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HYDRODYNAMICAL INSTABILITIES INDUCED BY ATOMIC DIFFUSION IN F AND A STARS : IMPACT ON THE OPACITY PROFILE AND ASTEROSEIMIC AGE DETERMINATION

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Abstract. Atomic diffusion, including the effect of radiative accelerations on individual elements, leads to important variations of the chemical composition inside the stars. The accumulation in specific layers of the elements, which are the main contributors of the local opacity, leads to hydrodynamical instabilities that modify the internal stellar structure and surface abundances. The modification of the initial chemical composition has important effects on the internal stellar mixing and leads to different surface and internal abundances of the elements. These processes also modify the age determination by asteroseismology.

Keywords: stellar evolution, atomic diffusion, instabilities, opacities

1 Introduction

Atomic diffusion is a process which occurs in every star. There are internal gradients inside stars (T, P, ρ, ...) and each chemical element behaves its own way between collisions due to these gradients. The transport of chemical element by atomic diffusion depends on different effects as the one of the concentration gradient, temperature gradient, electric field and the two main processes which are the gravity and the radiative accelerations. The effect of the gravity (or gravitational settling) on the ions of the plasma depends on their atomic masses and the effect of radiative accelerations depends on their atomic structure. All of these selective processes lead to a migration of the elements inside the star to the center or to the surface depending mainly on the predominance of the gravity or of radiative accelerations. This selective motion of elements depends on their ionisation states and the same element may move to the surface in some region of the stars and to the center in others which leads to local accumulations or depletions of the elements. This could also lead to hydrodynamical instabilities as convection. It was first shown by Richard et al. (2001) with the Montreal/Montpellier code (Turcotte et al. 1998) and then the same result was found by Théado et al. (2009) with the Toulouse Geneva Evolution Code (Hui-Bon-Hoa 2008; Théado et al. 2012). This convective zone appears in F and more massive stars when the star is a slow rotator. In these stars, atomic diffusion leads to accumulations of iron and nickel around T=200000K. As the elements accumulate where they are main contributors to the opacity, the local increase of the opacity triggers convection.

An other instability may occur in the case of local accumulation of elements, the so-called *fingering convection*. This instability occurs in the case of a stable temperature gradient and an inverse mean molecular weight gradient. Fingering convection is characterised by the density ratio R_0 which is the ratio between thermal and compositional gradients:

$$R_0 = \frac{\nabla - \nabla_{ad}}{\nabla_\mu}.$$

This instability can only develop if the thermal diffusivity is larger than the molecular one. This means that a heavy blob of fluid falls in the star and keeps falling because heat diffuses more rapidly than the chemical

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elements. Fingering convection cannot occur if the ratio of the diffusivities becomes smaller than ratio of the gradients, which leads to the following condition:

$$1 < R_0 < \frac{1}{\tau}$$

where τ is the inverse Lewis number, ratio of molecular and thermal diffusivity. For values of $R_0 < 1$ the region is dynamically convective (Ledoux criteria) and for values of $R_0 > 1/\tau$ the region is stable. This process was studied by Théado et al. (2009) for F and A type stars but only in the region of the iron/nickel convective zone.

In the following sections we describe the computation of models, then the effect of atomic diffusion on the structure of a 1.7 $M_\odot$ and finally we show the impact on the age determination using asteroseismic data of the 94 Ceti A star.

2 Models computation

All the models are computed using the Toulouse Geneva Evolution Code (TGEC) (Hui-Bon-Hoa 2008; Théado et al. 2012). This code includes the effect of atomic diffusion for several chemical elements (and isotopes) using the Chapman & Cowling equations (Chapman & Cowling 1970). We use the diffusion coefficients derived by Paquette et al. (1986) and the OPAL2001 equation of state (Rogers & Nayfonov 2002). The nuclear reaction rates are from the NACRE compilation (Angulo 1999). We use the OP opacities from the OPCD v3.3 package (Seaton 2005) to compute mean Rosseland opacity at each time step and each mesh point to take into account the local variation of abundances. In this way, the stellar structure is consistently computed all along the evolutionary tracks, as well as the individual radiative accelerations of C, N, O, Ne, Mg, Ca, and Fe. This is done by using the improved semi-analytical prescription (SVP approximation) proposed by LeBlanc & Alecian (2004).

3 Impact on the stellar structure of F and A stars

We computed a 1.7 $M_\odot$ taking into account atomic diffusion (left part of Fig. 1) and adding the effect of fingering convection (right part of Fig. 1). Atomic diffusion alone produces accumulations of iron at the surface, around $\log(\Delta M/M_*) = -6.5$ (region of the iron/nickel convective zone) and around $\log(\Delta M/M_*) = -7.8$ for the calcium (panel *a*). This is due to radiative accelerations which are larger than the gravity in these regions (panel *c*). These accumulations lead to inverse μ-gradients (panel *e*) and to local increases of the opacity because elements accumulate where they are main contributor to the opacity, ie. where the element absorbs most of the photons (panel *g*).

