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ROTATIONAL AND MAGNETIC EFFECTS ON STELLAR CONVECTION

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Abstract.
Discrepancies between predictions from standard stellar evolution models and observations, particularly for low-mass stars (LMS), suggest an incomplete understanding of physical mechanisms like rotation and magnetism. Standard models typically use the Mixing Length Theory (MLT) to parameterize convective efficiency with a free parameter, $\alpha_{\rm MLT}$, but this approach does not account for rotational and magnetic effects. Following Ireland and Browning (2018), we integrated rotational and magnetic modifications into MLT within the 1D stellar evolution code Cesam2k20 by introducing a depth-dependent $\alpha_{\rm MLT}$. Additionally, we implemented modified convection criteria to model these effects more consistently. Our work reveals that while rotational MLT has negligible impact on stellar structure, magnetic MLT can cause significant darkening and radius inflation.

Keywords: convection, stars: rotation, stars: magnetism, stars: evolution, low-mass stars

1 Introduction

Observations of low-mass stars (LMS; $M \lesssim 0.35 M_\odot$) reveal that their measured radii can be up to $\sim 15\%$ larger than predicted by theoretical models (e.g., Chabrier et al. 2007). Such stars are fully convective, often rotate rapidly and can sustain strong magnetic fields through dynamo action. In stellar evolution models, the convection is usually modeled using the ad hoc mixing length theory (MLT), which oversimplifies the process and, in particular, neglects the effects of rotation and magnetic fields. Consequently, the omission of these two processes is thought to contribute to the gap between observations and models Chabrier et al. (2007), as they can induce reduced convective efficiency.

To evaluate the impact of rotation and magnetic field on stellar radii, we used, following Ireland & Browning (2018, hereafter IB18), a modified version of the MLT that incorporates these effects, with the stellar evolution code Cesam2k20 (Morel 1997; Morel & Lebreton 2008; Marques et al. 2013, Manchon et al., 2024, in prep.). We also introduced new criteria for the onset of convection, as to account for the (de)stabilizing effect of rotation and magnetism. Our methods are described in Sect. 2, and the results are discussed in Sect. 3.

2 Methods

The classic version of MLT does not include rotational and magnetic effects and uses a free parameter, $\alpha_{\rm MLT}$, to describe the convective efficiency. IB18 showed that, to include these effects, instead of modifying the entire MLT formulation, one can fabricate these effects with a $\alpha_{\rm MLT}$ that varies with radius and time. Following IB18, we adopted the $\alpha_{\rm MLT}$ scaling relations based on formulations from Stevenson (1979) for the rotation (see Fig. 1 for a typical model),

$$\alpha_{\rm MLT\Omega}(r) = \frac{\alpha_{\rm MLT0}}{\left[\left(\frac{\alpha_{\rm MLT\Omega}(r)}{\alpha_{\rm MLT0}}\right)^{-10/3} - \frac{4}{41}\tau_{c_0}^2\Omega^2\right]^{3/4}}, \tag{2.1}$$

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and MacDonald & Mullan (2014) for magnetism (See IB18). Here τ_{c_0} is the convection turnover time, Ω is rotational velocity, and $\alpha_{\rm MLT0}$ is the MLT parameter of the unperturbed model. To achieve a more comprehensive modeling, we implemented the rotationally modified Solberg-Hoiland criterion (Wasiutynski 1946) and the magnetically modified Gough-Tayler criterion (Gough & Tayler 1966) to determine the convective boundaries in the presence of rotation and magnetic fields.

