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SPECTROSCOPIC AND ASTEROSEISMIC DIAGNOSTICS ON MIXING PROCESSES INSIDE RED GIANT STARS

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Abstract. The availability of asteroseismic constraints for a large sample of stars from CoRoT and *Kepler* paves the way for various statistical studies of the seismic properties of stellar populations, and becomes a powerful tool to better understand stellar structure and evolution. I will present predictions of stellar models computed with the code STAREVOL including thermohaline mixing together with rotational mixing. I will briefly present a comparison between our theoretical predictions and spectroscopic observations, and discuss why asteroseismic diagnostics are relevant in this context.

Keywords: Stars: evolution, stars: interiror, stars: rotation, instabilities, hydrodynamics

1 Introduction

The standard theory of stellar evolution predicts that during the first dredge-up (Iben 1967) the chemical composition of the stellar surface is modified when the deepening convective envelope mixes the external layers with hydrogen-processed material. Dilution then changes the surface abundances of helium-3, beryllium, boron, carbon, nitrogen, and in some cases sodium (e.g. Charbonnel 1994). Standard models predicts no variation of chemical composition at the surface of red giants between the first dredge-up and the RGB tip. However, numerous spectroscopic observations (e.g. Smiljanic et al. 2009; Tautvaišienė et al. 2013) show a clear signatures of "extra mixing" on the upper red giant branch (RGB) in low-mass stars, which modifies the surface composition. On the other hand, asteroseismology has emerged during the last decade as a powerful tool to investigate the internal structure of stars, and more particularly of red giant stars (Chaplin & Miglio 2013).

2 STAREVOL : Stellar evolution code

2.1 Physical inputs

The models are computed with the lagrangian implicit stellar evolution code STAREVOL (v3.00, see Siess et al. 2000; Palacios et al. 2003, 2006; Decressin et al. 2009; Lagarde et al. 2012). In the lagrangain description, the equations of stellar internal structure are written with two independent variables, a temporal one t, and a spatial one m_r which represents the mass of a fluid element. With this description we can write equations to describe the stellar structure as follow :

- Mass conservation:

$$\frac{dr}{dm_r} = \frac{1}{4\pi r^2 \rho} \tag{2.1}$$

- Energy conservation:

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{nuc} - \epsilon_{\nu} + \epsilon_{grav} \tag{2.2}$$

  where ϵ_{nuc}, ϵ_{ν}, and ϵ_{grav} are the energies produced by the nuclear reactions, lost by neutrinos, and due to gravitational heating, respectively.

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- Conservation of motion

$$\frac{\partial u}{\partial t} = -\left(4\pi r^2 \frac{\partial P}{\partial m_r} + \frac{Gm_r}{r^2}\right), \tag{2.3}$$

where P is the pressure given by the equation of state, and $u = \frac{\partial r}{\partial t}$.

- Heat transport

$$\frac{dT}{dm_r} = \frac{1}{\pi r^2}\left(g + \frac{du}{dt}\right)\frac{T}{P}\nabla, \tag{2.4}$$

where $\nabla = \frac{\partial lnT}{\partial lnP}$ corresponds to $\nabla_{\rm rad} = \frac{3}{16\pi acG}\frac{\kappa L_r P}{m_r T^4}$ and to $\nabla_{\rm conv}$ in radiative and convective zones respectively.

- Chemical species transport:

$$\left(\frac{dY_i}{dt}\right) = \left(\frac{\partial Y_i}{\partial t}\right)_{nuc} + \frac{\partial}{\partial m_r}\left[(4\pi r^2\rho)^2 \mathcal{D}\frac{\partial Y_i}{\partial m_r}\right] \tag{2.5}$$

where T is the temperature, ρ the density, L_r the luminosity, r the radius of the fluid, Y_i represents the abundance of species i, and $\mathcal{D}$ the diffusion coefficient.

The physical ingredients used to solve this system of equations, such as nuclear reaction rates, opacities, equation of state, the treatment of convection and atmosphere, are presented in details in Lagarde et al. (2012).

2.2 *Transport processes in radiative zones*

To follow the effects of transport processes on the evolution of chemical species, we have to introduce the corresponding diffusion coefficient $\mathcal{D}$ in equation 2.5. In STAREVOL, different transport processes of chemical species can be considered: e.g. overshooting, semi-convection, atomic diffusion, transport by gravity waves (see Decressin et al. in this volume), thermohaline instability, and rotation-induced mixing ; as well as the transport of angular momentum (Palacios et al. 2006).

