Mem. S.A.It. Vol. 75, 648

Memorie della

Can extended mixing in red giants be attributed to magnetic mechanisms?

M. Busso[1], M. C. Nucci[2], A. Chieffi[3], O. Straniero[4]

[1] Dipartimento di Fisica, Universitá di Perugia, via A. Pascoli, 06123 Perugia, Italy; e-mail: busso@fisica.unipg.it
[2] Dipartimento di Matematica, Universit'a di Perugia, via A. Pascoli, 06123 Perugia. Italy; e-mail: nucci@unipg.it
[3] INAF-IASF, Via Fosso del Cavaliere, Rome, Italy; e-mail: achieffi@iasf.rm.cnr.it
[4] INAF-Osservatorio di Collurania-Teramo, Italy; e-mail: straniero@te.astro.it

Abstract. This work presents estimates of the effects that magnetic fields might have on non-convective mixing phenomena in red giants of low mass. We discuss recent doubts on the effectiveness of purely rotationally-induced mixing and an alternative idea is illustrated, according to which kink modes of buoyant, toroidal magnetic flux tubes might guarantee matter circulation. This occurs not through downward motions from the envelope (as assumed so far), but through different buoyancy efficiencies of tubes born at different depths in the radiative zone, carrying upward material exposed to partial H burning. We adopt a simple formalism to estimate the strength of the magnetic fields necessary to guarantee cool bottom processes and the formation of the neutron source ^{13}C , which drives slow neutron captures in AGB stars. Our rough estimates do not allow final conclusions, but we find that the required magnetic field strengths are in the range foreseen for the stages and zones of interest. This tells us that the mechanisms here indicated are worth the (considerable) effort of a full MHD treatment. For the moment, magnetic fields are to be seen as a promising possibility for solving the mystery of red giant mixing.

Key words. Stars: evolution – Stars: rotation – Magnetic fields – Stars: mixing – Stars: Low Mass

1. Introduction

After the Main Sequence, low mass stars (LMS: objects below, say, M = 2 $M_{\odot}$) share with more massive objects (up to 7-8 $M_{\odot}$, hereafter Intermediate Mass Stars, or IMS) the property of evolving to the Red Giant phase and then of terminating their evolution through the so-called Asymptotic Giant Branch (AGB) stage (Busso et al. 1999), in which they lose mass efficiently thanks to stellar winds powered by radial pulsations and radiation pressure on dust grains (Habing et al. 1994). After this stage, LMS and IMS envelopes generate planetary nebulae, while their degenerate cores start blue-ward paths, which ultimately give birth to

Send offprint requests to: M. Busso
Correspondence to: M. Busso, Dipartimento di Fisica, Universitá di Perugia, via A. Pascoli, 06123 Perugia

white dwarfs. Stars of this type represent a fundamental component of the baryonic mass of galaxies and provide us with invaluable information on the physical and chemical evolution of the universe.

Unlike for IMS, observations of evolved stars below around 2 $M_\odot$ reveal the existence of fundamental problems in canonical stellar modelling, as the isotopic mix of light and intermediate-mass elements (up to oxygen at least) cannot be accounted for by convective mixing in the first dredge-up and in the third dredge-up (Straniero et al. 1997). Unexpected chemical anomalies are found above the so-called *luminosity bump* of the red giant branch (Charbonnel 2004) and more anomalies appear in the subsequent AGB phase (Boothroyd et al. 1994). The problem has emerged from data accumulated over a long time, at least since the early nineties (Gilroy & Brown 1991). It was subsequently confirmed to affect various elements between lithium and oxygen (Pilachowsky et al. 1993; Gratton et al. 2000). Excellent reviews of these phenomena exist (Kraft 1994; Charbonnel 2004).

Other isotopic anomalies and anti-correlations, affecting higher mass elements up to Mg in low metallicity (hence low mass) stars, have subsequently been discovered to be present already on the Main Sequence (Gratton et al. 2001). In fact, they are not related to phenomena typical of evolved stars (Charbonnel 2004)

Slow non-convective circulation of material exposed to partial H burning has been usually assumed to explain the above mentioned evidence (Charbonnel 2004). Meanwhile, new indications of the existence of slow mixing mechanisms in red giants has emerged for AGB atmospheres, e.g. high ^{26}Al/^{27}Al ratios, which can be inferred from presolar grains of AGB origin recovered in meteorites (Amari et al. 2001; Nollett et al. 2003).

