Magnetic Fields throughout Stellar Evolution
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Stellar models of rotating, pre-main sequence low-mass stars with magnetic fields

Luiz T. S. Mendes[1,3], Natália R. Landin[2,3] and Luiz P. R. Vaz[3]

[1]Depto. de Engenharia Eletrônica, UFMG, 31270-901 Belo Horizonte, MG, Brazil
email: luizt@cpdee.ufmg.br

[2]UFV, Campus Florestal, 35690-000 Florestal, MG, Brazil
email: nlandin@ufv.br

[3]Depto. de Física, UFMG, 31270-901 Belo Horizonte, MG, Brazil
email: vaz@fisica.ufmg.br

Abstract. We report our present efforts for introducing magnetic fields in the ATON stellar evolution code code, which now evolved to truly modifying the stellar structure equations so that they can incorporate the effects of an imposed, large-scale magnetic field. Preliminary results of such an approach, as applied to low-mass stellar models, are presented and discussed.

Keywords. Stars : Magnetic fields – Stars : Evolution – Stars : Rotation.

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1. Introduction and Method

The mean-field $\alpha - \Omega$ dynamo model has been the most explored theoretical tool for a better understanding of magnetic field generation in the Sun and probably also in sun-like stars. However, dynamo models are inherently 3-D, making them difficult to be integrated with 1-D stellar evolution codes. Fortunately, a method first proposed by Lydon & Sofia (1995, hereafter LS95) allows a self-consistent modification of the stellar structure equations in order to incorporate the effects of a large-scale magnetic field to 1-D stellar evolution codes. Here we report the application of that method to the ATON 2.3 evolution code and some preliminary results obtained with it.

The LS95 method treats the magnetic field as a perturbation on the stellar structure equations, by means of a new state variable $\chi = B^2/(8\pi\rho)$ representing the magnetic energy density. The true 3-D nature of the corresponding magnetic pressure P_χ is crudely simplified to represent only the radial dependence of the magnetic pressure. The transition from the intrinsic 3-D magnetic field geometry to this 1-D approximation is described by a numerical factor γ, so that $P_\chi = (\gamma - 1)\,\chi\,\rho$. The reader is referred to the LS95 work for full details regarding this technique.

2. The Models

The main features of the ATON 2.3 evolution code such as opacities, diffusive mixing, overshooting, convection treatment and structural effects of rotation are described elsewhere (Ventura *et al.* 1998; Mendes *et al.* 1999). We computed rotating stellar models of 1 and 0.6 $M_\odot$ with solar chemical composition, mixing-length convection treatment with $\alpha = \Lambda/H_\mathrm{P} = 1.5$, and initial rotation rate obtained from Kawaler's (1987) mass-radius and mass-moment of inertia relations for low-mass stars. A surface magnetic field strength < 100 G was adopted, that can be viewed as an "average" between the mean solar dipole field of 1 G and the kG values observed in T Tauri stars. The field scales throughout the stellar interior preserving the surface ratio between the magnetic and gas energy densities (D'Antona *et al.* 2000).

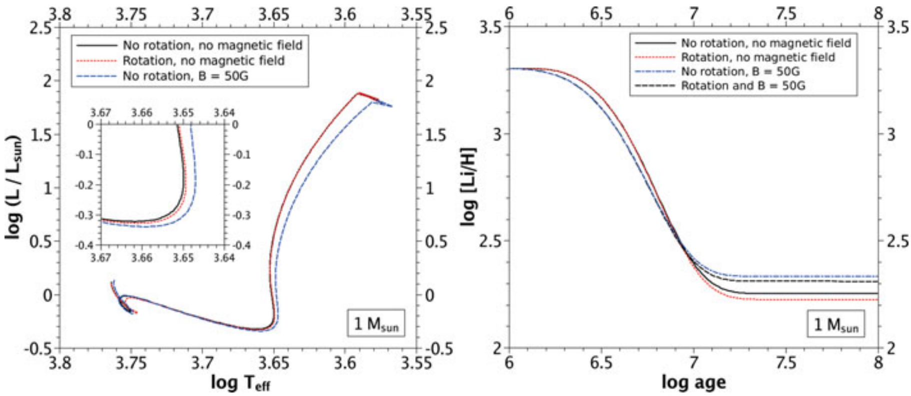

Figure 1. *Left panel:* Evolutionary tracks for 1.0 $M_\odot$ models corresponding to a standard model with no rotation and no magnetic field, a rotating model and a "magnetic" model. *Right panel:* Lithium depletion as a function of age for the 1 $M_\odot$ model. The long-dashed line represents the combined effects of rotation and magnetic fields.

3. Preliminary results

The effects of a magnetic field on the stellar structure are shown in the left panel of Fig. 1. We confirm previous findings that the magnetic field perturbation reduces the surface convection zone of the models (e.g. Mullan & MacDonald 2001; Feiden & Chaboyer 2012). At first, one could think that such a reduction could mimic a slightly more massive star resulting in a hotter track, but the role played by the excess overadiabacity induced by the magnetic perturbation actually makes the tracks slightly cooler, as explained in D'Antona *et al.* (2000). We also see that the magnetic perturbation has a larger effect than rotation on the stellar models, especially during the Hayashi tracks.

Another long-dicussed physical effect of a magnetic field on the structure of low-mass stars concerns the lithium depletion: as the magnetic field suppresses thermal convection, the surface lithium abundance should be higher as confirmed by Fig. 1 (right panel). However, our abundance levels under the presence of a magnetic field differ significantly from those of other researchers (e.g. Li & Bi 2012) and this deserves further investigation.

We plan to extend the model computations to a larger range of stellar masses and surface magnetic field strengths in the immediate future, in order to use the available observations of stellar magnetic fields as constraints to our models.

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