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Model physics in low-mass solar-type stars: atomic diffusion and metallicity mixture

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Abstract

Using asteroseismic data from the *Kepler* satellite, we explore the systematic uncertainties arising from changes in the input physics used when constructing evolution models of solar-type stars. We assess the impact of including atomic diffusion and of varying the metallicity mixture on the determination of global stellar parameters (i.e., radius, mass, and age). We find significant systematic uncertainties on global stellar parameters when diffusion is included in stellar grids. Furthermore, we find the systematic uncertainties on the global stellar parameters to be comparable to the statistical uncertainties when a different metallicity mixture is employed in stellar grids.

1 Introduction

Stellar model physics is known to play an important role in the evolution process and position of stars across the Hertzsprung–Russell diagram. It also plays a vital role towards the characterisation of stars and understanding their interiors. In preparation for recently launched NASA's Transiting Exoplanet Survey Satellite (TESS; Campante *et al.* 2016) and forthcoming ESA's PLAnetary Transits and Oscillations of stars (PLATO; Rauer *et al.* 2014) mission, we find it relevant to explore the systematic uncertainties on global stellar parameters (i.e., radius, mass, and age) that arise from the physics used in stellar models.

Atomic diffusion is known to be an important process in low-mass stars (e.g., Valle *et al.* 2014, 2015; Dotter *et al.* 2017), and we explore the systematic uncertainties arising from its inclusion in stellar grids. Furthermore, we highlight the impact of the uncertainty in the metallicity mixture and quantify the systematic uncertainties induced on the global stellar parameters.

This article is organised as follows. In Sect. 2, we describe our target stars, seismic and classical constraints, and provide a description of our model grids. In Sect. 3, we summarise our results and conclusions.

2 Target stars and model grids

Our sample consists of the 34 low-mass (i.e., below 1.2 $M_\odot$), solar-type stars with *Kepler* photometry (Borucki *et al.* 2010) shown in Fig. 1. These stars have high S/N in the oscillations. Individual oscillation frequencies for each star in the sample are adopted from Lund *et al.* (2017), while spectroscopic constraints (i.e., effective temperature, $T_{\rm eff}$, and metallicity, [Fe/H]) are from Silva Aguirre *et al.* (2017) and references therein.

Using the stellar evolution code MESA (Modules for Experiments in Stellar Astrophysics; Paxton *et al.* 2015), we set up three grids varying only in the specific model physics being

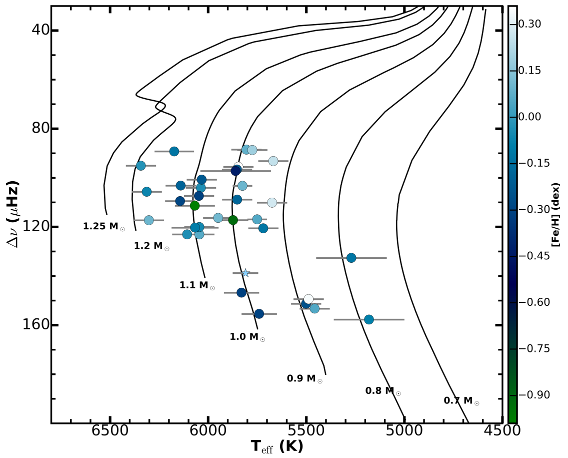

Figure 1: Evolution tracks constructed at solar metallicity and ranging in mass from 0.7 to 1.25 $M_\odot$. Stars are colour-coded according to their metallicity. The "star" symbol corresponds to the position of the Sun.

investigated (see Table 1). The evolution tracks vary in mass, $M \in [0.70, 1.25]M_\odot$ in steps of 0.05, initial metal mass fraction, $Z_0 \in [0.006, 0.031]$ in steps of 0.001, and mixing length parameter, $\alpha_{\rm mlt} \in [1.3, 2.9]$ in steps of 0.1. For further details on the grid properties, such as the nuclear reaction rates tables, equation of state, opacities, model atmosphere tables etc., please see Nsamba *et al.* (2018).

