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Buoyant magnetic flux tubes as a site for ^{26}Al production in AGB stars

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Abstract. We address the diffusive circulation of matter occurring in AGB stars above the H-burning shell, which triggers the production of p-rich isotopes like ^{13}C and ^{17}O and of the unstable nucleus ^{26}Al, observed in presolar grains and in Early Solar System materials. As a physical mechanism for these phenomena we consider the buoyancy of magnetic flux tubes formed below the convective envelope and we arrive at expressions for the relevant mixing parameters in terms of the required strength of the magnetic field $|\vec{B}|$. We show how values of $|\vec{B}|$ like those normally expected in the radiative layers above the H-burning shell of a red giant can indeed trigger chemical mixing at the required efficiency and should therefore be considered for explaining the abundance peculiarities induced in such stars by proton captures. The technique discussed here is suitable for chemically stratified regions. A different formalism should be used for studying the more internal, well-mixed He layers, where similar circulation phenomena induce the formation of the neutron source ^{13}C during dredge-up.

Key words. Star: nucleosynthesis – Star: low-mass – Star: mixing – MHD

1. Mixing models and their problems

Observations of evolved stars below $\sim 2\,M_\odot$ reveal isotopic mixes of light and intermediate-mass elements that cannot be accounted for by convective dredge-up Straniero et al. (1997). Such chemical anomalies are found above the so-called *luminosity bump* of the red giant branch. The problem has emerged from data accumulated since the early nineties, for various elements between lithium and oxygen (Gilroy & Brown 1991; Pilachowsky et al. 1993; Gratton et al. 2000). Higher mass elements up to Mg show peculiarities and anti-correlations already on the Main Sequence in low mass stars of Globular Clusters (Gratton et al. 2001): they might be related to mixing phenomena occurring in previous generations of red giants. Excellent reviews of these phenomena can be found in the literature (Kraft 1994; Charbonnel 2004).

Non-convective circulation of material exposed to partial H burning is usually assumed to explain the above anomalies (Charbonnel 2004; Herwig 2005). Partial p-captures in

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these circulating material are often called Cool Bottom Processes (hereafter CBP). Some form of non-convective mixing must occur also after the thermal pulses, in the He- and C-rich zones (Iben & Renzini 1982; Herwig et al. 2003), as discussed elsewhere in this book by S. Cristallo. Indeed, *s*-processing in AGB stars requires that ^{13}C is produced in the He-intershell region from p-captures on the abundant ^{12}C (Gallino et al. 1988; Arlandini et al. 1999), and this can only be obtained through diffusive proton flows below the convective envelope at dredge-up.

Processes invoked to account for the required CBP include shear instabilities and the meridional circulation induced by rotation (Zahn 1992; Denissenkov et al. 1998). Most models consider the chemical mixing through some diffusion-like treatment, leaving the values of the diffusion coefficient and of the mass mixed as free parameters (Denissenkov & Tout 2000). Such approaches are common also in modelling massive, radiatively stratified stars (Meynet et al. 2004).

In fact, in low mass red giants the internal structure leads us to envisage quite naturally the existence of a shear layer, at the contact between the almost rigid rotation of the stellar radiative core, and the differentially rotating convective envelope. Very recently, however, the idea of a purely rotationally-induced mixing has undergone strong difficulties (Palacios et al. 2003; Goriely & Siess 2004).

In this paper we try therefore a different approach. In section 2 we recall the expectations on CBP, as emerging from measurements on presolar grains and ESS radioactivities. Then in section 3 we consider the effects of magnetic fields, using previously published results from solar and stellar magneto-hydrodynamics (MHD). We then verify (section 4) that the chemical diffusion induced by magnetic buoyancy is indeed capable of yielding chemical mixing at the level required by meteoritic measurements.

2. Evidence of stellar extra-mixing from meteoritic abundances

In recent years the experimental constraints to stellar models coming from meteoritic sciences, and in particular from presolar grain analysis (Amari et al. 2001) has grown impressively, to become the most precise source of information on nucleosynthesis details, at least for evolved red giants, where most presolar grains formed.

Such constraints have added to the previous knowledge of red giant abundances in underlining the need for CBP, in order to account for the isotopic composition of light elements in presolar grains and for the presence of ^{26}Al in them (Wasserburg et al. 1995).

