)}{\rho_0})^{\frac{3}{4}} (\frac{r}{r_0})^{-\frac{1}{4}} (\frac{g_0 a_0}{C_D})^{\frac{1}{2}} (\frac{B_0}{\sqrt{P_r}}) \tag{1.1}$$

where B_0 is the magnetic field somewhere near the H-burning shell, a_0 is the initial radius of flux tubes in the same position, C_D is the aerodynamic drag coefficient, and the other quantities are given by the stellar structure. A fast uprise means, as stated above, that magnetized structures are rather small.

An upward motion will generate, by mass conservation, a downflow. For this we assume, as in [4], that the descending flow occupies a fraction $f_d = 0.5$ of the surface at fixed radius from the stellar centre.

We assume that CBP starts on the late RGB and is re-established on the AGB and we shall present results for a 1.5 $M_\odot$, $Z=Z_\odot/2$ model, computed with FRANEC [17]. We adopt the prescriptions by [4] for T_P, i.e. $\Delta LogT \leq 0.1$ with respect to the H shell temperature. (We remember that this choice for T_P was motivated by the need of not adding a significant amount of nuclear energy from proton captures occurring during the transport, as said before).

Concerning the circulation rate $\dot{M}$, it now depends on magnetic field strengths in the buoyant structures, following equations (2), (7a) and (8) in [1]. In the computations, T_P and the parameters of the velocity profile (equation 1.1) are taken from the stellar structure; the extra-mixing and the ensuing nucleosynthesis are then computed according to the assumed value of the maximum magnetic field in the tubes, hence according to the corresponding value of $\dot{M}$.

The occurrence of the third dredge-up (TDU) after each thermal instability of the He-shell (or *thermal pulse*) is then included. The timing and mixed mass of each dredge-up episode are taken from the original stellar models and their analytical approximations [17] and the composition of the dredged-up material is derived from [18].

We considered different values of the maximum field strengths B_0, namely 1.65, 5, 15, 25 and 50 MG, corresponding to $\dot{M} = 0.3, 1, 3, 5$ and $10 \cdot 10^{-6} M_\odot/yr$. Note that, with the chosen procedure, the maximum field values, through $\dot{M}$, determine both the amount of material processed and the time spent by the flow at each temperature.

2. Abundance changes induced by the extra-mixing episodes

In our calculations we adopted, as a starting choice, the NACRE compilation of reaction rates. Initial abundances were taken from [5], except for N and O, for which the revised abundances by [19] were adopted. As a consequence of this, the solar metallicity turns out to be $Z_\odot = 0.016$.

Typical results are presented in Fig.1 as a function of time, either excluding (left panel) or including (right panel) the large effects due to dredge up. Exclusion of dredge up is obtained simply by omitting to upgrade the abundances after each thermal pulse: the corresponding results are therefore incomplete, but in view of the complex interplay between CBP and dredge-up, they can serve to disentangle the separate contributions of each process. Some elemental and isotopic ratios relevant for a comparison with measurements in presolar grains and in S stars [20] are then shown in Fig.2 for the same cases. In general, the isotopic and elemental abundances obtained are very close to those already found by [4]. In fact, the only practical difference between those calculations and ours is in the fast upward velocity, which we take from [1]. However, this velocity is too fast to add any nucleosynthesis-induced modification of the pattern. In particular, it is found that CBP reduces the ^{12}C/^{13}C and the ^{18}O/^{16}O ratios and increases the ^{17}O/^{16}O, the ^{14}N/^{15}N and the ^{26}Al/^{27}Al ratios. The main effect of dredge-up for light and intermediate elements is instead to enrich the envelope with fresh ^{12}C and ^{22}Ne from the He shell.

