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Pre-main Sequence models with convection described by 2D-RHD numerical simulations

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Abstract. The $T_{\rm eff}$ location of Pre-Main Sequence (PMS) evolutionary tracks depends on the treatment of over-adiabaticity. We present here the PMS evolutionary tracks computed by using the mixing length theory of convection (MLT) in which the $\alpha_{\rm MLT} = l/H_p$ parameter calibration is based on 2D–hydrodynamical models (Ludwig *et al.* 1999). These MLT–$\alpha^{\rm 2D}$ stellar models and tracks are very similar to those computed with non–grey ATLAS9 atmospheric boundary conditions and Full Spectrum of Turbulence (FST) convection model both in the atmosphere and in the interior. As for the FST models, the comparison of the new tracks with the location on the HR diagram of pre–MS binaries is not completely satisfactory; and the pre–MS lithium depletion in the MLT–$\alpha^{\rm 2D}$ tracks is still much larger than that expected from the observations of lithium in young open clusters. Thus, in spite of the fact that 2D RHD models should provide a better convection description than any local model, their introduction is not sufficient to reconcile theory and observations. Lithium depletion in young clusters points towards a convection efficiency which, in pre–MS, should be smaller than in the MS.

Keywords. Convection, stars: abundances, binaries, evolution, pre-main sequence

1. Introduction

The efficiency of convection in the superadiabatic region at the top of the convective stellar envelope determines the asymptotic value of the entropy in the deep and adiabatically stratified layers and, therefore, the star radius and effective temperature. Any treatment of convection adjusted to obtain the correct adiabat will provide similar global structures. This is the base of the MLT solar calibration. The Sun yields only one calibration $\alpha_{\rm MLT}$ value, and no physical principle guarantees this value to be appropriate for the whole HRD, or the whole stellar structure.

During PMS evolution, $T_{\rm eff}$ and $\log g$ are such that convection extends in the stellar atmosphere. The current procedure of mixing different convection treatments in the atmosphere and in the stellar interior modeling introduces an uncertainty of ∼200 K in the 1 $M_\odot$ PMS track without changing the $T_{\rm eff}$ in the MS (see. Fig. 5 in Montalbán *et al.*, 2004). To overcome the problem, Ludwig *et al.* (1999) (thereafter L99) suggested to compute grey MLT models with the $\alpha_{\rm MLT}$ parameter given by a function $\alpha_{\rm MLT}(T_{\rm eff}, \log g)$ derived from the 2D radiative-hydrodynamics (RHD) simulations of stellar surface convection. Stellar models computed in this way provide the same adiabat as a complete 2D RHD computation, and therefore, the same stellar radius (R_*) and effective temperature. This procedure does not give information on the overadiabatic layers, but for a given M_*, R_* and $T_{\rm eff}$, the overall structure does not depend on the details of the treatment of overadiabatic regions. As a consequence, the HRD location and the lithium depletion of PMS stellar models computed with this approach will be the same we could obtain by

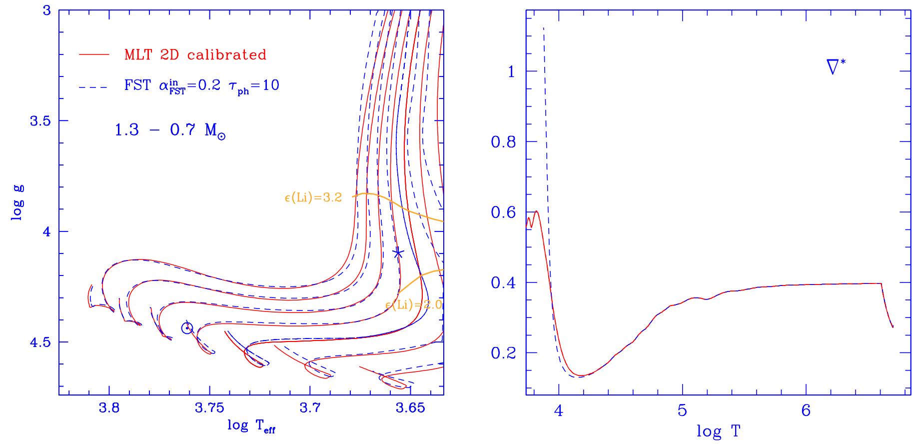

Figure 1. Left panel: HRD for FST (dashed lines) and 2D-MLT (solid line) evolutionary tracks. Two curves of iso-abundance of Li are also plotted. Right panel: stellar gradient ($d\ln T/d\ln P$) *vs.* $\log T$ for 1.0 $M_{\odot}$ FST and 2D-MLT models corresponding to the asterisk in the left panel.