Convergent indications come from the record of extinct radioactivities in the Early Solar System (ESS), and namely from the abundant ^{26}Al. Indeed, it was suggested (Wasserburg et al. 1994) that this ^{26}Al is produced in the same AGB stars where also the ^{26}Al present in presolar grains was manufactured (Nollett et al. 2003).

Very recently the abundances of ESS radioactive nuclei have been reviewed extensively (Wasserburg et al. 2006), considering the conditions for production of each isotope. It was found that, under suitable conditions for the neutron density (to produce enough ^{60}Fe) and for the mass circulation in the H-rich zone (to produce enough ^{26}Al), an AGB star of relatively low mass and metallicity ($3M_{\odot}$, $Z = Z_{\odot}/3$) might be at the origin of the ESS contamination with short-lived nuclei. Table 1 shows some of these findings from the above authors. Since their reference model does not require any amount of ^{13}C to be burnt for *s*-process production (the level of *s* processing is minimal and is provided by the ^{22}Ne source) the only free parameter is the amount of extra-mixing needed for ^{26}Al. As Table 1 shows, the required ^{26}Al production (in bold) is at the level of ^{26}Al/^{27}Al $\sim 10^{-2}$, as needed also to explain oxide grains rich in ^{26}Al (Nollett et al. 2003). A unique stellar process can therefore explain both sets of data.

CBP can be parameterized (Nollett et al. 2003) in terms of a mass circulation rate, $\dot{M}$,

Table 1. Some ESS Short-Lived Nuclei, as produced by a 3 $M_\odot$ AGB star ($Z = Z_\odot/3$)

$f_0 = 4 \times 10^{-3}$; (3 $M_\odot$, $Z = 1/3Z_\odot$)[1]				
	$(N_R/N_I)_w(q_I/q_0)^2$	$(N_R/N_I)_\Delta$		
		Δ_1 = 0 Myr	Δ_1 = 0.55 Myr	Δ_1 = 6.7 Myr
^{26}Al/^{27}Al	($\mathbf{2.0 \times 10^{-2}}$)	(8.0×10^{-5})	(5.0×10^{-5})	(8.5×10^{-8})
^{41}Ca/^{40}Ca	1.5×10^{-4}	5.9×10^{-7}	(1.5×10^{-8})	—
^{60}Fe/^{56}Fe	6.7×10^{-4}	2.7×10^{-6}	2.1×10^{-6}	1.0×10^{-7}
^{107}Pd/^{108}Pd	9.9×10^{-3}	4.1×10^{-5}	3.8×10^{-5}	(2.0×10^{-5})

Notes: [1]. Calculated to match (^{26}Al/^{27}Al)$_0$, (^{41}Ca/^{40}Ca)$_{0.55\rm Myr}$, (^{107}Pd/^{108}Pd)$_{6.7\rm Myr}$. [2]. Values in the envelope calculated for $Z = 1/3Z_\odot$ with the factor of q_I for this Z divided by $(q_0)_\odot$ for the unsalted solar cloud. (Wasserburg et al. 2006,the table is adapted from their Table 6).

and of the maximum temperature in the layers reached by the mixing (T_P). The values of these parameters accounting for the mentioned meteoritic constraints cluster around $\dot{M} \sim 10^{-6} M_\odot$/yr and (Log T_P−Log T_H) ~ -0.1, where T_H is the temperature of the H-burning shell. These are the typical numbers we must reproduce, when trying to explain CBP in terms of magnetic buoyancy.

Fig. 1. A sketch of toroidal flux tube in the radiative layers, oscillating (in its m=12 mode)

3. Magnetic Fields and their buoyancy

MHD effects in stellar physics have been addressed since many years (Chandrasekhar & Fermi 1953; Parker 1964; Tayler 1973). The conclusions indicated that, when in the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \lambda \nabla^2 \mathbf{B} \qquad (1)$$

one can neglect the diffusive term ('frozen field' approximation) a toroidal field (an envelope of flux tubes centered on the polar axis) is created from the originally poloidal one (and vice versa). The dynamics of flux tubes is governed by a global buoyancy, due to the presence of a magnetic pressure $B^2/8\pi$ in addition to the thermal pressure (Parker 1964, 1974). Moreover, the tubes are the site of Alfvén waves, developing into various types of instabilities (Spruit 1999).

