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PARSEC evolutionary tracks and isochrones including seismic properties

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Abstract. In the recent years it has been generally accepted that seismic parameters add an important observational constraint for the study of stellar populations and galaxy evolution. Padova-Trieste (PARSEC) evolutionary tracks are widely used to characterise stellar objects and stellar populations. Stellar models at the base of these studies suffer from uncertainties and, more important, degeneracy among different input parameters: stellar mass, chemical composition, central chemical mixing, age, etc. Adding seismic properties to the classic parameters for stars at different evolutionary states, from the H main-sequence to the asymptotic giant branch, is a powerful tool to calibrate physical processes in stellar models, and hence to improve our interpretation of Galactic and extra-Galactic observations.

Keywords. stars: evolution, stars: fundamental parameters

1. Overview

There exist different seismic observables which may be classified by their potential in deriving stellar properties and/or by the demanding computation time :

Level 0: Scaling relations between global features of oscillation spectra and stellar parameters $T_{\rm eff}$, M and R allow us to easily add the seismic parameters $\Delta\nu_{\rm SL}$ (large frequency separation) and $\nu_{\rm max}$ (frequency at maximum oscillation power) to the classical evolutionary tracks and isochrones tables. No additional model computations are required. These tabulated quantities have been used, for instance in Rodrigues *et al.* (2014) and in Miglio *et al.* (2013) to characterise populations of oscillating G-K red giants in *Kepler* and CoRoT fields, respectively.

Level 1: Seismic indices from asymptotic theory: asymptotic large frequency separation ($\Delta\nu_{\rm asym}$), asymptotic period spacing ($\Delta\Pi$), and factor of coupling (q) between acoustic and gravity cavities in the star. The first one is the inverse of the sound travel time across the stellar diameter, and it is linked to the square root of the stellar mean density. The two others strongly depend on the density stratification inside the star, and contain important information about evolutionary state (e.g. Bedding *et al.* 2011, Mosser *et al.* 2014, and Bossini *et al.* 2017). Theoretical values of these seismic indices result from the integration of some quantities (mainly sound speed and buoyancy frequency) over the stellar structure. They will be estimated at once with the evolutionary tracks and stored as additional global parameters resulting from stellar structure modelling.

Individual frequencies, specially those of non-radial modes, contain much more information about properties of the stellar interior, and hence on physical processes. However, the computation of radial and non-radial frequency modes might become very time consuming. To get as much seismic indices as possible while keeping a reasonable computation time, we adapt the type of oscillation modes to be calculated to the evolutionary stage.

Level 2: Radial adiabatic frequencies will be computed for the PARSEC (Bressan *et al.* 2012) stellar structure models using the oscillation code LOSC (Scuflaire *et al.* 2008). Different radial orders in the expected domain of solar-like oscillations will be used to estimate $\Delta\nu$ from the fit of the linear relation ($\nu_{n,0} = (n + \epsilon)\Delta\nu$). This value, obtained after correction of surface effects, is a better constraint to the observed $\Delta\nu$ than $\Delta\nu_{\rm asym}$ and $\Delta\nu_{SL}$ (see for instance Rodrigues *et al.* 2017). $\Delta\nu$ and the frequencies of 5 different radial orders will be included in the evolutionary track tables. Five modes around $\nu_{\rm max}$, for solar-like oscillation domain, and the fundamental mode plus four overtones for high luminosity red giants.

Level 3: As a star evolves, its central density increases and the oscillation spectra becomes complicated, increasing dramatically the computation time. Hence, depending on the density stratification :

(a) we compute non-radial modes (with angular degrees $\ell = 1$, and 2) for solar-like domain of frequencies, and provide mean linear fit for small frequency separations $\delta\nu_{02}$ and $\delta\nu_{01}$. These quantities depend on the stellar age and on the size of the convective core. Targets in main-sequence and Sub-Giant evolutionary phases.

(b) We skip non-radial mode computation (important coupling between propagation cavities).

(c) We compute only p-dominated non-radial modes (mainly for evolved red giants with very low coupling between gravity and acoustic cavities).

These new outputs will be included in PARSEC evolutionary tracks. These ones are used in the Stellar Population Synthesis code TRILEGAL (Girardi *et al.* 2005) and in the Bayesian stellar parameter estimation tool PARAM (da Silva *et al.* 2006), so far, using classical information or scaling relations. Evolutionary tracks computed with MESA (Paxton *et al.* 2013) together with seismic indices of Level 1 and 2 have been recently included in TRILEGAL and PARAM (Rodrigues *et al.* 2017). Adding PARSEC will allow us to perform studies of systematics in the properties of stellar populations and stellar parameters due to uncertainties in the input physics and to numerical implementation of physical process, of paramount importance for the exploitation of data from large surveys, such as CoRoT, Keple/K2, Gaia, TESS and PLATO.

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