26Al production from magnetically induced extramixing in AGB Stars

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Abstract

We discuss nucleosynthesis results obtained following the recent suggestion that extramixing phenomena in red giants might be driven by magnetic buoyancy. We explore for this model the production of the short-lived radioactive isotope 26Al and of stable light nuclei, considering both the case of the general buoyancy of flux tubes and that of the intermittent release of magnetized unstable structures. We show that abundant 26Al can be produced, up to, and above, the highest levels measured in presolar grains. This level would be also sufficient to explain the early solar system 26Al as coming from a nearby AGB star of low mass. The case of fast-moving instabilities is the most efficient, reaching almost the same effectiveness as hot bottom burning (HBB).

Key words: Stars:AGB, Stars: Evolution of, Extended mixing, H-burning, Nucleosynthesis in late stellar evolution, MHD
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1 Introduction

Previous studies have shown that AGB stars are a site where several short-lived radioactivities identified in early solar system (ESS) materials are produced (Wasserburg et al., 1995; Busso et al., 2003). In particular, the possibility that one such star polluted the early solar nebula, introducing the record of nuclei like 26Al, 41Ca, 60Fe, 107Pd, 135Cs, was explored by Wasserburg et al. (1994). They found that the polluting star must also experience extra-mixing phenomena, carrying to the envelope partially H-processed materials rich in 26Al (Wasserburg et al., 2006). These extended mixing episodes were also shown to account for the record of C and O isotopes in presolar grains that also show 26Al (Nollett et al., 2003). In the mentioned models circulation was treated parametrically, and the physical mechanism was left unspecified.
Among the processes invoked to explain extended mixing, rotation played a dominant role (Denissenkov et al., 2000), as it can induce shear instabilities and meridian circulation. However, attempts at considering rotational mixing in complete stellar models failed to reproduce the observed abundance changes (Palacios et al., 2006). This fact promoted a reappraisal of other forms of matter transport, like the so-called "tachohaline" mixing induced by the decrease in the molecular weight created by \(^{3}\)He combustion (Eggleton et al., 2008; Charbonnel and Zahn, 2007). The efficiency of such a mechanism, very important in other contexts, seems however to be in question in the environment we refer to, i.e. in AGB stars of about 2 \(M_\odot\) (Cantiello et al., 2007).

Guided by the existing models of magnetic buoyancy (Parker, 1974) and of other magnetic instabilities (Spruit, 2001, 1999; Eggenberger et al., 2005; Busso et al., 2007) [hereafter BWNC] recently proposed that matter transport in red giants be maintained by a magnetic dynamo, creating a system of buoyant toroidal flux tubes. In this paper we shall explore in a preliminary way some of the nucleosynthesis implications of such an idea. In particular, we analyze the synthesis of \(^{26}\)Al in AGB stars, implementing in a simplified way a mass circulation based on BWNC’s formalism.

2 The Model and the Numerical technique

From the original poloidal field of a rotating star, a toroidal field of similar strength can be generated by the dynamo mechanism (Parker, 1974). In physical conditions occurring above the H-burning shell of an evolved star several perturbations can affect a cylindrical or toroidal flux tube, and they can evolve into instabilities (Spruit, 1999). These are opposed by the magnetic field aligned with the cylinder, which acts as a stabilizing tension. The complex dynamical behavior of such a tube includes expansion (due to buoyancy), unstable oscillations (due to Alfvén waves, leading to the development of \(\Omega\)-shaped loops) and torsion due to the Coriolis force (Spruit and van Ballegooijen, 1982). The absence of X-ray emission from surface magnetic activity in AGB stars tells us that these magnetized structures, if they do exist, must be disrupted in the convective layers, thus depositing there their chemical peculiarities. BWNC showed that efficient buoyancy of magnetized regions requires that they achieve very high values of the magnetic fields, up to a few MG.

