DOI: 10.1051/epjconf/201716001012

Extraction of seismic indices and stellar granulation parameters for *CoRoT* and *Kepler* red giants using the MLEUP method. Main results and perspectives.

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Abstract. In the framework of the SPACEInn project, a Stellar Seismic Indices (SSI - http://ssi.lesia.obspm.fr/) database was developed in order to provide the scientific community with oscillations and granulation signatures for a large set of red-giant type stars. For this purpose, we have developed the method MLEUP able to extract simultaneously the seismic indices (the equidistance $\Delta\nu$, the frequency $\nu_{\rm max}$ and the height $H_{\rm env}$ of the maximum oscillation power) and granulation parameters (the *e-folding time* $\tau_{\rm eff}$ and the variance of the integrated brightness fluctuations σ^2). This method has been tested in terms of precision and accuracy, using Monte Carlo simulations. Then we applied it to all stars observed by CoRoT and all long-cadence *Kepler* light-curves. In total, we yield seismic indices and granulation parameters for about 5,000 stars for CoRoT and more than 13,000 for *Kepler*. In this paper, we focus on the main results for both seismic indices $\Delta\nu$ and $\nu_{\rm max}$ as well as for the stellar parameters (mass, radius and luminosity) seismically inferred. Then, in the perspective of Gaia, we discuss about the possibility to derive other seismic quantities like e.g. a seismic effective temperature.

1 Introduction

We have developed a new automatic method, called MLEUP, taking advantage of the MLE (Maximum Likelihood Estimate) algorithm combined with the parametrized representation of the red giants pulsation spectrum following the UP (Universal Pattern, cf. [1]) in order to measure simultaneously the oscillations and the granulation signatures. The full description of this method is in [2]. We describe briefly in Sect. 2 the mainlines of our method. In Sect. 3, we present the main results of the analysis of the CoRoT and *Kepler* datasets: PUBLI ! the mean large separation $\Delta\nu$, the peak frequency $\nu_{\rm max}$ as well as the "seismic" masses and radii. In Sect. 4, we discuss about the prospect, such as the possibility to derive the "seismic" effective temperature using the Gaia data. Finally, we conclude in Sect. 5.

2 Mainlines of the Method MLEUP

The model used to fit the power density spectrum is based on two Lorentzian-like functions for the granulation and activity component, a red giant parametric oscillations pattern based on the Universal Pattern [1] for the oscillations and a constant for the white noise (see Fig. 1). The oscillations are characterised by three seismic indices: The mean large separation, $\Delta\nu$, corresponding to the mean frequency spacing between two consecutive p-modes with same angular degree; $H_{\rm env}$ which is the maximum height of the oscillation envelope and $\nu_{\rm max}$, the corresponding frequency. Concerning the granulation, it is characterised by two parameters: the effective timescale $\tau_{\rm eff}$ (or the *e-folding time*), which measures the temporal coherence of the granulation in the time domain and the characteristic amplitude σ^2 which corresponds to the variance brightness fluctuation of the granulation. The method has been tested in order to characterize its bias and dispersion using Monte Carlo simulations. These simulations revealed that MLEUP presents low dispersions, especially for $\Delta\nu$ and $\nu_{\rm max}$, and that the internal errors are reasonably representative of the real dispersions

3 Mean large separation $\Delta\nu$ and peak frequency $\nu_{\rm max}$ – "seismic" mass and radius

We analysed all CoRoT data[1] with a duration of observation larger than 50 days and all long-cadence (dt = 29.42 min) *Kepler* data[2]. We yield 4783 CoRoT stars and 13,689 *Kepler* stars for which we get the seismic indices, and 1520 CoRoT stars and 12,879 *Kepler* stars for which we get also the granulation parameters. The results of the analysis of the large sets of *Kepler* and CoRoT stars are presented and discussed in [2]. Here, we focus on the results of both seismic indices $\Delta\nu$ and $\nu_{\rm max}$, and the stellar parameters inferred by them.

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[1] CoRoT data archive: http://idoc-corot.ias.u-psud.fr
[2] *Kepler* data archive: http://archive.stsci.edu/kepler/

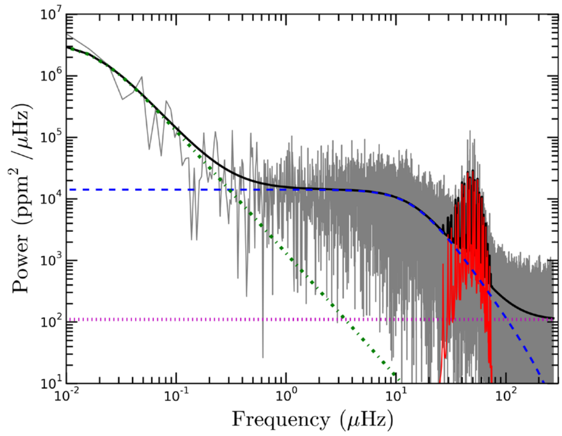

Figure 1: Results of the final adjustment of the background and oscillations of MLEUP (black line). In grey, the raw PSD of KIC 2850913. The dash-dot green line and the dashed blue one correspond respectively to the activity and granulation component. The dotted magenta line represents the white noise component and the solid red one is the Universal Pattern.

