*SF2A 2011*
*G. Alecian, K. Belkacem, R. Samadi and D. Valls-Gabaud (eds)*

# DIFFUSION-INDUCED IRON ACCUMULATIONS AND THERMOHALINE CONVECTION IN A TYPE STARS : ASTEROSEISMIC IMPLICATIONS

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**Abstract.** The radiative acceleration on iron inside stars may lead to an accumulation of this element in stellar internal layers. This iron accumulation may have many important consequences. It may lead to an extra convective zone, and in some cases it may help triggering stellar pulsations. In this framework diffusion induced-iron accumulations are sometimes invoked to reconcile seismic observations and stellar modelling. These accumulations provide a natural answer to the $\kappa$-mechanism boost required to explain the mode excitation in several kind of pulsating stars (e.g. $\beta$ Cephei, SPB, sdB stars). However, the computations which have been done up to now ignore an important effect: the double-diffusive or "thermohaline" convection induced by the inverse $\mu$-gradients. Radiative diffusion and thermohaline convection have been introduced in the Toulouse-Geneva stellar evolution code. We present here stellar models computed in this context. We show how thermohaline convection modifies the iron profiles inside stars, with important consequences for the chemical stratification and the seismic properties of stars.

Keywords: stars:abundances, stars:oscillations, hydrodynamics, convection, asteroseismology

## 1 Introduction

The atomic diffusion theory predicts in A and hotter stars the occurrence of iron peak element accumulations in stellar interiors (Richer et al. 2000; Turcotte et al. 2000; Richard et al. 2001). Such accumulations, due to radiative diffusion effects are expected to take place in particular in the opacity bump region (around 200000K). In this region, the induced opacity increase may lead to local convection and may help triggering stellar oscillations through the iron $\kappa$-mechanism.

Asteroseismic observations support the iron accumulation theory in pulsating A and B type stars. The stability analysis of chemically homogeneous models fails to reproduce seismic observations in $\beta$ Cephei, SPB and sdB stars (cf. Théado et al. 2009, and references therein for a review on this subject). Introducing iron accumulation profiles in the opacity bump region of models drastically improves the agreement between the theoretical and observed frequency spectra : e.g. Pamyatnykh et al. (2004); Bourge & Alecian (2006); Miglio et al. (2007) for the SPB and $\beta$ Cephei stars and Charpinet et al. (1996, 1997); Brassard et al. (2001); Charpinet et al. (2001, 2005, 2006, 2008) for the sdB stars. These diffusion-induced iron accumulations provide a natural explanation to the $\kappa$-mechanism boost required to explain the mode excitation in A and B type stars.

However in all previous computations the question of the stability of the diffusion-induced iron accumulations was not adressed. In this framework a crucial process was ignored: the thermohaline convection.

## 2 The thermohaline instability

The iron accumulation due to radiative diffusion induces a local increase of the molecular weight $\mu$. Metal-rich layers may then overlay regions with smaller molecular weights which results locally in $\mu$-values increasing upward. As discussed in many papers (see Théado & Vauclair 2011, for a review on this subject), this situation

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where a positive $\mu$-gradient builds in a convectively stable region gives rise to a double diffusive instability called thermohaline convection. This instability takes the form of elongated cells called fingers. Since heat diffuses faster than the chemical composition these fingers sink because they grow increasingly heavier than their environment until they become turbulent and dissolve. The induced motions will result in a partial mixing of the stellar material which proceeds until a stable $\mu$-stratification has been restored (i.e. $d\ln\mu/dr \leq 0$).

The effects of thermohaline convection as a mixing process in stars are far from trivial. They are traditionally modelled as a diffusive process. The relevant expression for the diffusion coefficient had long been a matter of debate (Ulrich 1972; Kippenhahn et al. 1980; Charbonnel & Zahn 2007). Recent 2D and 3D numerical simulations of the thermohaline instabilities (Denissenkov 2010; Traxler et al. 2011) seem to converge with similar orders of magnitude for the diffusion coefficient as that of Kippenhahn et al. (1980) (see also Théado & Vauclair 2011, for a detailed discussion about the Denissenkhov et al. and the Traxler et al. coefficients).

In the following, using the Kippenhahn et al. (1980) prescription for the mixing, we show how thermohaline convection may affect the diffusion-induced iron accumulations.

## 3 Computations

Two 1.7 $M_\odot$ models were computed using the Toulouse-Geneva stellar evolution code TGEC (Hui-Bon-Hoa 2008; Théado et al. 2009). In the first model, atomic diffusion including radiative accelerations was introduced, in the second model, the effects of the thermohaline mixing were added. The two models were evolved from the ZAMS up to H core exhaustion.

The two models included the atomic diffusion of H, He, C, N, O, Ca and Fe followed separately. The radiative accelerations were computed following the semi-analytical prescription proposed by Alecian & LeBlanc (2002) and LeBlanc & Alecian (2004). The opacities were computed using the OPCDv3.3 codes and data (Seaton 2005) which allow re-computing in each shell of the model and for each timestep accurate opacities taking into account the modifications of the detailed composition of the stellar material. The initial metal mixture used in the computations was the Grevesse & Noels (1993) one with $X_0 = 0.7112$ and $Y_0 = 0.2714$.