It is difficult for a star to maintain very strong fields buried in its interior: if the average field is strong, than it is ejected in a short interval of time and a whole toroidal flux tube can be assumed to float to the envelope (see Figure 1 left panel). In this case, maintaining the dynamo for subsequent episodes of magnetic activity depends on the possibility that energy is resupplied from the convective envelope to the interior and the differential rotation is re-established.
Fig. 1. Left. A buoyant flux tube, laying in the equatorial plane, with Alfvén wave oscillations. If the field is strong enough (MG) it floats to the envelope, depositing there its composition. Right. Detachment of a magnetized structure due to the tilting and reconnection of an unstable Ω-shaped loop. The released bubbles move rapidly to the envelope, carrying material synthesized close to the H-shell (Nordhaus and Balckman, 2008). If this occurs, than flux tubes emerge, break into the envelope and force local matter to be pushed down in a downflow. This probably occurs over a wide area, and reaches down to regions where p-captures are active. The upward velocity \( v_u \) of the buoyancy can be taken from BWNC. Assuming local mass conservation in each shell crossed by the upward and downward motions, the downward velocity would be such that \( v_d f_d = v_u f_u \), where \( f_d \) and \( f_u \) are the fractional areas occupied by the upflow and by the downflow, respectively. The dimensions of a flux tube as discussed by BWNC require that \( f_d/f_u \) be very large (>200) even in the case where the activity phenomena related to toroidal fields are constrained within a limited range in latitude (in the Sun, this is normally ±30-50°, corresponding to \( f_d = 0.5 - 0.75 \)). In such conditions, H burning has time to occur only in the downward movement, due to the lower velocity. When a new magnetic flux tube forms, everything is repeated: the net effect is a sort of matter circulation. We shall refer to this scheme as Case 1. As discussed in BWNC, the chemical changes to be explained require that, in the process, the envelope is mixed with a roughly equal mass of partially H-burned material.

Alternatively, magnetic instabilities might be released intermittently. This corresponds, for example, to the scheme of Figure 1 right panel, in which a kink of an Alfvén oscillation evolves into an Ω-shaped instability of high internal fields. It can then be tilted by the Coriolis force, and detached from the rest of the flux tube as an independent bubble. We shall refer to this scheme as Case 2. We shall present here preliminary results for both cases.
3 Effects of magnetic extra-mixing on $^{26}\text{Al}$ and other isotopes

We use the model for a star of $2M_\odot$ and solar metallicity, previously calculated with the FRANEC code using a limited reaction network for energy production. A mass loss rate as described by the parametrization by Reimers (1975), with $\eta = 0.5$ was used. On this basis we recomputed the full nucleosynthesis in the radiative layers above the H shell and followed the mixing of processed materials into the convective envelope. For Case 1, this was done in a way similar to that of Nollett et al. (2003), but adopting the upward velocity given in BWNC and taking $f_d = 0.75$. For Case 2, we assumed instead that every 50 years the phenomenon of Figure 1 (right panel) occurs, carrying to the surface H-processed material. The period of 50 years was chosen because it is comparable to the magnetic cycles in active stars and to the duration of magnetic bursts in evolved stars found by Nordhaus (2007).

In Case 1 we assume a maximum temperature for the circulation of $\text{Log}T_P = \text{Log}T_H - 0.1$. This condition was taken from Nollett et al. (2003), who showed that for higher temperatures excessive energy production would occur. In the second case, due to the long duration of the burning at $T_P$ in between two episodes of bubble release, we had to reduce $T_P$ not to disturb the stellar structure ($\Delta \text{Log}T_P = 0.15$). In several runs we explored the range of mass circulation from $\dot{M} = 10^{-7}$ to $\dot{M} = 10^{-5} M_\odot/\text{yr}$, following the indications by Nollett et al. (2003) that this is the interval in which the isotopic shifts observed in presolar grains of AGB origin can be explained. We notice that, although the value of $\dot{M}$ is not self-consistently obtained, but rather adopted from the quoted work, there are specific relations linking the mass circulation to the magnetic field $B$ (at least in Case 1). Indeed, for flux conservation, calling $a$ the radius of the flux tube, $\dot{M} \propto B a^2$. On the other hand, the buoyancy velocity $v$ is related to the field by the relation $v \propto B$ (see Busso et al., 2007, Eq.4), therefore $\dot{M} \propto B \times a^2$.