We also know that some form of non-convective mixing, maybe a diffusion, must occur below the limit of purely convective dredge-up after the thermal pulses of the He-shell, in the He- and C-rich layers (Iben & Renzini 1982; Herwig et al. 2003). This must be so because the present understanding of the slow neutron captures (Gallino et al. 1998), which produce the heavy ($A \geq 60$) nuclei observed in AGB photospheres (Smith & Lambert 1990; Abia et al. 2002; Busso et al. 2001) tells us that the neutrons must be released as a consequence of α-captures on ^{13}C in the intershell region. There, ^{13}C with the required concentration can only exist if it is produced locally from proton captures on the abundant ^{12}C (Gallino et al. 1988). This scenario therefore requires the existence of proton flows below the convective envelope at dredge-up.

Among the processes invoked to explain the above mentioned mixing phenomena, the shear and the meridional circulation induced by rotation have been the most popular ones for a long time (Zahn 1992; Denissenkov et al. 1998; Weiss et al. 2000). Despite minor formal differences in the various approaches, all the models consider the chemical mixing (and the associated angular momentum transport) as occurring under the form of a diffusion process and introduce some sort of parameterization to fix the value of the diffusion coefficient (Denissenkov & Tout 2000). This mechanism has also been very common in modelling massive, radiatively stratified stars (Meynet et al. 2004). In low mass stars, the basic reason for this approach is that the expected internal structure of a red giant 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 (induced by Eddington-Sweet effects), and the differential rotation of the convective envelope.

Very recently, however, the idea of a purely rotational mixing has met with strong difficulties, encountered when the mechanism is studied not as a post-process, but directly inside stellar models (Charbonnel 2004). The star counter-reacts with structural and energetic changes such that isotopic anomalies at the surface virtually disappear (Palacios et al. 2003). The above authors then make the hypothesis that the meridional circulation is enforced by a specific phenomenon occurring after the RGB bump, i.e. Li-burning in a flash. This suggestion still waits for an independent confirmation, and moreover it offers only a local explanation good for this specific evolutionary stage. The appealing idea that rotation can account for all the mixing phenomena required in low mass stars seems now to fade away. Similar difficulties with purely mechanical mixing are encountered for the formation of the ^{13}C reservoir (often called the ^{13}C *pocket*), which is necessary to produce the *s*-elements in He-burning layers. In recent computations that couple diffusion and burning for AGB stars it was found (Goriely & Siess 2004) that contamination of the burning layers with the neutron poison ^{14}N strongly inhibits neutron-captures on heavy seeds, so that diffusive mixing alone seems not to be effective in producing the required conditions for the *s*-process.

2. Magnetic fields and their effects

As stars are systems of rotating charged particles, they naturally develop poloidal magnetic fields. When rotation is differential, the already mentioned meridional circulation represents a new current, organized with a different geometry, and suitable to ensure a dynamo mechanism. The dynamo is enforced especially when convective motions exist, which couple with rotation providing a long-lasting system of currents with strong orthogonal components. Through these ingredients the magnetic cycles of active stars (including the Sun) are born: here the Lorentz force allows the dynamo to generate a toroidal field from the poloidal one, and vice versa.

Magnetic effects in stars have been recently shown to offer mixing opportunities with effects that are orders-of-magnitude larger than in the case of pure rotation of non-magnetized matter (Maeder & Meynet 2004). Their inclusion in stellar models will probably make the controversies on rotational mixing look purely academic.

The magnetohydrodynamics (MHD) of magnetized stars has been an active research field since the sixties (Parker 1964; Tayler 1973). The conclusions indicate that, when in the induction equation of the dynamo:

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

one can neglect the second, diffusive term (i.e. in the 'frozen field' approximation) the toroidal field can be seen as an envelope of flux tubes centered on the polar axis. Their dynamics is characterized by a global buoyancy, due to the presence, in the tubes, of a magnetic pressure $B^2/8\pi$ in addition to the thermal one (Parker 1964, 1974). Moreover, their simplest vibrational properties include modes of 'kink' and 'pinch' type (Spruit 1999).

While in large radiative structures (e.g. massive stars) kink modes are inefficient, being limited to a small scale by the stratification of molecular weight (Spruit 2002; Meynet et al. 2004), we can speculate that in the thin radiative layers below the convective envelopes of LMS kink modes might survive long enough to allow a local circulation of material between the radiative and the convective zone. If the buoyant amplification of kink modes can guarantee that matter exposed to partial proton captures reaches the border of convection, then the combined effect of the usual border instabilities of the Kelvin-Helmoltz and Rayleigh-Taylor types will allow the material to be effectively mixed into the convective layers and hence to reach the surface, thus favoring the appearance of photospheric isotopic anomalies.

3. Two exercises: cool bottom processes and the ^{13}C pocket

In order to give a zero-order approximation to what amplified magnetic kink modes can do in the layers immediately below the envelope of a red giant, let's consider an AGB star in the two crucial stages of: i) pure shell-H burning (interpulse), where cool bottom processes (CBP) have been suggested to occur (Nollett et al 2003); and ii) third dredge-up, where downflows of protons have been assumed to explain the formation of the ^{13}C neutron source (Busso et al. 1999, 2001).