The results arise from the interplay of ^{12}C production in TDU, its (incomplete) conversion into ^{13}C and ^{14}N in the CBP burning material, and the enrichment of the envelope with H-burning ashes at a rate $\dot{M}$. This can explain the relatively low ^{12}C/^{13}C ratios observed in some S and C stars, as being due to CBP. Note, however, that the above interplay is complex and induces non-linear trends, ar revealed by the apparently anomalous behavior of the magenta curve in Fig.2. In particular, the ^{12}C/^{13}C ratio is low for $\dot{M}$ values around 10^{-8} M$_\odot$/yr [1], where ^{14}N is not significantly produced. Then the carbon isotopic ratio increases gradually, as more ^{13}C is converted to ^{14}N, up to about $\dot{M} \sim 10^{-6}$ M$_\odot$/yr. Above this value, dredge-up effects are compensated by fast CBP, which actually burns efficiently the newly produced ^{12}C into large (primary) ^{13}C and ^{14}N abundances, and the ^{12}C/^{13}C ratio decreases again. Nitrogen, whose destruction rate is always rather small, shows instead a simpler, monotonic increase with $\dot{M}$ This different behavior of ^{13}C and ^{14}N is shown in Fig.3.

The star that we considered never becomes carbon-rich, ending its life as an S star; it has a high N/O ratio, as indeed observed in S stars [21]. Reaching a ratio C/O>1 while CBP is active is still possible, but requires either more massive stars (e.g. $M = 2M_\odot$, where TDU is more effective than CBP) or a fine tuning of the CBP parameters $\dot{M}$ and T_P.

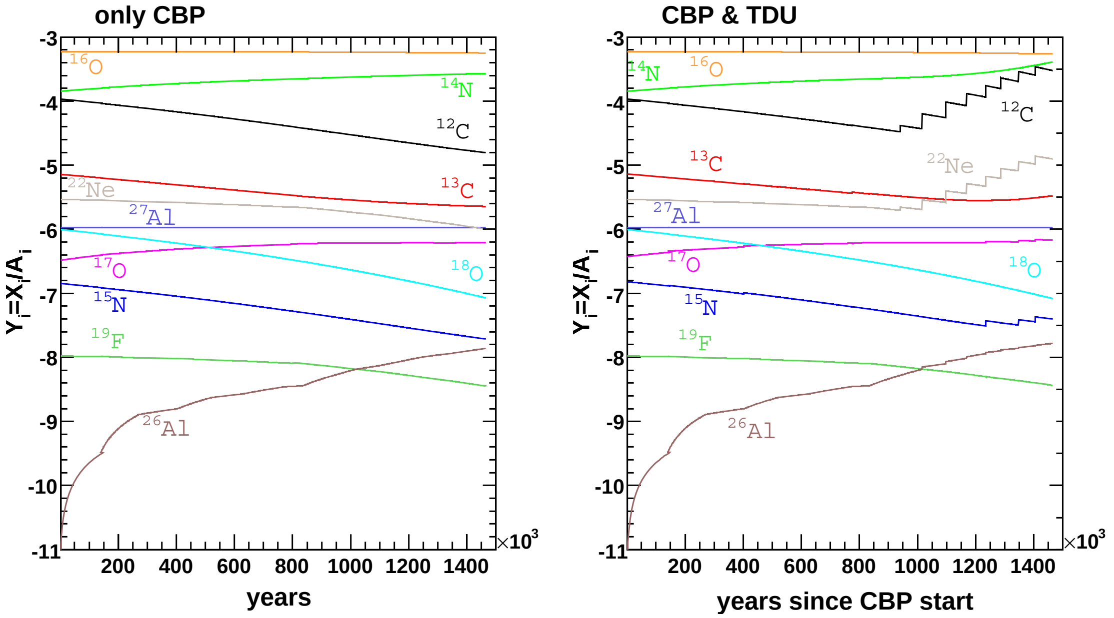

Figure 1: Left: Evolution of the envelope abundances along the AGB due to the occurrence of magnetically-induced extra-mixing. Right: Chemical composition of the stellar envelope as modified by both CBP and TDU. The discrete occurrence of dredge-up produces a saw-tooth structure, mainly on the trends of ^{12}C, ^{15}N and ^{22}Ne.