We note that the initial helium mass fraction of our evolution models was determined using the helium-to-heavy-metal enrichment law, expressed as

$$Y = \left(\frac{\Delta Y}{\Delta Z}\right) Z + Y_0 \,, \quad (1)$$

with Y_0 set to the big bang nucleosynthesis primordial value of 0.2484 when $Z = 0.0$ (Cyburt *et al.* 2003) and $\Delta Z/\Delta Y = 2$. The treatment of Y is expected to be a significant source of systematic uncertainty on the stellar properties and is currently being addressed in Nsamba et al. (in prep.).

Adiabatic pulsation frequencies for each evolution model were calculated using GYRE (Townsend & Teitler 2013) for spherical degrees $l = 0$, 1, 2, and 3. The surface effect is corrected using the two-term surface correction by Ball & Gizon (2014) implemented in AIMS (Asteroseismic Inference on a Massive Scale; Lund & Reese 2018, Rendle et al. submitted). Stellar parameters and their corresponding uncertainties are obtained from the statistical mean and standard deviation of the posterior probability density functions (PDFs) returned by AIMS.

3 Results and conclusions

The systematic uncertainties arising from the inclusion of atomic diffusion are shown in Fig. 2. They amount to 0.8%, 2.1%, and 16% in radius, mass, and age, respectively. The lower panel of Fig. 2 shows that stellar ages computed based on the grid with diffusion are on average lower than those from the grid without diffusion. The systematic uncertainties in stellar mass and age are significantly larger than the corresponding statistical uncertainties. For a comprehensive discussion, please refer to Nsamba *et al.* (2018). It is interesting to note that the mass and age seem to be anti-correlated (see Fig. 2) as expected from stellar evolution.

The systematic uncertainties arising from the adoption of a different metallicity mixture are shown in Fig. 3. They amount to 0.5%, 1.4%, and 6.7% in radius, mass, and age, respectively. The statistical uncertainties are comparable to the systematic uncertainties in this case, consistent with the findings of Silva Aguirre *et al.* (2015).

In conclusion, we find that atomic diffusion plays a vital role in the input physics with regard to low-mass, solar-type stars, its impact being significant on the computed mass and age. Our findings also show that the uncertainty in the metallicity mixture has a limited impact on the global stellar parameters. Note that variation of the metallicity mixture implies setting the appropriate opacities during grid construction. Therefore, the systematic uncertainties found are from both these inputs. We refer to Nsamba *et al.* (2018) for further details on the discussion of the model physics highlighted here, including the systematic uncertainties on the global stellar parameters arising from different surface correction methods.