We can attack the problem by answering two basic questions. i) How deep must a flux tube be born in the radiative layers, to reach the convective zone in the maximum interval of time available? ii) How much mass can circulate? 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.

In order to estimate the relevant parameters we can take advantage of the wide literature available from solar physics. To make things as simple as possible, we take the extension of the 'mixed layer' as the length over which phase mixing would dissipate the kink instabilities, damping the modes (Vishniac 1995a,b). From the same approach, we estimate the (maximum) allowed mass circulation as the amount of mass that can be dissipated locally by turbulence, once the convective layers have been reached. The relevant formulae are again taken from Vishniac's work:

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

and

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

Here $\Omega_A = B/((4\pi\rho)^{1/2} R_*)$ is the Alfvén pulsation over the stellar radius; $q_A = 1/(\Omega_A \Delta t_A)$; 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 quoted works (Vishniac 1995a,b). We take the turbulent velocity to be equal to the convective velocity near the base of the convective envelope (not really *at* the formal base, because here this velocity, which depends on the difference between the actual thermal gradient and the adiabatic one, goes to zero). The magnetic field is then easily estimated (Gross 1978).

We now have to compute the mass circulation induced by magnetic modes, to see if it is sufficient to account for CBP and the formation of the ^{13}C source. This can be done by estimating the parameters depending on the thermodynamical variables T, P, ρ from the actual stellar structure provided by stellar models. Figures 1 and 2 show two such structures, in advanced stages of evolution of an AGB star of 2 M$_\odot$ (Straniero et al. 1997).

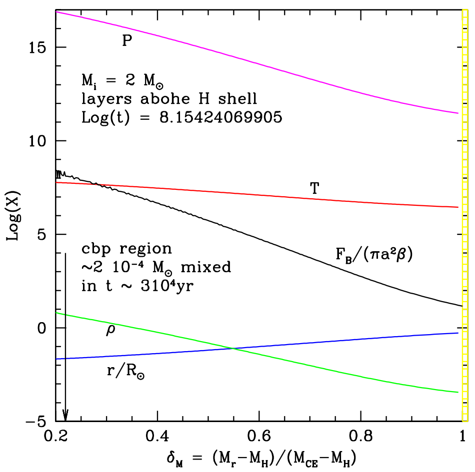

Fig. 1. Structure of a 2 M$_\odot$star in the layers below the convective envelope (which is the shaded region) when the H shell is active in an advanced interpulse phase. The arrow shows the mixing depth necessary to ensure a CBP efficient enough to explain the oxygen isotopic anomalies of presolar grains and the ^{26}Al production (Nollett et al. 2003). Also shown is the necessary strength of the magnetic force

4. Results and Conclusions

In the two cases of Figures 1 and 2 we need to account for the following conditions, necessary to activate efficently CBP and the ^{13}C pocket:

i) CBP case: the extension of the mixed layer must be such (Nollett et al. 2003) that the innermost zones reached have a temperature near log T = 7.75, with a mass circulation of about 10^{-6} M$_\odot$/yr (in a time interval of about 3×10^4yr, during which the H-shell is active).

ii) ^{13}C pocket case: the extension of the mixed layer must be such that a total mass of 10^{-3} M$_\odot$ is covered in about 100yr, so that about 5×10^{-6} M$_\odot$ of ^{13}C can be formed (Gallino et al. 1998).

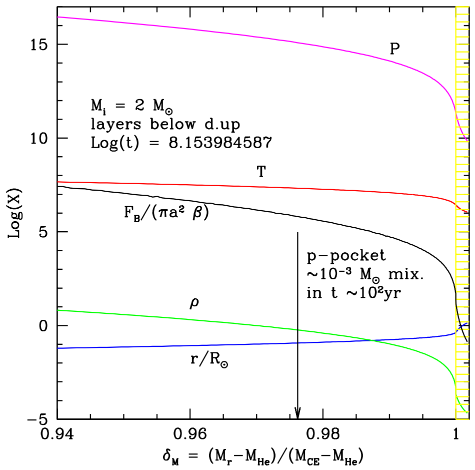

Fig. 2. Structure of a 2 $M_\odot$star in the layers below the convective envelope (which is the shaded region) when the third dredge-up reaches its maximum penetration. The arrow shows the mixing depth necessary to ensure a ^{13}C pocket large enough to yield the concentration of neutrons generally defined as 'ST' (Gallino et al. 1998). Also shown is the necessary strength of the magnetic force

The magnetic forces needed to obtain such results are shown in Figures 1 and 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). The corresponding values of the magnetic fields are:

i) for CBP: B $\simeq 10^4$ G at the convective envelope base; B $\simeq 1.5\times 10^6$ G in the lowermost layers from which the tubes must come.

ii) for the ^{13}C pocket: B $\simeq 3\times10^7$G at the convective envelope base; B $\simeq 3.1\times 10^8$ in the lowermost layers from which the tubes must come.