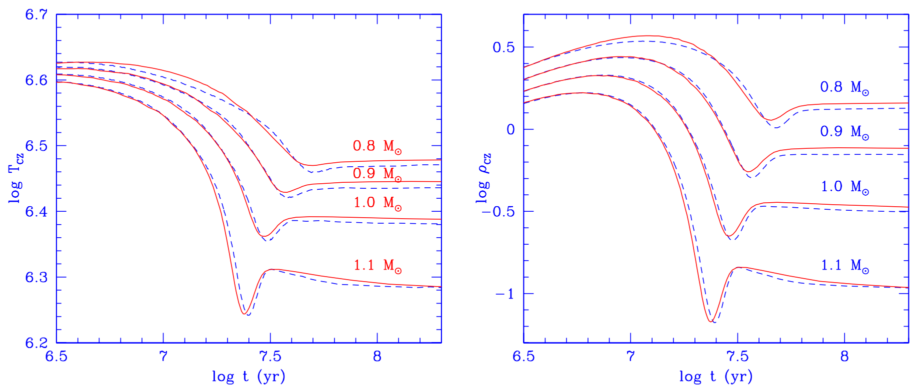

Figure 2. Evolution of temperature (left panel) and density (middle panel) at the bottom of the convective envelope for 0.8, 0.9, 1.0 and 1.1 $M_{\odot}$ tracks. Solid lines correspond to 2D-MLT models and dashed lines to FST ones.

solving the hydrodynamic equation coupled to the equation of radiative transfer in the same way that 2D-RHD numerical simulations do.

2. Stellar Models

2D-MLT stellar models were computed by using ATON2.0 stellar evolution code (Ventura *et al.* 1998) with gray boundary condition option, and MLT convection treatment with $\alpha_{\rm MLT}(T_{\rm eff}, \log g)$ as derived by L99 for the domain: $T_{\rm eff}$: 4300 – 7100 K, and $\log g$: 2.54 – 4.74. 2D-RHD atmosphere models by L99 indicate that efficiency of convection increases as $T_{\rm eff}$ decreases. So, for the PMS domain, $\alpha_{\rm MLT}$ is larger than the solar calibration value $\alpha_{\odot}$. As consequence, the 2D-MLT PMS tracks will be hotter than those obtained by using, as it is currently done, the $\alpha_{\rm MLT}$ value from the solar calibration.

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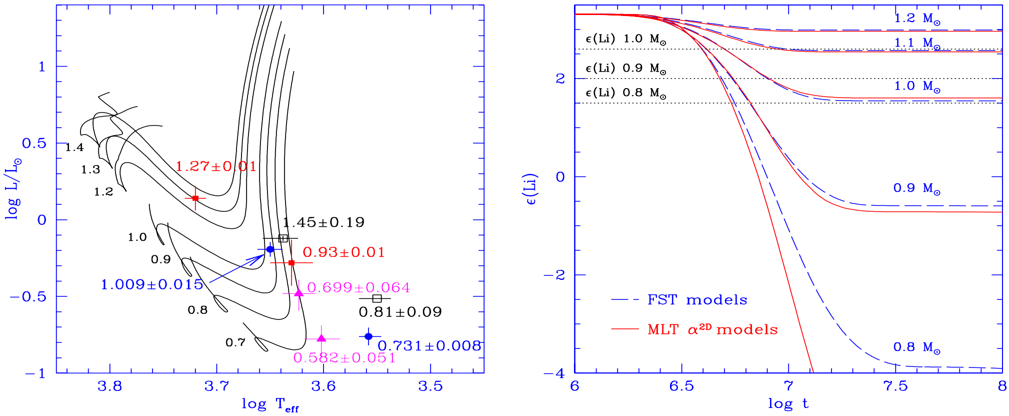

Figure 3. FST evolutionary tracks for solar metallicity. Observational points corresponds to RXJ0529.4+0041 (full squares); V1174Ori (full circles), NTT045251+3016 (empty squares), HD 98800B (full triangles). Right panel: Lithium abundance evolution predicted by FST (dashed lines) and 2D-MLT (solid lines) models. The horizontal dotted lines indicate the minimum lithium observed in α Per stellar cluster at the $T_{\rm eff}$ corresponding to 0.8, 0.9 and 1.0 $M_\odot$ models.

Fig. 1 shows that, both, PMS evolutionary tracks for FST and 2D-MLT models are very similar. The location of PMS binaries in the HR diagram is a powerful way of constraining stellar models. The comparison of the FST tracks (equivalent to 2D-MLT ones) with the parameters of four binary systems are shown in Fig. 3 (left panel).

On the other hand, the overall structure of late-type stars does not depend on the details of the over-adiabatic region: for the 1 $M_\odot$ marked in Fig. 1 by an asterisk, the stellar structures are different only in the most external layers (Fig. 1, right panel). The evolution of the internal structure is also quite similar for both sets of models (Fig 2). Since the temperature and density at the bottom of the convective zone during the PMS evolution are similar for FST and 2D-MLT models, we expect that the PMS-Li depletion predicted 2D-MLT models will be of the same order than that from FST modes, as Fig. 3 (right panel) shows.

3. Conclusions

While stellar parameters of binaries and lithium abundance in young clusters require a low efficiency of convection in the late-type domain of the HR diagram, 2D and 3D numerical simulations of convection predict the opposite, that is, an equivalent value of $\alpha_{\rm MLT}$ that increases as $T_{\rm eff}$ decreases. The high stellar activity level shown by PMS stars supports the suggestion that other physical processes (such as rotation and magnetic field) affect the efficiency of convection in late-type stars.

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