Updating the Dartmouth Stellar Evolution Model Grid: Pre-main-sequence Models & Magnetic Fields

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Abstract. We present the current status of an effort to create an updated grid of low-mass stellar evolution mass tracks and isochrones computed using the Dartmouth stellar evolution code. Emphasis is placed on reliably extending the present grid to the pre-main-sequence, where modeling uncertainties have the greatest impact. Revisions to the original code release include: updated surface boundary conditions, the introduction of deuterium burning, and magnetic fields. The mass track grid contains models with a mass above 0.1 $M_\odot$ and metallicities in the range of -0.5 to $+0.5$ dex. Magnetic mass tracks are calculated for surface magnetic field strengths between 0.1 kG and 4.0 kG using two different prescriptions for magneto-convection. Standard and magnetic model isochrones are available for ages older than 1 Myr. Tabulated quantities include the stellar fundamental properties, absolute photometric magnitudes, magnetic field properties, convective turnover times, apsidal motion constants, and lithium abundances. The complete grid of mass tracks and isochrones will be made publicly available.

1. Motivation, or "why another grid?"

The wealth of high precision data on stellar fundamental properties has revealed shortcomings in the predictive power of stellar evolution theory across the HR diagram (e.g., Mathieu et al. 2007; Torres et al. 2010, Mann et al. this volume). Discrepancies between observations and theory are predominantly found for low mass main-sequence (MS) and pre-main-sequence stars (PMS) (e.g., Hillenbrand & White 2004; Ribas 2006; Feiden & Chaboyer 2012a; Spada et al. 2013), where real stars appear to have larger radii and cooler effective temperatures ($T_{\rm eff}$). Interplay between magnetic fields and convection, either deep in the interior or near the stellar photosphere, is the favored explanation (e.g., Mullan & MacDonald 2001; Chabrier et al. 2007). Magnetic fields can stabilize a fluid against convection, causing a reduction in convective flux that leads to a steeper temperature gradient and forces radiation to carry the excess energy. Although well established on theoretical grounds and observationally in Sun spots, it is not clear whether magnetic fields are causing a *global* re-structuring of low mass stellar interiors.

Stellar models developed to investigate the influence of magneto-convection on stellar interior structure yield mixed results. Models of stars with radiative cores and convective outer envelopes suggest that magnetic fields may be responsible for observed discrepancies between models and observations (Feiden & Chaboyer 2012b, 2013; MacDonald & Mullan 2014). For models of fully convective stars, on the other hand, it appears that magnetic fields can influence their global structure, but only if strong interior magnetic field strengths are invoked (Mullan & MacDonald 2001; MacDonald & Mullan 2012, 2014; Feiden & Chaboyer 2014). Whether the strong interior magnetic fields are physically plausible remains a matter of debate (MacDonald & Mullan 2012; Feiden & Chaboyer 2014). However, these studies have focused primarily on the MS, but it has been shown that PMS models are sensitive to magnetic field perturbations (D'Antona et al. 2000; Malo et al. 2014), suggesting that PMS stars may provide strong tests of magnetic models.

To better understand the strengths and weaknesses of these magnetic models, it is important to apply them in a variety of astrophysical contexts across the HR diagram to see where they succeed and where they fail or where it is too difficult to tell. This is best achieved through the development of a model grid covering several evolutionary phases (PMS to red giant branch) with a range of magnetic field parameters (dynamo type, surface strength, etc) and made publicly available to the wider community. Here, we report on progress to update the Dartmouth stellar evolution model grid[1] (Dotter et al. 2008) by extending it to the PMS phase and adding magnetic models.[2]

2. Updates to the Grid

2.1 Pre-Main-Sequence Models

Before developing a grid of magnetic PMS and MS stellar models, improvements to the standard Dartmouth stellar evolution code had to be carried out. First, deuterium burning was added by explicitly including the deuterium burning reaction, ^{2}H(^{1}H, ^{3}He)γ, in the *p-p* chain nuclear reaction network. Second, the surface boundary conditions defined by non-gray model atmospheres had to be determined at a sufficiently large optical depth so that convection in optically thin layers was more accurately portrayed. Though the effects on the stellar radius are relatively insensitive to this fitting point, the stellar effective temperature derived from the models can be influenced by up to 100 K at young ages. Instead of matching