Tube dimensions were assumed from the solar case; then increasing $B$ is required to obtain higher $\dot{M}$ values. Similarly, lower mass circulations would imply lower fields, as indeed found by BWNC for RGB stars. While small values of the mass circulation are certainly possible, it seems unlikely that a much faster transport (say, by a factor 100) can be magnetically supported, unless the tube dimensions are very different from the solar case. Indeed, the field values obtained by BWNC for $\dot{M} \sim 10^{-6} M_\odot/\text{yr}$ are already quite high. In the scheme of Case 2, the analogy with solar magnetic tubes is less important, because the achieved envelope abundances are essentially controlled only by the long burning periods (tens of years) at $T_P$. In this case, magnetic buoyancy simply transports in discrete bubbles matter synthesized by the H shell, but continuously resupplying the fuel with material descending from the envelope (by mass conservation). High $B$ values are required only in the buoyant bubbles, not in the buried magnetic structures, and a faster mass
transport is a priori possible.

In general, computing extra-mixing requires describing nuclear physics phenomena coupled with dynamics. This can be obtained by solving a system of differential equation of the type:

\[
\frac{dN_i}{dt} = \frac{\partial N_i}{\partial t} + \frac{\partial N_i}{\partial M} \frac{\partial M}{\partial R} \frac{\partial R}{\partial t} \tag{1}
\]

where the partial time derivative due to nucleosynthesis is:

\[
\frac{\partial N_i}{\partial t} = -N_p N_i \lambda_{i,p} + N_p N_{i-1} \lambda_{i-1,p} - N_i \lambda_{d} + N_{i'} \lambda_{d} \tag{2}
\]

Here the parameters \( \lambda \) are the reaction rates, which we take from the NACRE compilation (Angulo et al., 1999). In practical cases, the phenomenon might become simpler than that. For example, in the fast upward flux the time scale for motion is smaller than the one for burning, and no nucleosynthesis occurs. On the contrary, in a sufficiently slow descending flux everything depends only on the path integral of reaction rates, as in previous extra-mixing calculations by Wasserburg et al. (1995)

In our work we first recomputed the "static" H burning through the radiative region for the whole AGB phase, with an extended network going from H to \(^{32}\)S. Then we applied separately our mixing schemes for Cases 1 and 2.

Figure 2 shows preliminary results thus obtained, in terms of abundances of affected isotopes in the envelope, as a function of the time spent on the thermally-pulsing AGB stage. The changes in abundances introduced by the third dredge-up have for the moment been neglected.

Preliminary conclusions drawn from Figure 2 can be summarized as follows:

- Case 1 (Figure 2 left panel) gives results very similar to what was previously obtained in parameterized extra-mixing (or cool bottom processing, CBP, as this phenomenon is sometimes called) by Nollett et al. (2003). \(^{26}\)Al is produced at a moderate efficiency, reaching final abundance ratios in the envelope in the range \(^{26}\)Al/\(^{27}\)Al = 10\(^{-3}\) to 10\(^{-2}\) (depending on the choice of parameters). This corresponds to values found by Wasserburg et al. (2006). \(^{16}\)O is virtually untouched (i.e. we have only CN cycling), while heavier oxygen isotopes are largely modified, covering the region where presolar grain data lay.

- Case 2 (Figure 2 right panel) shows a somewhat different burning process. The abundances of nuclei modified at high \( T \) (like \(^{16}\)O) are more affected, and \(^{26}\)Al/\(^{27}\)Al reaches values close to 0.1. By contrast, fragile nuclei like \(^{18}\)O and \(^{15}\)N, already burning at low \( T \), are less affected than in Case 1, where
Fig. 2. Left: envelope abundance evolution along the TP-AGB phase for nuclei affected by CBP, in a star of $2M_\odot$ and $Z_\odot$, in Case 1 (circulation). Right: envelope abundances in Case 2 (detached bubbles). Here $t_i$ is the time spent between the release of two successive bubbles they have more time to be consumed. The high abundance of $^{26}$Al found makes this case interesting for the possibility that the encounter of an AGB star be at the origin of the early solar system concentration of $^{26}$Al.