The regions where there are inverse μ-gradients are unstable and lead to fingering convection. The results are presented on the right part of Fig. 1. Fingering convective regions are in light grey. There is one at the bottom of the surface convective zone and one at the bottom of the calcium accumulation region. There is no fingering convection at the bottom of the iron convective zone because of the stabilising helium gradient in this region (see Deal et al. 2016 for more details). These unstable regions modify the abundance profiles and we see an increase of the calcium surface abundance and a decrease of the iron surface abundance. There is also a modification of the internal abundance profiles (panel *b*). If there is a modification of the abundance profile, there is a modification of the opacity profile and we can see panel *h* a global smoothing of the opacity profile due to the reduction of abundance gradients induced by the fingering convection mixing. These results are published in Deal et al. (2016).

4 Asteroseismology

In this section we study the effect of atomic diffusion (including the effect of radiative accelerations) on the age determination using asteroseimology. We use seismic data obtained with HARPS for the 94 Ceti A star. This is a F type star of 1.44 $M_\odot$ in which the effect of radiative accelerations are lower than the previous case (Section 3). We see that there is no effect on iron and a small effect on calcium (Fig. 2). In this case the accumulation of calcium is not large enough to triggers fingering convection.

We determine the age of the 94 Ceti A star using the asteroseimic data and a grid of models taking into account only atomic diffusion without radiative accelerations in a first time. We then did it with a model including radiative accelerations. In this case we obtain an age 4% large and a radius 1% larger when radiative