The above numbers can be compared with known situations in stars.

For the first case, let's remember that the most active regions of the solar magnetic structures do reach 10^4 G, and values considerably in excess of 10^5 G are inferred for the radiative layers (Mestel 1999); this makes the requirements for CBP quite 'normal', and suggests that magnetic fields might indeed be the cause of such a kind of mixing.

For the second case, the numbers found are much larger, due to the strong pressure barrier that has to be overcome (see figure 2). However, in this case we reach zones deep in the core, where rotation is stronger and most probably rigid-body like, so that huge fields would not be a surprise. Moreover, it is known that white dwarfs (born shortly after the stages we consider and from the *same* H-poor cores relevant here) do have very large magnetic fields, in excess of 10^8 G. Hence, also in this case, the values of B required for generating the mixing appear quite reasonable.

The conclusion of these simple-minded exercises is therefore that magnetic fields as those expected in the regions and in the evolutionary stages interested by the studied mixing phenomena do have the capability of providing a suitable engine for driving the required mass circulation, and would mimic a diffusion process from the envelope.

The full verification of the idea presented here must then follow, within a complete MHD treatment of the advanced stages of LMS evolution.

References

Abia C., Domínguez I., Gallino R., Busso M., Masera S., Straniero O., de Laverny P., Plez B., Isern J., 2002, ApJ, 579, 817
Amari S., Nittler L. R., Zinner E., Gallino R., Lugaro M., Lewis R. S., 2001, ApJ, 546, 248
Boothroyd A. I., Sackmann I. -J., Wasserburg G. J., 1994, ApJ, 430, L77
Busso M., Gallino R., Wasserburg G. J., 1999, ARAA, 37, 239
Busso M., Gallino R., Lambert D. L., Travaglio C., Smith V. 2001, ApJ, 557, 802
Charbonnel C., 2004, in Origin and Evolution of the elements, ed. A. McWilliams and M. Rauch, (Pasadena: Carnegie Observatories)
Denissenkov P. A., Da Costa G. S., Norris J. E., Weiss A., 1998, A&A, 333, 926
Denissenkov P. A., Tout C. A, 2000, MNRAS, 316, 395

Gallino R., Busso M., Picchio G., Raiteri C. M., Renzini A, 1988, ApJ, 334, L45
Gallino R., Arlandini C., Busso M., Lugaro M., Travaglio C., Straniero O., Chieffi A., Limongi M., 1998, ApJ, 497, 388
Gilroy K. K., Brown J. A., 1991, ApJ, 371, 578
Goriely S., Siess L., 2004, A&A, 421, L25
Gratton R. G., Carretta E., Matteucci F., Sneden C., 2000, A&A, 358, 671
Gratton R. G., Bonifacio P., Bragaglia A., Carretta E., Castellani V., Centurion M., Chieffi A., et al., 2001, A&A, 369, 87
Gross P. G., 1978, in IAU Symp 80, The HR Diagram, (Dordrecht: Reidel), 323
Habing H., Tignon J., Thielens A. G. G. M, 1994, A&A 286, 523
Herwig F., Langer N., Lugaro M., 2003, ApJ, 593, 1056
Iben I. Jr, Renzini A., 1982, ApJ, 263, L23
Kraft R. P., 1994, PASP, 106, 553
Maeder A., Meynet G., 2004, A&A, 417, 235
Mestel L., 1999, Stellar Magnetism. Oxford: Oxford Univ. Press.
Meynet G., Maeder A., Mowlavi N., 2004, A&A, 416, 1023
Nollett K. M., Busso M., Wasserburg G. J., 2003, ApJ 582, 1036
Palacios A., Talon S., Charbonnel C., Forestini M., 2003, A&A, 399, 603
Parker E. N., 1964, ApJ, 139, 208
Parker E. N., 1974, Ap. Sp. Sci, 31, 261
Pilachowski C. A., Sneden C., Booth J., 1993, ApJ, 407, 699
Smith V. V., Lambert D. L., 1990, ApJ Suppl., 72, 387
Spruit H. C., 1999, A&A, 349, 189
Spruit H. C., 2002, A&A, 381, 923
Straniero O., Chieffi A., Limongi M., Busso M., et al. 1997, ApJ, 478, 332
Tayler R. J., 1973, MNRAS, 163, 77
Vishniac E. T., 1995a, ApJ, 446, 724
Vishniac E. T., 1995b, ApJ, 451, 816
Weiss A., Denissenkov P. A., Charbonnel C., 2000, A&A, 356, 181
Zahn J. -P., 1992, A&A, 265, 115