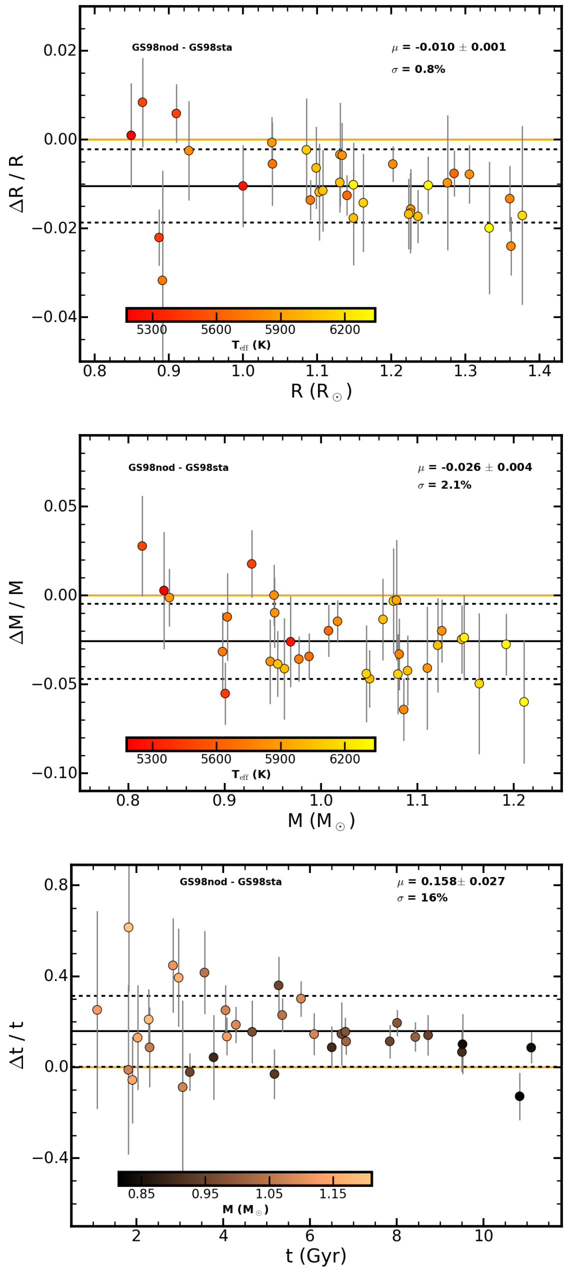

Figure 2: Fractional differences in stellar radius, mass, and age resulting from the inclusion of diffusion (abscissa values are from GS98sta). GS98nod corresponds to the grid without diffusion. The orange line is the null offset, the black solid line represents the bias (μ), and the scatter (σ) is represented by the dashed lines.

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Table 1: Summary of the main model grid properties.

Name	Mass ($M_\odot$)	Solar mixture	$\frac{\Delta Y}{\Delta Z}$	Overshooting	Diffusion
GS98sta	0.70 - 1.25	Grevesse & Sauval (1998)	2.0	No	Yes
GS98nod	0.70 - 1.25	Grevesse & Sauval (1998)	2.0	No	No
AGS09	0.70 - 1.25	Asplund *et al.* (2009)	2.0	No	Yes

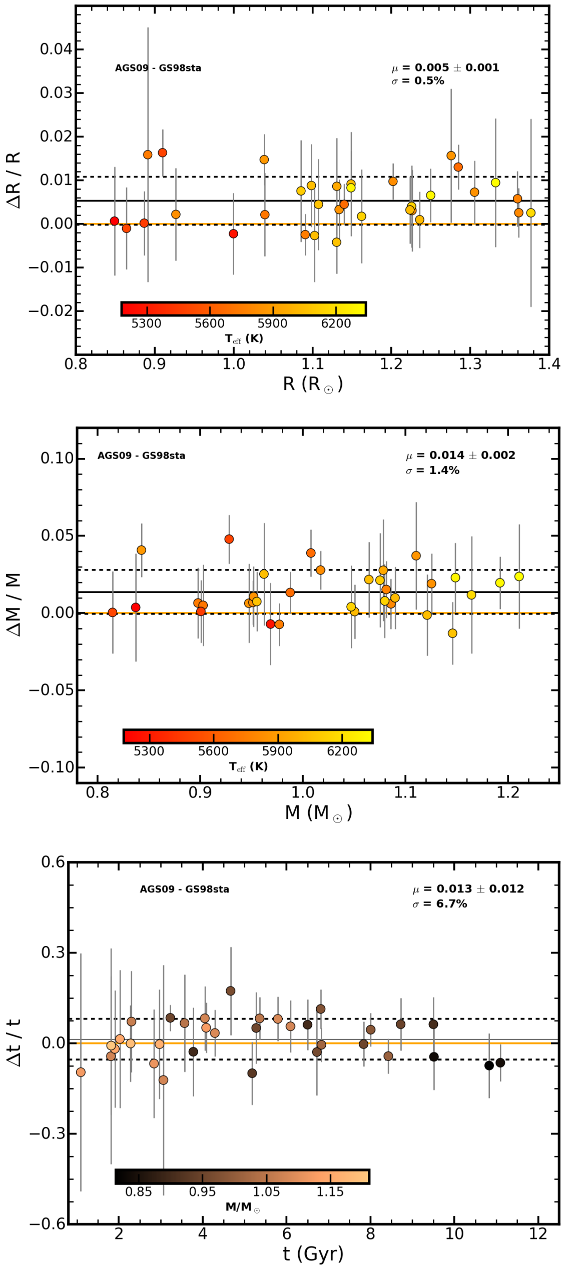

Figure 3: Fractional differences in stellar radius, mass, and age resulting from the adoption of a different metallicity mixture (abscissa values are from GS98sta). The orange line is the null offset, the black solid line represents the bias (μ), and the scatter (σ) is represented by the dashed lines.

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