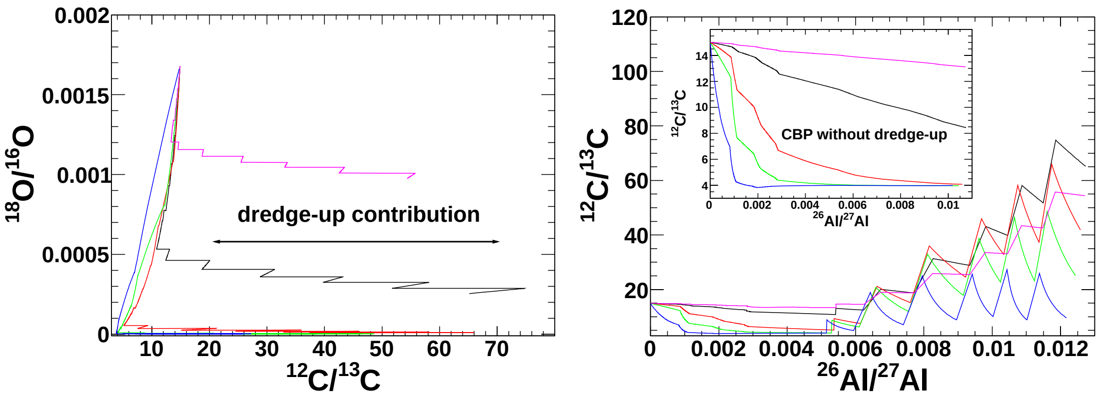

Figure 2: Some isotopic ratios of intermediate elements as resulting from our calculations, for $\dot{M} = 0.3$ (magenta), 1 (black), 3 (red), 5 (green) and 10 (blue) $\cdot 10^{-6} M_\odot/yr$. In order to disentangle the effects of CBP and TDU the insert of the right panel shows the effects of CBP alone

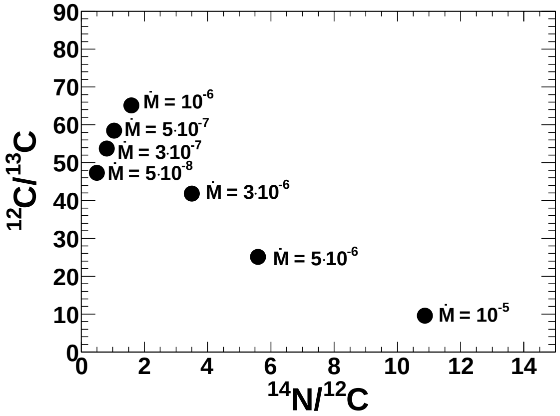

Figure 3: Left: Evolution of the envelope ratios ^{12}C/^{13}C and ^{14}N/^{12}C, as produced by the combined effects of CBP and of convective dredge-up.

Extra-mixing affects oxygen isotopic ratios by rapidly destroying ^{18}O and by producing ^{17}O, up to values of the ^{17}O/^{16}O ratio close to equilibrium CNO (0.012).

Finally, the aluminium isotopic ratio is confirmed to be essentially a thermometer, ^{26}Al being primarily sensitive to the T_P value (and growing with it), and depending only weakly on $\dot{M}$, as already found in [4]. ^{26}Al is then also slightly affected by dredge-up; this is due to the fact that of the large amount of ^{26}Al engulfed in the He shell during shell H burning, a small amount (10%) survives the neutron captures occurring in thermal pulses and can be returned to the envelope.

3. The case of Li

While the fast buoyancy does not allow nucleosynthesis to occur in the upflow, this occurs in the slow descending flow, where $\dot{M} = 4\pi\rho R^2 f v$. Here f is the filling factor (assumed to be 0.5 in the descending flow). Using the values of the parameters as presented in [1], it is easy to see that the downward velocities are in the range $(1-20)$ cm/sec. The thickness of the radiative layer is about 5×10^{10} cm, so that the typical crossing time is of a few hundred years. During this period any fresh ^{3}He taken from the envelope has time to be destroyed (by either ^{3}He+^{3}He $->$ ^{4}He + 2p or ^{3}He+^{4}He $->$ ^{7}Be + γ). The velocity profile is of relevance here: if it is such that the last process (occurring at higher temperature) prevails, then ^{7}Be can be synthesized in the circulation and then carried untouched to the envelope by fast buoyancy, producing some Li. Otherwise, both the residual ^{3}He of the envelope, and the envelope Li abundance are destroyed. (A detailed analysis of the competition of the two channels of ^{3}He destruction is under way).