The global buoyancy (like some of the Alfvén modes) is opposed by the stratification of molecular weight (Spruit 2002; Meynet et al. 2004). However, purely sinusoidal oscillations of the tubes, evolving into large Ω-shaped loops are always buoyant (Parker 1994). We can therefore study the upward movement of structures originally similar to that in Figure 1. The upward motions are accompanied by downward fluxes, also present in the Sun (Frutiger & Solanki 1998), thus guaranteeing a circulation pattern.

Let's notice here that this type of mixing, if efficient enough, would mimic a diffusion process. Indeed, in the assigned time several tubes born very close to the border will reach it, while fewer tubes born in deeper layers will be able to do the job. This will give rise to a mixing process less and less efficient as the distance from the border grows, like in a diffusive case. However, here we are not pushing matter from top to bottom; rather, the reverse is true.

We need now to verify how much mass can circulate with the tubes, and at which T_P must they be formed, to buoy up to the convective envelope in a given time. (On the AGB this time must coincide with an interpulse time).

Then these data must be compared to those required for efficient production of ^{26}Al.

The extension of the 'mixed layer' can be assumed equal to the length over which phase mixing would dissipate the Ω-shaped instabilities, damping the modes (Spruit 1999, 2002). Subsequently, one can use published models to derive the amount of mass that can be dissipated by turbulence in the convective envelope (Vishniac 1995a,b). The relevant formulae are taken from the quoted works:

$$l/R_* = \pi/(q_A \Omega_A t) \tag{2}$$

and

$$dM/dt = 8\pi r^2 \rho V_T/(C_d(V_T/(K_T\eta))^{1/2}) \tag{3}$$

Here $\Omega_A = B/((4\pi\rho)^{1/2}R_*)$ is the Alfvén pulsation over the stellar radius; $q_A = \Omega_A \Delta t_A$; Δt_A is the crossing time of Alfvén waves over the star's dimension; B is the magnetic field strength; V_T is the turbulent velocity; η is the resistivity; C_d is the turbulent drag coefficient. Most parameters are estimated in the already quoted papers (Vishniac 1995a,b; Spruit 1999, 2002). We take the (macro)-turbulence velocity to be equal to the convective velocity near the base of the convective envelope. In the radiative layers, instead, only micro-turbulence survives, for which one can assume a velocity roughly equal to that of sound. The magnetic field is then easily computed (Gross 1978).

The parameters of the model were estimated on the basis of outputs from stellar evolutionary calculations made with the Franec code, for a 2$M_\odot$ star, spanning metallicities from solar to 1/3 solar (Straniero et al. 1997; Wasserburg et al. 2006). Details on how to express the parameters in terms of known quantities can be found elsewhere (Busso et al. 2005, 2006). Here we want only to summarize the basic results for the magnetic field strengths and for the corresponding diffusion efficiency. For estimating the diffusion coefficient we follow the same procedure as originally done in CBP calculations (Nollett et al. 2003).

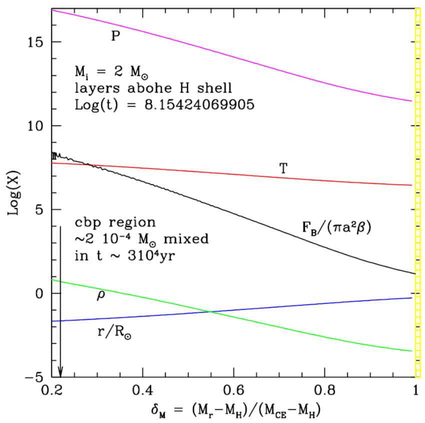

Fig. 2. Structure of a 2 $M_\odot$ star below the convective envelope in an interpulse phase. The arrow shows the mixing depth necessary for efficient CBP (Nollett et al. 2003). Also shown is the needed buoyancy force.

4. Results and Conclusions

In the CBP case exemplified in Figure 2, in order to fulfil the CBP requirements (Nollett et al. 2003), the extension of the mixed layer must be such that its innermost zones reach a temperature up to Log T_P = 7.70, with a mass circulation of about 10^{-6} $M_\odot$/yr (in a time interval of about 3×10^4yr, during which the H-burning shell is active).

