Mem. S.A.It. Vol. 78, 507

Memorie della

Extra-mixing in AGB Stars from magnetic buoyancy

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Abstract. We study the circulation of matter in AGB stars above the H-burning shell, which is known to yield the appearance of p-rich isotopes like ^{13}C, ^{17}O and the unstable ^{26}Al at the stellar surface. These nuclei were observed in presolar grains of AGB origin and in some cases (e.g. C isotopes) in spectroscopic observations of evolved stars. For the physical mechanism driving the mixing we consider magnetic flux tube buoyancy. Magnetic tubes are formed below the convective envelope and one can express the parameters of the required mixing phenomena in terms of the magnetic field intensity $|\vec{B}|$. We show that the required values of $|\vec{B}|$ can span a considerable range. If the mixing arrives only at the innermost layers of the convective envelope, fields smaller than the solar ones are sufficient, according to our previous analysis. If instead magnetic fields have to appear at the surface, as is suggested by recent observations, than field intensities in the Megagauss range are necessary.

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

1. Mixing models and their problems

Evolved stars below $\sim 2\ M_{\odot}$ show abundance anomalies at their surface as compared to what is predicted by canonical stellar models. In particular, the isotopic mix of light and intermediate-mass elements cannot be accounted for by purely convective dredge-up (Straniero et al. 1997). The mentioned chemical peculiarities are found after the *luminosity bump* of the red giant branch and continue through the AGB stages. The observational database has grown since the early nineties, for various elements between lithium and oxygen (Gilroy & Brown 1991; Pilachowsky et al. 1993; Gratton et al. 2000). Good reviews exist of the available evidence (Kraft 1994; Charbonnel 2004).

Furthermore, higher mass elements up to Mg show anomalies and anti-correlations since the Main Sequence in low mass stars of Globular Clusters (Gratton et al. 2001). This might be interpreted as due to mixing phenomena in previous generations of red giants.

Non-convective circulation of material that underwent partial H burning is necessary to explain the above scenario (Charbonnel 2004; Herwig 2005). These circulation phenomena are often called Cool Bottom Processes (hereafter CBP). Some form of non-convective mixing must occur also after the thermal pulses,

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in the He- and C-rich zones (Iben & Renzini 1982; Herwig et al. 2003), as discussed by many authors. 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, meridional circulation and in general phenomena 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 modeling massive, stratified stars (Meynet et al. 2004).

In fact, in low mass red giants the internal structure leads us to infer 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. These zones of changing rotational properties are called *tachoclines*. Very recently, however, the idea of a purely rotationally-induced mixing has undergone strong difficulties (Palacios et al. 2006; 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, but with field intensities that are a critical function of the length covered by magnetic buoyancy.

2. Evidence of stellar extra-mixing from meteoritic abundances

In recent years the experimental constraints to stellar models coming from meteoritics, and in particular from presolar grains recovered in pristine compounds formed in the early Solar System (Amari et al. 2001) has grown impressively, becoming 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 radioactive nuclei 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.

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

$f_0 = 4 \times 10^{-3}$; ($3\ M_\odot, Z = 1/3 Z_\odot$)[1]				
	$(N_R/N_I)_w(q_I/q_0)$[2]	$(N_R/N_I)_\Delta$		
		$\Delta_1 = 0$ Myr	$\Delta_1 = 0.55$ Myr	$\Delta_1 = 6.7$ 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 $(^{26}\text{Al}/^{27}\text{Al})_0$, $(^{41}\text{Ca}/^{40}\text{Ca})_{0.55\text{Myr}}$, $(^{107}\text{Pd}/^{108}\text{Pd})_{6.7\text{Myr}}$. [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).

CBP can be parameterized (Nollett et al. 2003) in terms of a mass circulation rate, $\dot{M}$, 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 $(Log\ T_P - Log\ T_H) \sim -0.1$, 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.

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 a downward flux, 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

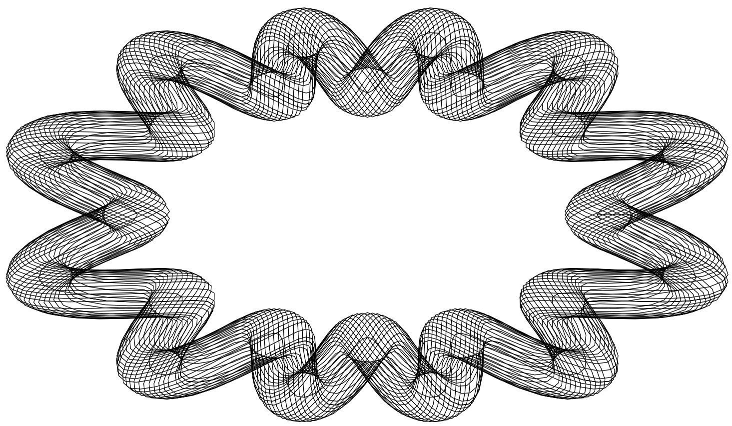

Fig. 1. A sketch of toroidal flux tube in the radiative layers, oscillating (in its m=12 mode)

taken from the quoted works:

$$l/R_* = \pi/(q_A \Omega_A t) \quad (2)$$

and

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

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.

