# SpaceInn

**Exploitation of Space Data for Innovative Helio- and Asteroseismology**

**Grant Agreement No.: 312844**

## Deliverable D5.8
## New models of single main sequence stars and subdwarf stars

## Objectives

This deliverable concerns the calculation of new models for single main-sequence stars more massive than the sun. The work was led by Ehsan Moravveji (KU Leuven) and Valentina Schmid (KU Leuven).

## Achievements

Preliminary model grids tuned towards two specific B-type stars have been computed and made available to the community through the open-access papers Moravveji et al. (2015, 2016), along with their open websites. These papers laid the foundation for a more general grid of models of use to the community. This was completed in two steps by Valentina Schmid.

First, stellar models are computed with the open-source stellar evolution code MESA (Paxton et al. 2011, 2013, 2015). A six-dimensional grid of MESA models has been completed. It comprises a large mass-range (2-20 solar masses), a range of initial compositions (in X and Z), convective-core overshooting, diffusive mixing, and evolutionary phases form the zero-age main sequence up to the terminal-age main sequence. The extent of the five free grid parameters can be seen in Table 1.

| **Parameter** | **Begin** | **End** | **Step** |
|---|---|---|---|
| Mass, $M$ ($M_{\odot}$) | 2 | 10 | 1 |
| Mass, $M$ ($M_{\odot}$) | 12 | 20 | 2 |
| Metallicity, $Z$ | 0.012 | 0.02 | 0.002 |
| Initial Hydrogen content, $X_i$ | 0.68 | 0.72 | 0.02 |
| Exponential core-overshooting, $f_{ov}$ ($H_P$) | 0.0 | 0.05 | 0.01 |
| Diffusive mixing, $\log(D_{mix})$ ($cm^2 s^{-1}$) | 0 | 3 | 1 |

***Table 1:*** *Ranges of the free grid parameters.*

Prior to the second SpaceInn Periodical Report, different descriptions of input physics and input parameters have been tested at KU Leuven. The current grid uses the solar metal mixtures by Asplund et al. (2009), OPAL opacity tables (Iglesias & Rogers 1993, 1996), the mixing-length theory by Cox and Giuli (1968, chap. 14), and the Schwartzschild instability criterion. Rotation is ignored in the calculation of the equilibrium stellar models, but the effect of rotation is taken into account in the second step (see below).

Chemical mixing was included in the form of exponential convective-core overshooting. This parameter governs the mixing in the intersection between the convective core and the radiative region. In the radiative region, the strength of chemical mixing was tweaked by the diffusion coefficient $D_{mix}$. The strength of the chemical mixing influences the chemical composition gradient, which in turn influences the periods of high-order *g* modes. It is theoretically predicted that these modes are equally spaced in period for non-rotating ZAMS stars. A deviation from the equidistant spacing is expected for chemically stratified and rotating stars. The theoretically predicted asymptotic period spacing value is computed for each stellar model and allows for a fast comparison of observations to the models.

A wider overshooting layer and stronger diffusive mixing in the radiative part of the model, furthermore, lead to an enrichment of the core with hydrogen and, thus, increase the main-sequence lifetime. This is illustrated in Fig. 2.

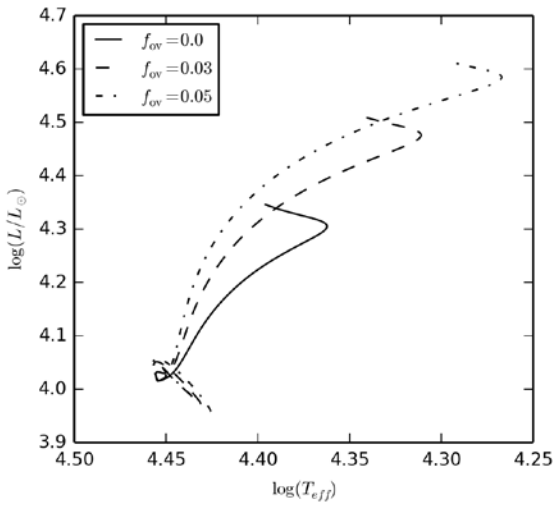


***Fig. 2:*** *Evolutionary tracks of a 12 $M_\odot$ model with initial composition Xi = 0.70 and Z = 0.014, diffusive mixing log($D_{mix}$) = 100, and a different widths of the overshooting layer.*

The second step of this deliverable is the computation of adiabatic frequencies with the open-source pulsation code GYRE (Townsend & Teitler 2013). For each stellar model in the grid *g* and *p* modes of degrees $\ell$ = 0,1,2 are computed. The effect of rotation on the modes is taken into account using the Traditional Approximation of Rotation with three different rotation rates (non-rotating, 10% and 20% of critical rotation). These calculations are currently on going and will be finished and made available publicly by the end of SpaceInn.

## Ambition

The ambition of this tool is to set out a two-dimensional stellar evolution code, which fully takes into account the effects of rotation, at any rate and in a self-consistent way.

The difficult, but important point is that rotating stars are spheroidal and are never in hydrostatic equilibrium. They are pervaded by flows everywhere, even in the stably stratified radiative regions. These flows are essentially convective flows in thermally unstable regions (convection zones) and baroclinic flows in the radiative regions. These latter flows are grosso modo a differential rotation and a meridional circulation, with likely some small-scale turbulence. Radiative regions of non-rotating stars experience very little mixing (only due to microscopic phenomena). Rotation induces flows and therefore some mixing, well-known as "rotational mixing". This is a key feature of the evolution of rotating stars. Besides, these stars also oscillate, and astronomers would like to get from the oscillation frequencies some good constraints on the structure of these stars. The foregoing reasons and many others motivated us to construct a two-dimensional model of rotating stars that is kind enough to enlight us on the numerous questions we are wondering about.

### Resulting Publications

Ghasemi, H., Moravveji, E., Aerts, C., et al. 2016, MNRAS in press
Moravveji, E., Townsend, R. H. D., Aerts, C., & Mathis, S. 2016, ApJ, 823, 130

### Access to Models:

Two 300 MB (with and without extra mixing) subdwarf B star models are available via the the SpaceInn website and at
https://fys.kuleuven.be/ster/Projects/sdbgrid/

The extensive grid of MESA stellar models for massive stars has been computed at the Insitute of Astronomy, KU Leuven.
The data are currently available upon request (valentina.schmid@kuleuven.be).

Adiabatic frequencies for the stellar models are currently being computed with GYRE and will be made available publicly by the end of SpaceInn via the SpaceInn website and at
https://fys.kuleuven.be/ster/Projects/spaceinn/spaceinn