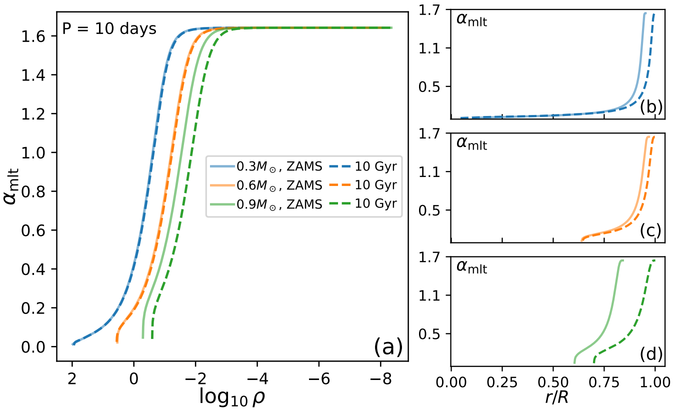

Fig. 1. Depth dependence of $\alpha_{\rm MLT}$ for different evolution stages and masses: $0.3M_\odot$ (blue), $0.6M_\odot$ (orange), $0.9M_\odot$ (green), at Zero-Age Main Sequence (ZAMS) (solid) and an age of 10 Gyr (dashed). The initial periods are set to be 10 days. (a) $\alpha_{\rm MLT\Omega}$ as a function of the logarithm density, $\log_{10}\rho$. (b)-(d) $\alpha_{\rm MLT\Omega}$ as a function of the normalized radius.

3 Discussion and Conclusion

Comparision between rotational models using classic MLT and those with rotational modifications reveals no significant difference within the precision of Cesam2k20. However, magnetic modifications lead to ~ 1–3% of darkening and ~ 0.1–0.4% of radius inflation for a $0.3\ M_\odot$ model (Fig. 2), compared to the $\sim 6\%$ inflation reported by IB18 for $\delta_{\mathbf{B}} = 0.04$–$0.06$. The discrepancy is likely due to the smaller magnetic inhibition applied in our models. Unlike IB18, who varied the mixing-length parameter $\alpha_{\rm MLT}$ based on a precomputed unperturbed model, we adjust $\alpha_{\rm MLT}$ dynamically at each time step. Our computations indicate that their values are unsuitable for our approach.

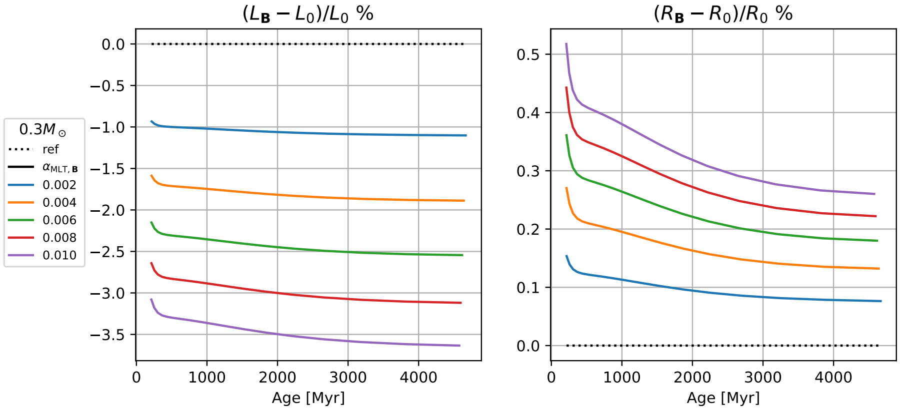

Fig. 2. Relative difference of luminosity and radius between $0.3M_\odot$ reference model (no magnetic field) and magnetic models, with a magnetic inhibition parameter $\delta_{\mathbf{B}} = 0.002 - 0.010$. The magnetic MLT leads to ~ 1–3% of darkening and ~ 0.1–0.4% of radius inflation.

Our results indicate that rotational and magnetic inhibition of convection can partially explain the discrepancies between observations and models. This preliminary study employed simplified setups, and uncertainties remain in relevant coefficients. Our implementation marks the first inclusion of magnetic fields in Cesam2k20. The significant differences between magnetically modified and standard models suggest that the perturbation method may be inadequate. A more accurate approach is to apply magnetic modifications directly, rather than by varying α_{MLT}. This implementation, along with a more comprehensive study of magnetic effects on convection, will be addressed in a forthcoming paper.

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