One has to know which is the extension l over which the tubes are buoyant. If this is restricted to the radiative layers, so that extra-mixing deposits its material at the envelope bottom, then one can close the system of equations by imposing angular momentum conservation through the rigidly-rotating internal regions and by taking a proper expression for the field scaling with the radius and the angular velocity, as done e.g. in Gross (1978). This approach will be quoted in what follows as *Case A*.

Alternatively, fields might cross the entire convective envelope, as indeed is the case for the Sun. This hypothesis was considered until recently as rather unlikely, due to the enormous extension of the AGB convective envelopes and the absence of evidence for the existence of magnetic coronae. However, recently surface fields of a few Gauss have been measured for AGB stars (Herpin et al. 2006), so that the situation appears now as quite different. In fact, it is obvious that, in order to allow the fields appear at the photosphere, much larger values of the magnetic pressure will be necessary as compared to the scenario where only the radiative layers are affected by magnetic buoyancy. This also implies much larger values of the fields. We shall therefore examine this second possibility by abandoning angular momentum conservation (because the envelope rotates differentially) and assuming instead a typical

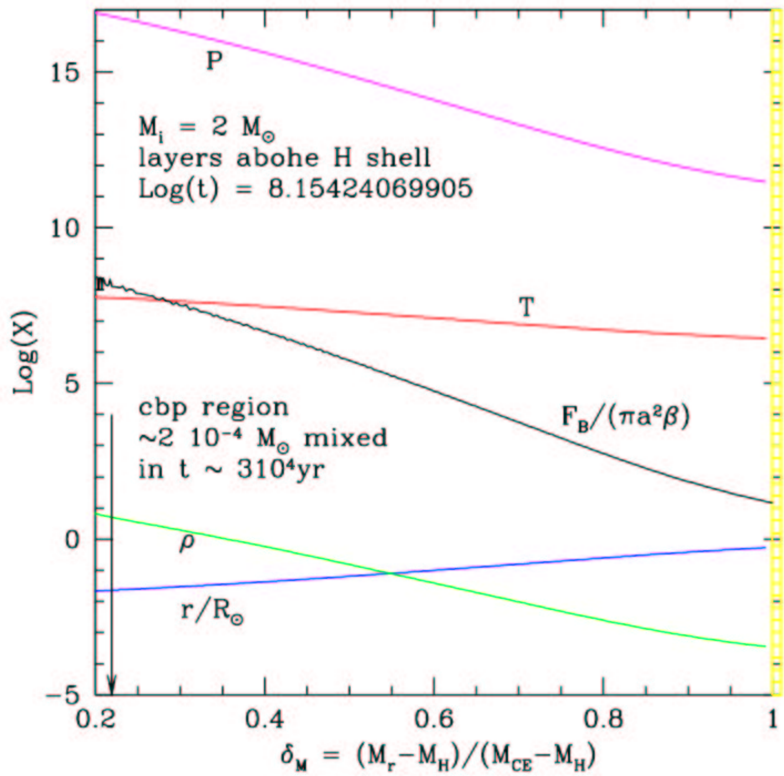

Fig. 2. Structure of a 2 $M_\odot$ star below the convective envelope in an interpulse phase. The arrow shows the mixing depth necessary for efficient cbp (Nollett et al. 2003). Also shown is the needed buoyancy force.

field value of 10 G at the surface. This is quoted in the following as *Case B*.

The parameters of the model were estimated on the basis of outputs from stellar evolutionary calculations made with the FRANEC code, for a $2M_\odot$ star, with solar metallicity (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, 2007). Here we want only to summarize the basic results for the magnetic field strengths and for the corresponding diffusion efficiency, underlining the big difference in the results induced by the observed photospheric fields. For estimating the diffusion coefficient we follow the same procedure as originally done in CBP calculations (Nollett et al. 2003).

4. Results and Conclusions

As mentioned above, we make two alternative hypotheses on the extension of the region over which the fields must induce circulation. In case A (Busso et al. 2005) we consider the thickness of the radiative zone (about 1 $R_\odot$). In case B we introduce instead the much more challenging condition that flux tubes can survive through the extremely extended convective envelope and up to the surface ($\sim 300R_\odot$). For this second attempt we assume a photospheric field of 10 G (Herpin et al. 2006).