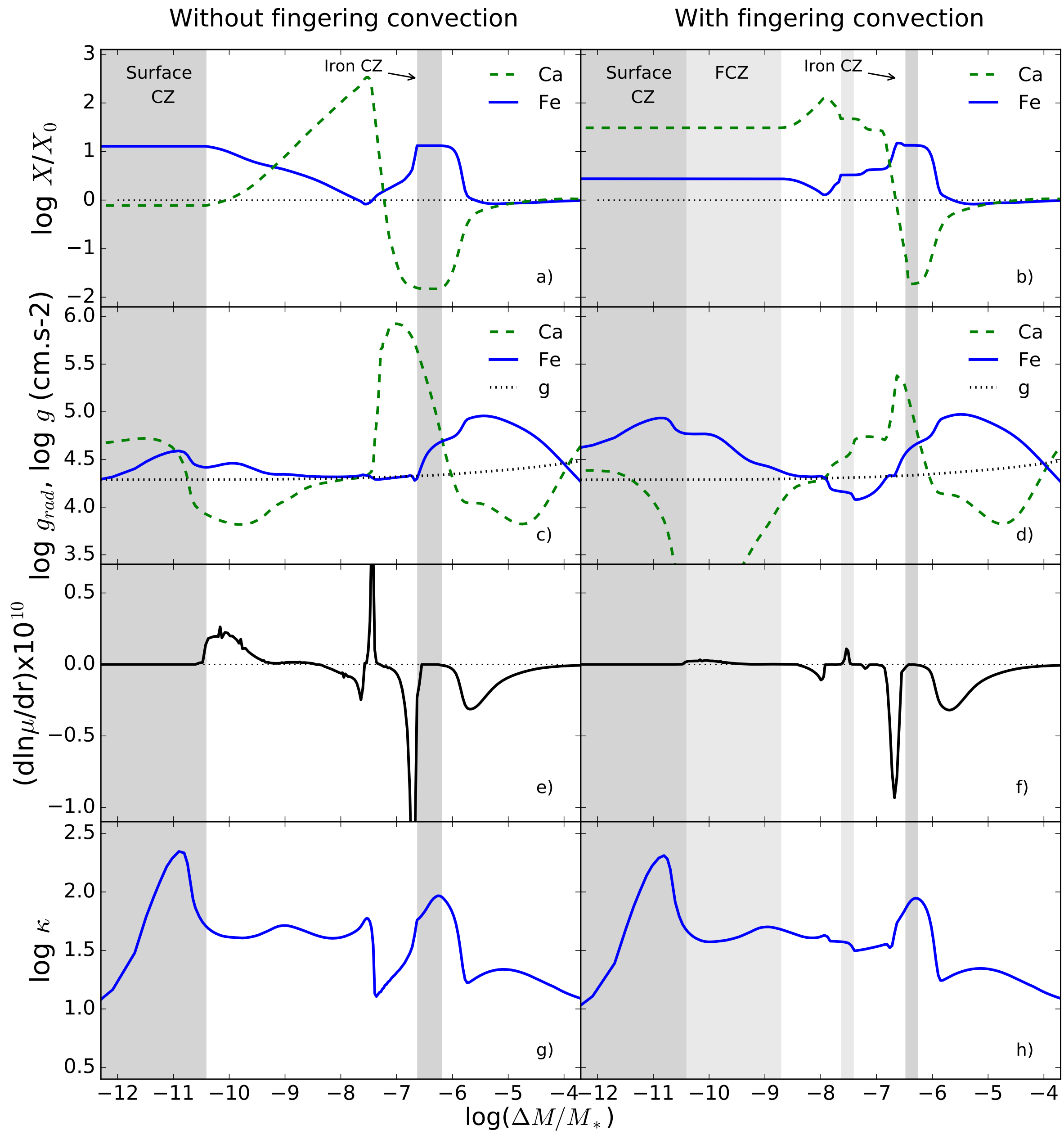

Fig. 1. Profiles of important physical quantities as a function of log($\Delta M/M_*$) in two 1.7 $M_\odot$ models at 100 Myrs with (right panel) and without (left panels) computation of fingering convection. Dynamical(CZ) and fingering (FCZ) convective zones are represented by dark and light grey regions, respectively. Panels *a* and *b* show calcium (green dashed lines) and iron (blue solid lines) abundances compare to their initial value. Panels *c* and *d* show calcium (green dashed lines) and iron (blue solid lines) radiative accelerations. The black dotted line represents the gravity. Panels *e* and *f* show the $\ln \mu$-gradient (black solid lines), panels *g* and *h* show the opacity profile (blue solid lines).

accelerations are taken into account. These differences come from the modification of the size of the surface convective zone which is deeper when element accumulates and when the mean Rosseland opacity increases. See Deal et al. (2017) for more details about this study.

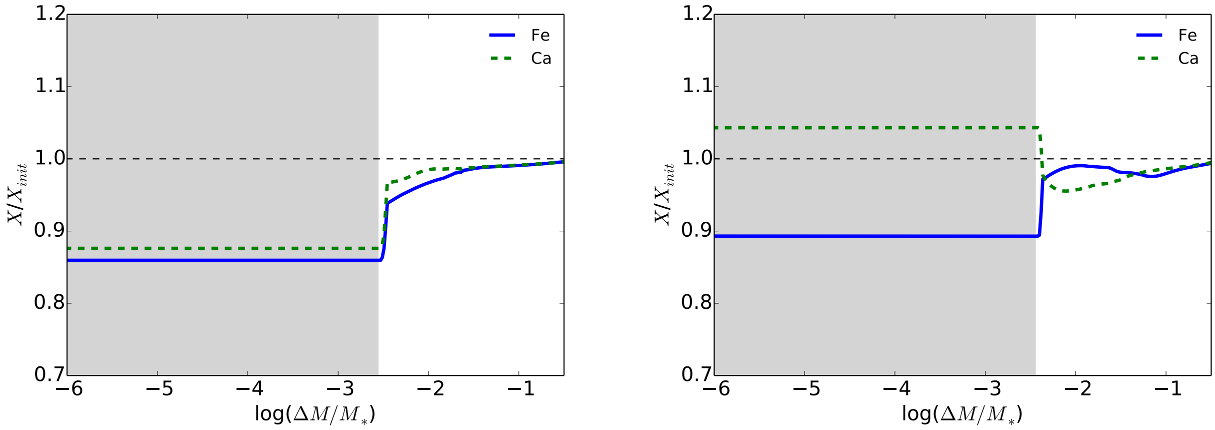

Fig. 2. Abundance profiles of calcium (green dashed lines) and iron (blue solid lines) for the model of 1.44 $M_\odot$ with $Y_{init} = 0.297$ and $Z_{init} = 0.0305$ with gravitational settling only (left panel) and including radiative acceleration (right panel). The dark grey areas represent the surface convective zone.

5 Conclusions

We saw with these two examples that atomic diffusion leads to hydrodynamical instabilities in A type stars and in both cases to a modifications of the structure of the star. This should be taken into account especially if we want to determine precise stellar parameters for the incoming space missions as PLATO and TESS. We will need, for an optimal treatment of the PLATO data, precision up to 10% on the ages, 15% in mass and 2% radius. In the case of 94 Ceti A, where radiative accelerations are not very efficient, we obtain 4% on the age and 1% on the radius which is half the precision needed. We can imagine that this difference in the parameter determination, taken into account radiative accelerations, should be larger for star where the accumulation of elements are larger. It is no longer possible to neglect the effect of atomic diffusion and the induced hydrodynamical instabilities if we want to model correctly the stars we observe with more and more precise instruments.

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