We plotted in figure 2 $\Delta\nu$ as a function of $\nu_{\max}$ from the 4783 CoRoT and 13,689 *Kepler* stars for which we extracted the seismic indices. We can see that the dispersion for CoRoT and *Kepler* is small, as well as the internal error (cf. Tab. 1). We deduced the two following scaling relations by adjusting the CoRoT and *Kepler* datasets:

- $\Delta\nu = (0.242 \pm 0.003)\ \nu_{\max}^{0.778\pm0.003}$ (CoRoT)
- $\Delta\nu = (0.282 \pm 0.001)\ \nu_{\max}^{0.7506\pm0.0010}$ (*Kepler*)

The *Kepler* scaling relation is consistent with the [3]'s scaling relation ($\Delta\nu = (0.274 \pm 0.002)\ \nu_{\max}^{0.751\pm0.002}$), determined by an average of scaling relations obtained by various different methods with the *Kepler* data, as well as the theoretical one [$\beta = 0.75$, e.g. 4]. Between our CoRoT and *Kepler* scaling relations, we note slopes significantly different. This difference is not yet understood. It could come from the difference in the stellar populations considered.

The previous seismic indices are very valuable to characterised large sets of stars. To illustrate this, we considered 13,408 of the *Kepler* selected dataset for which we have the effective temperature from [5]. Combining with $\nu_{\max}$ and $\Delta\nu$, one can estimate the mass, radius and luminosity [e.g. 6] seismically inferred with a high precision (cf. Tab. 1). The figure 3 shows the distribution of our results in the Hertzsprung–Russell (H-R) diagram where the red giant branch (RGB) and the red clump are well recognizable.

4 Perspective – The “seismic” effective temperature $T_{\rm eff}$

The arrival of Gaia data opens new perspectives. As an illustration, we introduce the “seismic” effective temperature. Indeed, if we combine the apparent magnitude m, the parallax p and the interstellar extinction $A_{\rm m}$ with both seismic indices $\nu_{\max}$ and $\Delta\nu$, it is possible to derive the $T_{\rm eff}$ via the following equation (cf. Sect. 5 for detailed derivation):

Table 1: Median of the relative internal errors given in percentage, for the results obtained with the *Kepler* and CoRoT selected datasets.

	δ_{err} *Kepler* (%)		δ_{err} CoRoT (%)	
	negative	positive	negative	positive
$\nu_{\max}$	−0.545%	+0.545%	−1.53%	+1.53%
$\Delta\nu$	−0.0386%	+0.0386%	−0.144%	+0.144%
$M/M_\odot$	−3.98%	+3.98%	—	—
$R/R_\odot$	−1.33%	+1.33%	—	—
$L/L_\odot$	−11.6%	+11.6%	—	—

$$T_{\rm eff} = 10^{\frac{(M_\odot - 5 + A_{\rm m} - m)}{12.5}}\, p^{-2/5} \left(\frac{\Delta\nu}{\Delta\nu_{\rm ref}}\right)^{4/5} \left(\frac{\nu_{\max}}{\nu_{\rm ref}}\right)^{-2/5} {\rm T}_{{\rm eff},\odot}\,, \quad (1)$$

with $A_{\rm m}$ the interstellar extinction (mag), m the apparent magnitude (mag), p the parallax (arcsec), $\nu_{\max}$ the peak frequency (μHz) and $\Delta\nu$, the large separation (μHz). The constant ${\rm T}_{{\rm eff},\odot}$ corresponds to the solar values and the constants $\nu_{\rm ref}$ and $\Delta\nu_{\rm ref}$, to the reference values defined by [7].

The corresponding error is given by:

$$\delta T_{\rm eff} = T_{\rm eff} \sqrt{\left(\frac{\ln 10}{12.5}\delta A_{\rm m}\right)^2 + \left(\frac{\ln 10}{12.5}\delta m\right)^2 + \left(\frac{2}{5}\frac{\delta p}{p}\right)^2 + \left(\frac{2}{5}\frac{\delta\nu_{\max}}{\nu_{\max}}\right)^2 + \left(\frac{4}{5}\frac{\delta\Delta\nu}{\Delta\nu}\right)^2}\,. \quad (2)$$

The MLEUP method provides the seismic indices $\nu_{\max}$ and $\Delta\nu$ with a high precision. The relative errors obtained with the selected *Kepler* dataset are 0.55% and 0.04% respectively (cf. Tab. 1). Regarding m, p and $A_{\rm m}$, they could be provided by Gaia. The precision that Gaia will soon provide should be of the order $\delta p \sim 10\ \mu$as for parallaxes, $\delta m \sim 3$ mmag for apparent magnitudes and $\delta A_{\rm m} \lesssim 0.1$ mag for extinctions[3]. Thereby, the relative incertitude on $T_{\rm eff}$ would be about 2%, mainly dominated by the interstellar extinction. For a star with $T_{\rm eff} = 5000$ K, we have $\delta T_{\rm eff} \sim 100$ K, which is very competitive with spectroscopic determination.