The buoyancy force needed to obtain such a result is shown in Figure 2 (per unit area of the magnetic flux tube, and per unit value of the ratio β between magnetic and thermal pressure in the tubes). From the simple equations of the problem (Busso et al. 2005, 2006) we find values of the magnetic field strength lower than B $\simeq 10^2$ G at the convective envelope base, and typically of a few $\times\, 10^4$ G in the lowermost layers from which the tubes must come. An example of these findings is presented in Table 2, where the required magnetic fields, and the corresponding values of the diffusion coefficient, are shown for five representative moments along the thermally-pulsing AGB stage of a 2 $M_\odot$ star of solar metallicity; these time steps were considered previously for CBP calculations (Wasserburg et al. 2006).

The above numbers must be compared with known situations in stars. In particular, let's remember that even in the Sun (a Main Sequence

Table 2
Parameters of interest for magnetic mixing on the AGB:
M=2 $M_{\odot}$, Z=$Z_{\odot}$

Stage	Time (Myr)	B_i (gauss)	B_c (gauss)	$\dot{M}$ ($M_{\odot}$/yr)	D_{mix} (cm^2/s)	$\log T_P$
1 ...	141.3390	0.2010D+05	0.3965D+02	0.2486D-05	0.2360D+11	7.62000
2 ...	141.7645	0.3305D+05	0.6305D+02	0.2260D-05	0.2468D+11	7.66080
3 ...	142.1347	0.4206D+05	0.7638D+02	0.1985D-05	0.2518D+11	7.67080
4 ...	142.5279	0.6047D+05	0.8019D+02	0.1254D-05	0.2059D+11	7.70200
5 ...	142.6398	0.6958D+05	0.8416D+02	0.9379D-06	0.1714D+11	7.68970

Notes:"Time" is in years after core He flash; B_i and B_c are the magnetic field strengths at the maximum depth reached into the radiative zone and at the convective boundary, respectively; $\dot{M}$ is the mass circulation rate; D_{mix} is the equivalent diffusion coefficient (Nollett et al. 2003). LogT_P is the innermost (then highest) temperature involved in the mixed zone.

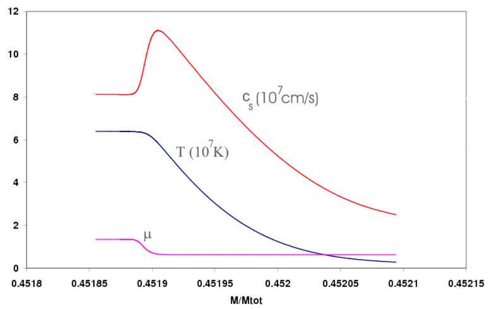

Fig. 3. Values of some relevant parameters over the mixed region in step 5 of Table 2

star) the most active regions of the magnetic structures do reach 10^4 G, and values around 10^5 G are inferred for the radiative region below the convective zone (Mestel 1999). In evolving to red giant phases these values are expected to grow (if angular momentum conservation is valid), not to decrease. This makes the above requirements for CBP quite 'normal'; they are actually necessarily expected to hold. This suggests that magnetic fields should indeed have a role in extended mixing.

As a final comment, consider the values of the relevant parameters c_s (sound speed, here assumed equal to the micro-turbulence velocity V_T), T (temperature) and μ (mean molecular weight). For phase 5 in Table 2, these parameters are plotted in Figure 3 in the region interested by the buoyancy of flux tubes. As is shown in the Figure, the innermost regions are characterized by a gradient in μ, which corresponds to the layers immediately above the H-burning shell where the composition changes due to p-captures. It is this gradient that limits the extension of the mixed zone: actually, in equation (3) c_s ($\equiv$ V_T in radiative layers) decreases when μ increases ($c_s = [\gamma(k_B/\mu m_H)T]^{1/2}$).

The treatment considered here is in fact devised explicitly for the situation described, in which the chemical stratification is the dominant factor opposing buoyancy. Hence, in order to address the other partial mixing problem of AGB stars, i.e. the formation of the neutron source ^{13}C in the He-intershell region, a different procedure must be followed, suitable to express magnetic buoyancy in well mixed zones. We recall, indeed, that the interested layers have in that case a homogeneous composition, due to convective mixing established by the thermal pulse before the ^{13}C-pocket formation. The conclusions of this exercise require now to be verified by a more complete MHD treatment of the advanced stages of LMS evolution.

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