2.2.1 Rotation-induced mixing

For the treatment of rotation-induced mixing, we use the complete formalism developed by Zahn (1992) and Maeder & Zahn (1998), that takes into account advection by meridional circulation and diffusion by the shear turbulence (for a decryption of the implementation in STAREVOL, see Palacios et al. (2003, 2006); Decressin et al. (2009)). The transport of chemicals resulting from meridional circulation and both horizontal and vertical turbulence is computed as a diffusive process throughout evolution.

2.2.2 Thermohaline mixing

When the density of a fluid depends on variation of two components, a stably stratified system can undergo instability leading to significant vertical transport corresponding to thermohaline instability. It is a mixing process that corresponds to a double diffusive instability. Indeed, this instability evolves with two components, one of which is the stabilizing one (temperature), that diffuses faster than the other, whose stratification is unstable.

Thermohaline mixing develops along the red giant branch at the bump luminosity in low-mass stars and on the early-AGB in intermediate-mass stars, when the gradient of molecular weight becomes negative ($\nabla_\mu = \frac{d\ln\mu}{d\ln P} < 0$) in the external wing of the thin hydrogen-burning shell surrounding the degenerate stellar core (Charbonnel & Zahn 2007b,a; Siess 2009; Stancliffe et al. 2009; Charbonnel & Lagarde 2010). This inversion of molecular weight is created by the ^{3}He(^{3}He, 2p)^{4}He reaction (Ulrich 1971; Eggleton et al. 2006, 2008).

We use the prescription advocated by Charbonnel & Zahn (2007a); Charbonnel & Lagarde (2010). It is based on Ulrich (1972) with an aspect ratio (length/width) of instability fingers α =5, in agreement with laboratory experiments (Krishnamurti 2003). It includes the correction for non-perfect gas (Kippenhahn et al. 1980) in the diffusion coefficient for thermohaline mixing that is given by:

$$\mathcal{D}_{th} = \mathcal{C}_T K_T \frac{\varphi}{\delta} \frac{-\nabla_\mu}{\nabla_{ad} - \nabla} \tag{2.6}$$

where K is the thermal diffusivity; $\varphi = (\partial ln\rho/\partial ln\mu)_{P,T}$; $\delta = -(\partial ln\rho/\partial ln\mu)_{P,\mu}$; and with the non-dimentional coefficient $\mathcal{C}_{\rm t}$=$\frac{8\pi^2}{3}\alpha^2$.

The value of α in actual stellar conditions was recently questionned by the results of two- and three-dimentional hydrodynamical simulations of thermohaline convection for which α is close to unity (Denissenkov 2010; Denissenkov & Merryfield 2011; Rosenblum et al. 2011; Traxler et al. 2011). However, these simulations are still far from the stellar regime, hence we decided to use in the following discussion the prescription described above since it successfully reproduces the abundances data for evolved stars of various masses and metallicities (see Charbonnel & Lagarde 2010; Lagarde et al. 2011, for a more detailed discussion).