There is another way for producing Li in mixing processes induced by magnetic fields, if a fast but intermittent process of bubble release, under the form of magnetic instabilities, occurs. In this case we essentially mimic the so-called Cameron-Fowler mechanism: ^{7}Be is produced by equilibrium radiative burning itself, and magnetic instabilities must occur rarely enough to give it time to accumulate. We would in this case have upflows and downflows occurring erratically, both at a very fast speed, as often observed in the Sun [22]. Then ^{7}Be would be simply "sampled" at high T and delivered into the envelope without further processing, thus increasing the Li abundance

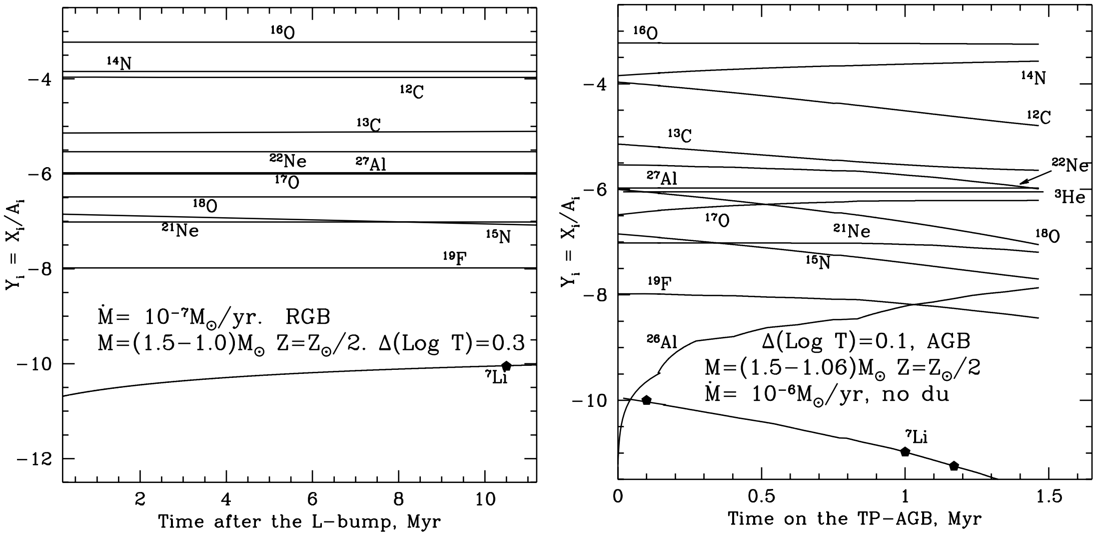

Figure 4: Left panel: results of CBP nucleosynthesis as occurring in very fast mixing episodes produced by magnetic instabilities (the dot shows the typical Li abundance observed after the RGB); right panel: results from subsequent slower mixing episodes, like those of Fig. 2, using the results of the left panel as inputs (dots indicate Li abundances in late RGB and O-rich AGB stars according to [26, 27])

there. Depending on the value of T_P chosen, we can either have a process in which only Li is contributed (as is the case for the first panel of Fig.4), or obtain also a decrease in the ^{12}C/^{13}C ratio and other effects.

Leaving the peculiar cases of CJ stars and of super-Li rich red giants out of our discussion, Fig. 4 shows the effects of a specific choice in the velocities of magnetic mixing, suitable to interpret the observational evidence in normal RGB and AGB stars. The assumptions for the models presented in the Figure are "ad hoc" and only serve for illustration purposes: a more complete analysis based on more extended calculations will then be needed. For the moment we have made the following (tentative) hypotheses. i) At the bump of the luminosity function, on the RGB (after the occurrence of the first dredge-up), the average toroidal magnetic field is still sufficiently low that only small unstable "bubbles" can efficiently travel through the radiative zone. If they are small enough, they avoid temperature readjustments and travel at their typical Alfvén velocity, of the order of a few Km/sec. If the downflows are equally fast, then the results displayed in the first panel of the figure are found, where Li is produced at the typical level observed in Li-rich red giants, i.e. Log(ε) = 2. ii) If, after a transient phase, an averagely slower circulation is established, like the one discussed in the previous section, then Li is readjusted as in panel 2 of Fig.4, and is slowly consumed. Dots in Fig.4 show the average position of evolved RGB stars (from [26]) and of O-rich, low mass AGB stars (form [27]). The proper position of the observed points in the plots is obtained by ascertaining that the model luminosity at that moment is the same as for the observed stars. As is clear, the resulting trend is a gradual reduction of Li after the initial production, apparently well reproduced by model curves. The emerging picture is supportive of our tentative scenario, and motivates further efforts for a more thorough modeling of dynamo mechanisms in evolved stars also in connection with the Li problem.