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References

Angulo, C., Arnould, M., Rayet, M., Descouvemont, P., et al., A compilation of charged-particle induced thermonuclear reaction rates, 1999, Nucl. Phys. A, 655, 3-183
Busso, M., Gallino, R., Wasserburg, G. J., Short-Lived Nuclei in the Early Solar System: A Low Mass Stellar Source?, 2003, PASA, 20, 356-370
Busso, M., Wasserburg, G. J., Nollett K. M., Calandra A., Can Extra Mixing in RGB and AGB Stars Be Attributed to Magnetic Mechanisms?, 2007, ApJ, 671, 802-810
Cantiello, M., Hoekstra, H., Langer, N., and Poelarends, A.J.T., Thermoha-
line Mixing in Low-mass Giants: RGB and Beyond, 2007, in UNSOLVED PROBLEMS IN STELLAR PHYSICS, AIPC 948, pp 73-77.  
Charbonnel, C., and Zahn, J.-P. Thermohaline mixing: a physical mechanism governing the photospheric composition of low-mass giants, 2007, A&A, 467, L15-L18  
Weiss, A., Denissenkov, P. A., Charbonnel, C., Evolution and surface abundances of red giants experiencing deep mixing, 2000, A&A, 356, 181-190  
Eggleton, P.P., Dearborn, D.S.P., Lattanzio, J.C., Compulsory deep mixing of 3He and CNO isotopes in the envelopes of low-mass red giants, 2008, ApJ 677, 581-592.  
Eggenberger, P., Maeder, A., Meynet, G., Stellar evolution with rotation and magnetic fields IV. The solar rotation profile, 2005, A&A, 440, L9-12  
Nollett, K. M., Busso, M., Wasserburg, G. J., Cool Bottom Processes on the Thermally Pulsing Asymptotic Giant Branch and the Isotopic Composition of Circumstellar Dust Grains, 2003, ApJ, 582, 1036-1058  
Nordhaus, J., and Blackman, E.G., Dynamos and Chemical Mixing in Evolved Stars, 2008, in THE NINTH TORINO WORKSHOP ON EVOLUTION AND NUCLEOSYNTHESIS IN AGB STARS, AIPC 1001, pp. 306-312.  
Nordhaus, J., Common Envelope Dynamos in Asymptotic Giant Branch Stars, 2007, AAS, 211, 6504  
Palacios, A., Charbonnel, C., Talon, S., Siess, L., Rotational mixing in low-mass stars. II. Self-consistent models of Pop II RGB stars, 2006, A&A, 453, 261-278  
Parker, E. N., The instability of strong magnetic fields in stellar interiors, 1974, Ap&SS, 31, 261-266  
Spruit, H. C., van Ballegooijen A. A., Stability of toroidal flux tubes in stars, 1982, A&A, 106, 58-66  
Spruit, H. C., Differential rotation and magnetic fields in stellar interiors, 1999, A&A, 349, 189-202  
Spruit, H. C., Overview of Solar Luminosity Variation Mechanisms, American Geophysical Union, Spring Meeting, 2001, American Geophysical Union, SP31, B01  
Wasserburg, G. J., Busso, M., Gallino, R., Raiteri, C. M., Asymptotic Giant Branch stars as a source of short-lived radioactive nuclei in the solar nebula, 1994, ApJ, 424, 412  
Wasserburg, G. J., Busso, M., Gallino, R., Nollett,K.M. Short-lived nuclei in the early Solar System: Possible AGB sources, 2006, NuPhA, 777, 5  
Reimers, D., Circumstellar envelopes and mass loss of red giant, 1975, Problems in stellar atmospheres and envelopes, Springer-Verlag New York, Inc., 229-256  
Wasserburg, G. J., Boothroyd, A. I., Sackmann, I.-J., Deep Circulation in Red Giant Stars: A Solution to the Carbon and Oxygen Isotope Puzzles?, 1995, ApJ, 447L, 37