3 Theoretical predictions

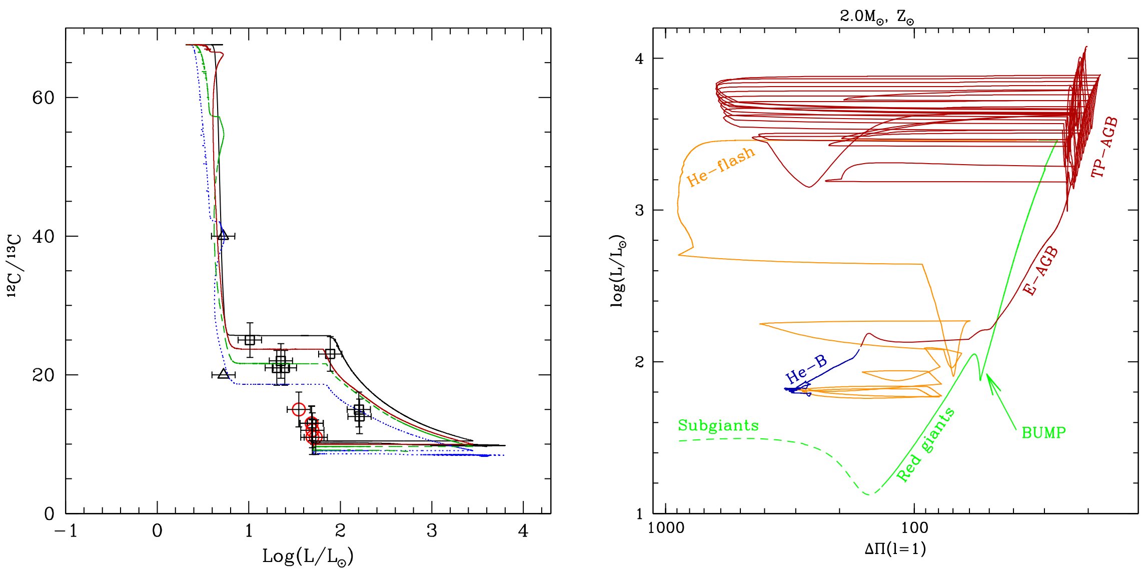

Fig. 1. *left panel: figure from Charbonnel & Lagarde (2010).* Evolution of ^{12}C/^{13}C value as a function of stellar luminosity for the 1.25 M$_\odot$ models including thermohaline instability and rotation-induced mixing (for initial rotation velocities of 50, 80, and 110 km.s^{-1} shown as solid red, dashed green, and dotted blue lines respectively). The black solid line represents the non rotating case. Spectroscopic observations along the evolutionary sequence of the open cluster M67 (Gilroy & Brown 1991) are represented by black triangles which only a lower value could be obtained, black squares, and red circles, for sub giants, RGB and clump stars respectively. *Right panel: figure from Lagarde et al. (2012).*The stellar luminosity as a function of the asymptotic period spacing of g-modes for the standard 2.0 M$_\odot$ model at solar metallicity. Evolutionary phases are color-labeled: sub giant (green dashed), helium-flash episodee (orange), helium-burning (blue), and asymptotic giant branch (red).

3.1 Spectroscopic properties

Rotation-induced mixing has an impact on the internal abundance profiles during the main sequence, although its signature are revealed only later in the evolution when the first dredge-up occurs on the sub giant branch (e.g. Palacios et al. 2003; Smiljanic et al. 2010; Charbonnel & Lagarde 2010). Indeed, when rotation-induced mixing is accounted for, the post-dredge-up value^{12}C/^{13}C ratio, for example, is lower than in non-rotating case (see left panel of Fig. 1). Figure 1 displays observations of ^{12}C/^{13}C ratio in stars of open cluster M67 (M$_{TO}$ =1.2M$_\odot$) from Gilroy & Brown (1991), compared with theoretical prediction of our 1.25M$_\odot$ models computed with three different initial velocities, and including thermohaline mixing. The dispersion for stars that have not yet reached the bump luminosity (log (L/L$_\odot$)$_{\rm bump}$ ∼2.2) reflects only the dispersion in initial rotation velocity.

On the other hand, thermohaline instability occurs at the bump luminosity by inversion of gradient molecular weight. Contrary to standard predictions, models including thermohaline mixing leads to decrease the carbon isotopic ratio (see Fig 1) at the BUMP luminosity, and then reproduce very well the low value of $^{12}C/^{13}C$ in evolved stars (i.e., red giants brighter than the BUMP luminosity, and clump stars).

3.2 Asteroseismic diagnostics

Asteroseismic observations with CoRoT and *Kepler* pave the way for various statistical studies of seismic properties of stellar populations. In Lagarde et al. (2012), we have evaluated the impact of thermohaline mixing and rotation-induced mixing using our new stellar evolution models, on global asteroseismic quantities as large separation, acoustic radii, and period spacing of g-modes. We showed a net signature of rotation-induced mixing on the global asteroseismic parameters. Thermohaline instability cannot be characterized by these asteroseismic parameters, although it can be identified by its effects on spectroscopic studies. The right panel of Fig. 1 presents the asymptotic period spacing of gravity modes $\Delta\Pi(l = 1)$ for standard model of 2.0 $M_\odot$ at solar metallicity. This quantity allows us to distinguish two stars that have the same luminosity, one being at the RGB bump and the other one being at the clump undergooing He burning (e.g. Bedding et al. 2011). $\Delta\Pi(l = 1)$ is larger in clump stars compared to in RGB stars, because of the differences in the stellar structure, and the presence of convective core affecting the domain where the g-modes are trapped (Montalbán et al. 2013). Asteroseismic parameters help us to establish the evolutionary stages, as well as its radius, and mass (e.g. Kallinger et al. 2010). The large number of evolved stars observed by CoRoT and *Kepler* will allow us to run detailed comparisons between models predictions and observations, which were so far limited to giants in clusters.

Moreover, thanks to asteroseismology, we can now determine the internal rotation profile of giant stars (Deheuvels et al. 2012; Beck et al. 2012; Mosser et al. 2012), and then in the future better test models of transport of angular momentum (Eggenberger et al. 2012; Ceillier et al. 2013).

Asteroseismic studies represent a very useful tool to understand structure and evolution of giant stars, and to better constrain the physics of different transport processes as rotation-induced mixing. Moreover, these observations sampling in different regions of the Galaxy, promises to improve our understanding on the Milky Way's constituents. To exploit all potential of asteroseismic data from CoRoT and *Kepler* missions, it would be crucial to combine them with spectroscopic constraints (APOGEE and GAIA surveys).

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