4. Acknowledgement

The work at Argonne was supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract DE-AC02-06CH11357. This work was also supported by the Italian Ministry of Research (Contract PRIN-2006-022731). SP thanks the Argonne National Laboratory, which gave her the opportunity to participate at the Exchange Visitor Program NO.P-1-4866, thanks to which this work was completed.

References

[1] M. Busso, G.J. Wasserburg, K.M. Nollett and A. Calandra, ApJ, 671, (2007) 802.

[2] A.I. Boothroyd, I.-J. Sackmann and G.J. Wasserburg, ApJ, 430 (1994), L77.

[3] C. Charbonnel, and J.D. Jr. Do Nascimento, A&A, 336, (1998), 915.

[4] K.M. Nollett, M. Busso, M. and G.J. Wasserburg, ApJ, 582, (2003), 1036.

[5] A. Palacios, C. Charbonnel, S. Talon and L. Siess, A&A, 453, (2006), 261.

[6] P.P. Eggleton, D.S.P. Dearborn, J.C Lattanzio, Sci, 314, (2006), 1580.

[7] C. Charbonnel, and J.-P. Zahn, A&A, 476, (2007), 29.

[8] S. Palmerini, M. Busso, G. Guandalini, PASA (2008), submitted.

[9] Denissenkov, P.A., Pinsonneault, M., & MacGregor, K.B. 2009, ApJ in press.

[10] Parker, E.N. 1974, Ap. Space Sci. 31, 261

[11] J.-P. Zahn, A.S. Brun, S. Mathis, A&A, 474, (2007), 145.

[12] E. Pitts, R.J. Tayler, MNRAS, 216, (1985), 139.

[13] H.C. Spruit, A&A, 349, (1999), 189.

[14] H.C. Spruit, arXiv:astro-ph/0607164v1, (2006).

[15] O. Straniero, R. Gallino, S. Cristallo, NuPhA, 777, (2006), 311.

[16] J. Nordhaus, M. Busso, G.J. Wasserburg, E.G. Blackman, S. Palmerini, ApJ, 684, (2008), 29.

[17] O. Straniero, I.Dominguez, S. Cristallo and R. Gallino, PASA 20, (2003), 389.

[18] G.J. Wasserburg, M. Busso, R. Gallino and K.M. Nollett, Nucl. Phys. A. 777, (2006), 5.

[19] F. Caffau, E. Maiorca, P. Bonifacio, R. Faraggiana et al., A&A, (2008), submitted.

[20] H. Palme and A. Jones, in "Meteorites, Comets and Planets. Treatise of Geochemistry, Vol. I", edited by A. M. Davis (Elsevier: Amsterdam), (2005), 41.

[21] V.V. Smith and D.L. Lambert, ApJ, 361, (1990), 69.

[22] C. Briand R.K. and Solanki, A&A 330 (1998), 1160.

[23] S. Uttenthaler, T. Lebzelter, S. Palmerini, M. Busso, B. Aringer and M.T. Lederer, A&A 471, 2007, L41.

[24] J. Nordhaus, E.G. Blackman and A. Frank, MNRAS, 376, (2007), 599.

[25] S. Palmerini and M. Busso, New Astron. Review 52, (2008) 412.

[26] Charbonnel, C., Balachandran, S. C. 2000, A&A, 359, 563

[27] Uttenthaler, S., Lebzelter, T., Palmerini, S., Busso, M., Aringer, B., Lederer, M. T. 2007, A&A, 471, L41