[1] The current Dartmouth model grid is at http://stellar.dartmouth.edu/models

[2] Our full poster is available at https://zenodo.org/record/10649

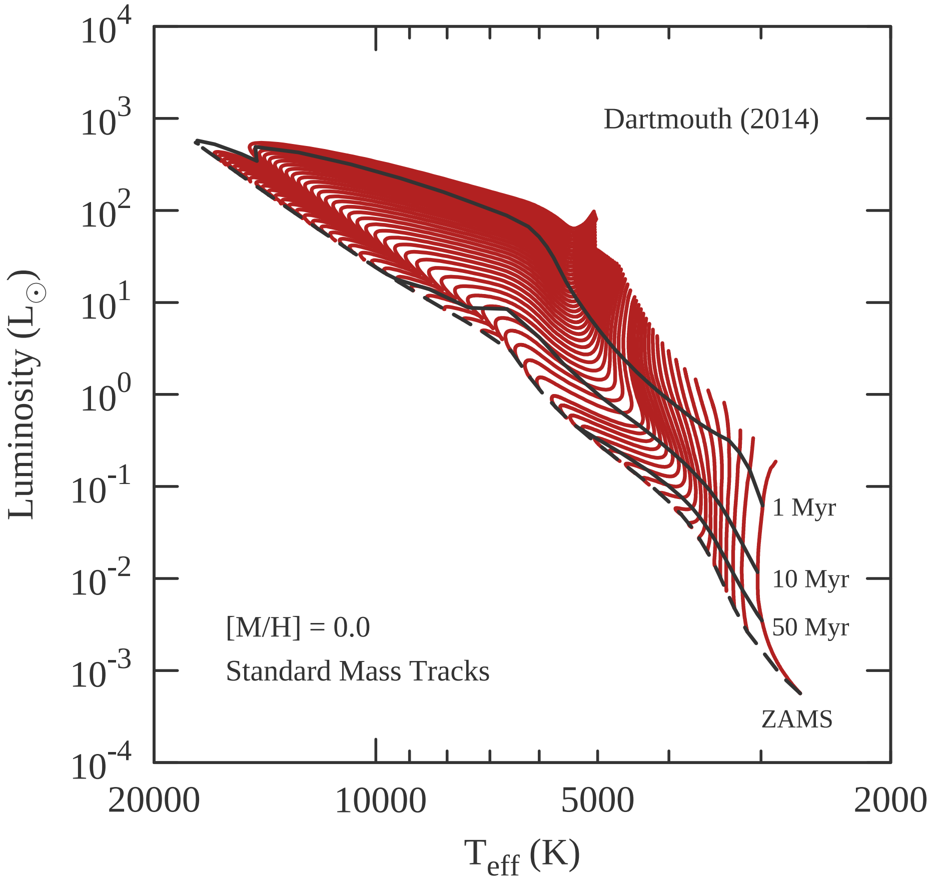

Figure .1: HR diagram for a subset of pre-main-sequence stellar evolution mass tracks at solar metallicity (maroon). Masses range from 0.08 to 5.0 $M_\odot$. Three isochrones at 1, 10, and 50 Myr are shown as black solid lines while the zero-age-main-sequence track is a black dashed line.

the boundary conditions at the location where $T = T_{\rm eff}$ (Dotter et al. 2007, 2008), we now adopt the location where the optical depth $\tau = 10$. Examples of mass tracks for a solar metallicity grid are shown in Figure .1 along with representative PMS isochrones and the zero-age-main-sequence line. The full grid, still under development, will include masses between 0.08 – 5.0 $M_\odot$ with a mass resolution of 0.02 $M_\odot$ up to 1.2 $M_\odot$ at 11 metallicities between -0.5 and $+0.5$ dex. Isochrone ages will range from 1 Myr up to 250 Myr (where the present Dartmouth grid begins) with an age resolution of 0.1 Myr between 1 and 20 Myr.