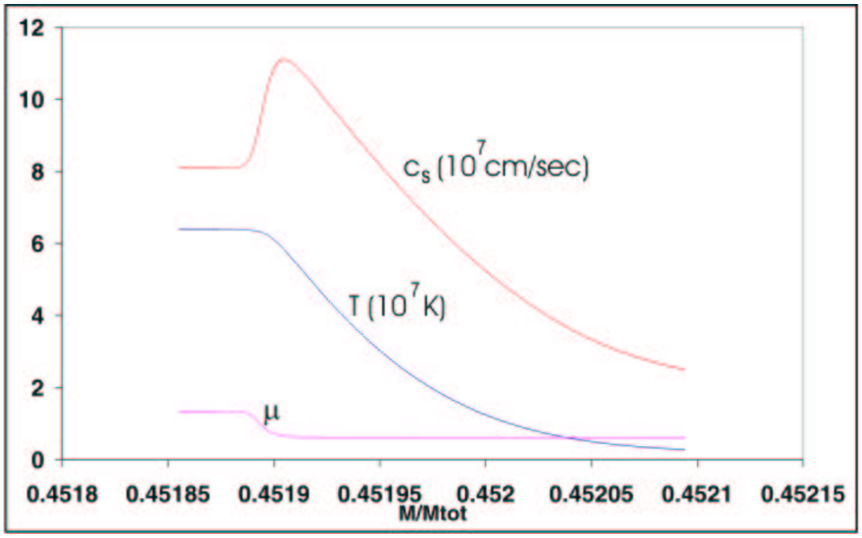

Fig. 3. Values of some relevant parameters over the mixed region in step 2 of Table 4

In efficient CBP circulation (Figure 2), in order to fulfill the envelope abundance requirements (Nollett et al. 2003), the mixing process must reach down to zones at a temperature $Log\ T_P$ = 7.70, with a mass circulation of about 10^{-6} $M_{\odot}$/yr. CBP occurs in the interpulse stages, lasting for a few $\times 10^4$yr. In the model discussed here the total thermally-pulsing phase lasts for 10^6 yr, split in several similar interpulse periods.

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). Adopting the simple formulation discussed in the previous section we find the following results.

Case A. Values of the magnetic field strength lower than B $\simeq 10^2$ G are found at the convective envelope base. They must reach up to several units $\times$ 10^4 G in the innermost zones where the tubes form. An example of these findings is presented in Table 4(upper panel), where the required magnetic fields, and the values of the diffusion coefficient, are shown for two representative moments along the thermally-pulsing AGB stage of a 2 $M_{\odot}$ star; these time steps were considered previously for CBP calculations (Wasserburg et al. 2006).

Case B. Values higher by a factor of 20−30 are instead necessary at CBP bottom, if the fields have to appear at the surface. This is summarized in Table 4(lower panel) for the same two zones considered before. Note that the diffusion coefficient (a local parameter depending only on conditions for mass transfer across the envelope border) are same as in case A.

The above numbers must be compared with known situations in stars. In particular, let's remember that in the Sun (a Main Sequence star) the most active regions of the magnetic structures do reach 10^4 G, and values of a few 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 requirements of case B more reasonable, so that this condition appears in this moment as the more realistic one. We are now trying to devise an independent formulation based on the dynamics of the magnetized material to arrive at more firm conclusions about the field strengths.

As a final comment, consider the values of the relevant parameters c_s (sound speed, here

Table 2
Parameters of interest for magnetic mixing on the AGB:
M=2M$_\odot$, Z=Z$_\odot$

Stage	Time (Myr)	B_i (Gauss)	B_c (Gauss)	D_{mix} (cm^2/s)	$\log T_P$ (K)
Case A 1 ...	141.7645	3.31 10^4	63	0.2468D+11	7.66080
Case A 2 ...	142.6398	6.96 10^4	84	0.1714D+11	7.68970
Case B 1 ...	141.7645	1.15 10^6	7.3 10^3	0.2468D+11	7.66080
Case B 2 ...	142.6398	1.14 10^6	1.1 10^3	0.1714D+11	7.68970

Notes:"Time" is in million 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; D_{mix} is the diffusion coefficient (Nollett et al. 2003). Log T_P is highest temperature in the mixed zone. The first panel shows the case where fields are disrupted at the envelope base, the second is for fields reaching the surface with the observed strengths (Herpin et al. 2006)

assumed equal to the micro-turbulence velocity V_T), T (temperature) and μ (mean molecular weight). For phase 2 in Table 4, 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 inward 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 conclusions of this exercise require now to be verified by a more complete MHD treatment of the advanced stages of LMS evolution.

Acknowledgements. We acknowledge financial support by MIUR through the contract PRIN2006-022731.

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