The convective zones were instantaneously homogenized. The HI and HeII convective zones were assumed connected by overshooting. The iron convective zone which may appear in much deeper regions was assumed disconnected from the surface convective envelope because of the large distance between them. The effects of the thermohaline convection were introduced as a diffusion process using the diffusion coefficient proposed by Kippenhahn et al. (1980).

## 4 The thermohaline mixing effects

Figures 1 and 2 present the iron abundance and the molecular weight profiles inside the two models at various evolutionary steps along the main sequence phase. The two models reach the main sequence with chemically homogeneous envelopes. During the stellar evolution, He sinks and creates a stable $\mu$-gradient ($d\ln\mu/dr < 0$) below the convective envelope of the two models, while the radiative diffusion induces an iron accumulation in the iron-peak element opacity bump ($\log \mathrm{T} \simeq 5.2$). This iron enhancement leads to an opacity increase which results in a new convective zone already well developed at 299 Ma (cf. the plateau in the iron- and $\mu$-profiles around $\log T = 5.3$). The models with and without thermohaline mixing are for now similar.

At 403 Ma, the two models (with and without thermohaline mixing) begin to differ. In the model without thermohaline mixing, the iron accumulation drastically increases with time up to a factor 95 at 1388 Ma. In this case the iron convective zone persists during most of the main sequence lifetime. The large iron accumulation leads to large inverse (i.e.positive) $\mu$-gradients, highly unstable.

In the model including thermohaline convection, the $\mu$-gradient is kept close to zero along the main sequence phase. As a result of the induced mixing the iron accumulation in the opacity bump is strongly reduced and never exceeds a factor 15. It is however important to stress that an iron accumulation still occurs. This model does not show a persistent iron convective zone: the opacity bump region undergoes alternatively convective and radiative episodes during the main sequence evolution.

## 5 Discussion-Conclusion

We have investigated the effects of thermohaline convection on diffusion-induced iron accumulations in A type stars. Our computations demonstrate that thermohaline convection drastically reduces the iron enhancement in