2.2 Magnetic Models

Magnetic models will be computed for a more limited set of masses between 0.1 and 1.2 $M_\odot$ with an initial resolution of 0.05 $M_\odot$. The initial release of the grid will have a smaller range of metallicities clustered around the solar value. However, this will be expanded after the release. Models implementing the two "dynamo mechanisms" (rotational vs. turbulent) described in Feiden & Chaboyer (2012b, 2013) will be computed with different grids of surface magnetic field strengths. For the turbulent dynamo prescription, we will create models with surface magnetic field strengths of 0.1 to 0.9 kG with a spacing of 0.2 kG, and for the rotational dynamo prescription, surface magnetic field strengths of 1.0 to 4.0 kG will be made with a spacing of 0.5 kG. Both PMS and MS magnetic models will be made available. Presently, we have completed the full set of magnetic models at solar metallicity.

3. Data Products

3.1 Mass Tracks

Once completed, the full set of stellar evolution mass tracks will be made publicly available. Mass tracks will provide evolutionary information regarding the stellar fundamental properties (radius, $T_{\rm eff}$, luminosity, $\log g$), properties of the stellar convection zone(s) (mass, radial boundary, overturn timescales), the apsidal motion constant k_2, and surface abundances of the light elements deuterium and lithium. Photometric magnitudes, if not provided, will be made accessible via web-based post-processing routines.

3.2 Inflation & Cooling Relations

Aside from mass tracks, a set of relations will be published that provide an estimate of radius inflation and temperature suppression expected for a model of a given mass and age for a specified surface magnetic field strength. Examples of radius inflation curves are shown in Figure .2 at a few different masses using both dynamo types.

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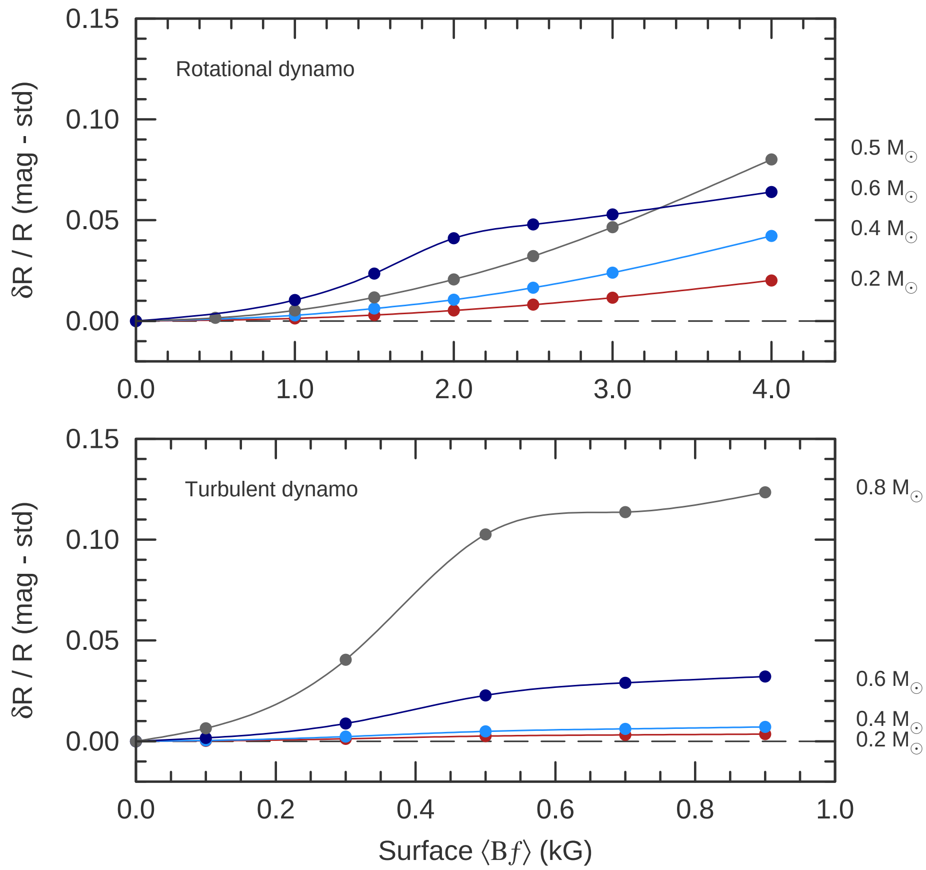

Figure .2: Relative difference (inflation) between magnetic and standard stellar evolution models at an age of 1 Gyr with solar metallicity. Masses are labelled to the right of their associated inflation curve. (*top*) Models computed with a rotational dynamo prescription. (*bottom*) Models computed with a turbulent dynamo formulation.

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