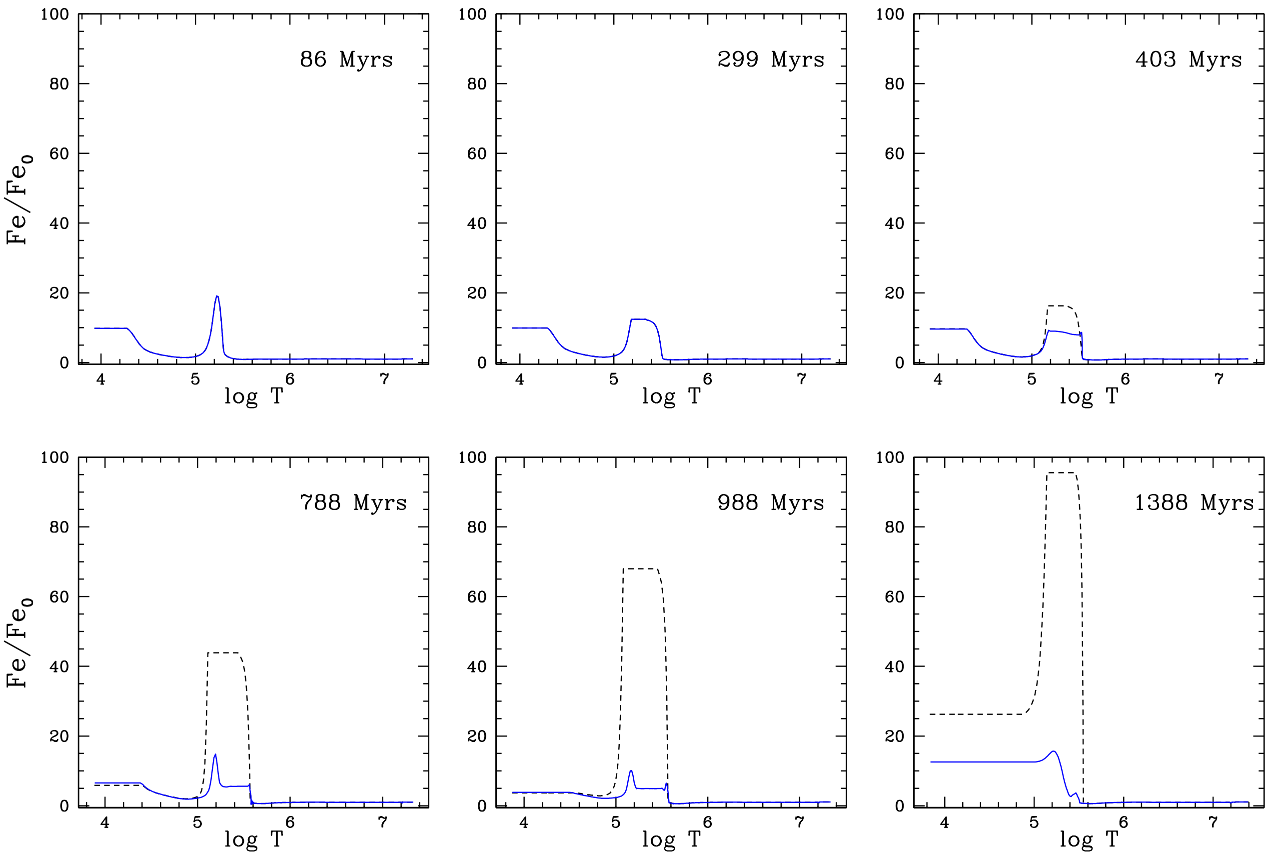


**Fig. 1.** Iron accumulation profiles in two 1.7 $M_\odot$ models at different evolutionary steps. The dashed lines show a model including atomic diffusion (with radiative pressure effects), the solid lines present a model including both atomic diffusion and thermohaline mixing. Fe/Fe$_0$ represents the ratio between the current iron abundance and its initial value on the ZAMS.

the opacity bump region and that it also affects the iron convective zone boundaries. This process is expected to take place in all types of stars where heavy element accumulations occur (i.e. in F, A and B type stars). As a result the real iron accumulations in A and B type stars are probably smaller than those deduced from atomic diffusion computations. The effects of the thermohaline mixing on the iron abunbance may have strong implications for the oscillations driven by the iron $\kappa$-mechanism, the influence of this mixing on the iron convective zone may also affects the oscillations excited through the convective blocking. As a consequence thermohaline instabilities must be introduced in the stellar evolutionary computations and the stability analysis of pulsating A and hotter stars (i.e. in $\beta$-Cephei, SPB, HgMn, sdB or $\gamma$-Doradus models).

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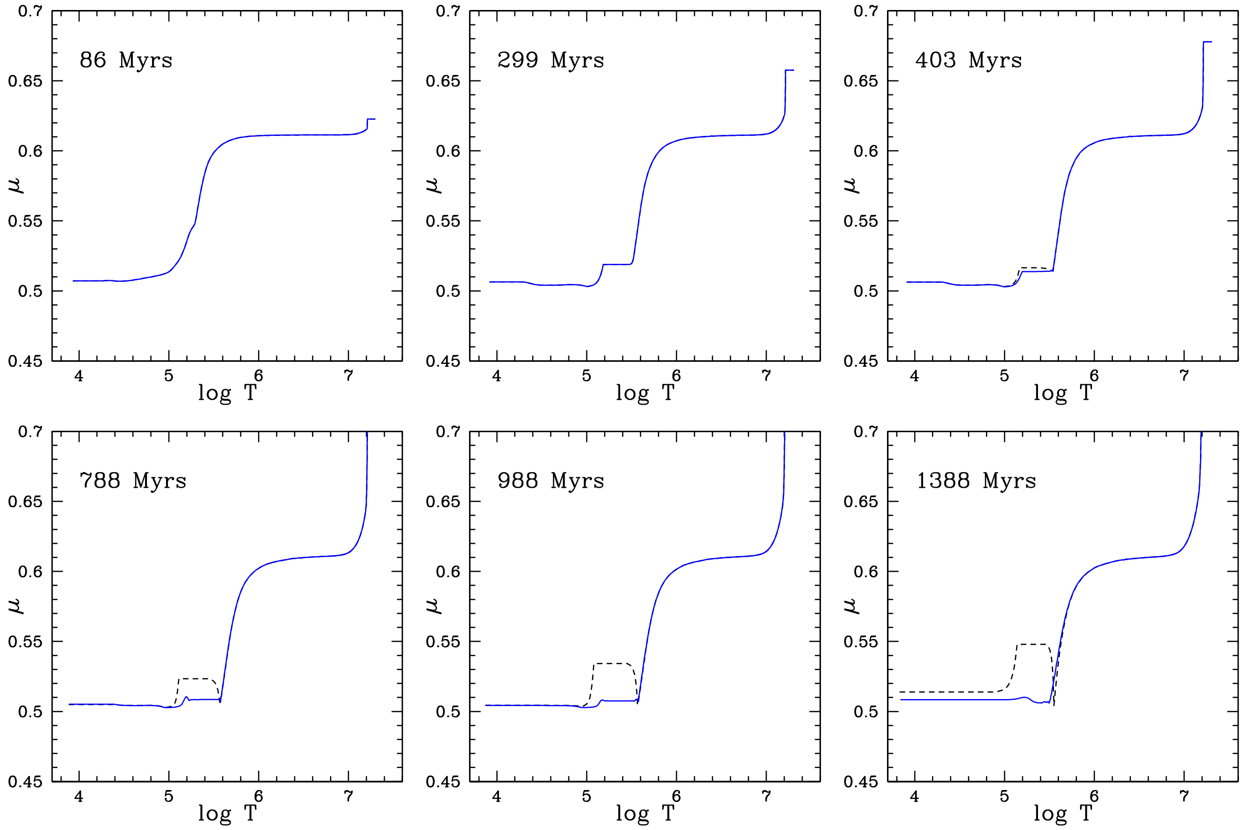


**Fig. 2.** Molecular weight profiles for the same models as presented on Fig. 1.

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