Alternatively, we could also imagine to derive the seismic interstellar extinction given the spectroscopic $T_{\rm eff}$.

5 Conclusion

The MLEUP method allowed us to extract simultaneously with a high precision the seismic indices and the granulation parameters from a large number of *Kepler* and CoRoT stars. We yield 4783 CoRoT stars and 13,689 *Kepler* stars for which we extracted the seismic indices, and 1520 CoRoT stars and 12,879 *Kepler* stars for which we get both the seismic indices and the

[3]For more details, see: http://www.cosmos.esa.int/web/gaia/science-performance

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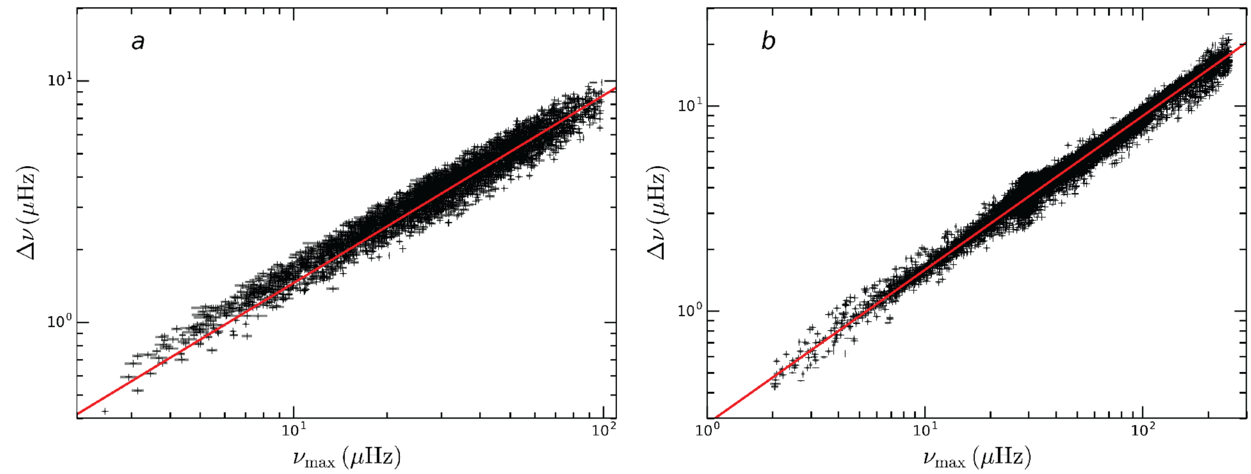

Figure 2: Mean large separation $\Delta\nu$ obtained with 4783 CoRoT stars (*a*) and 13,689 *Kepler* stars (*b*). Black crosses represent the values obtained, with their error bars in grey. The red line is the deduced scaling relations. Fig. from [2].

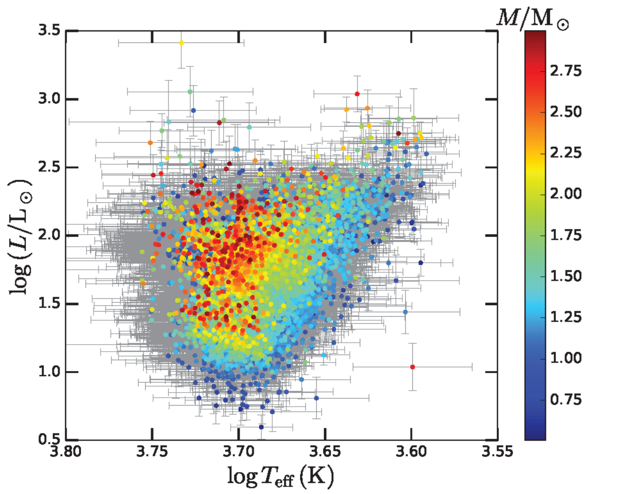

Figure 3: Hertzsprung–Russell diagram with 13,408 *Kepler* stars. The colour code represents the stellar mass. For better visibility of the mass variation, only stars with a mass included in the range $0.5 \leqslant M/\mathrm{M}_{\odot} \leqslant 3.0$ are plotted. Fig. from [2].

granulation parameters. Those indices and parameters are available in the *Stellar Seismic Indices* (SSI) database[4].

The measurements of ν_{max} and $\Delta\nu$ obtained with MLEUP are very precise. Thereby, given an effective temperature, we could derive seismic masses and radii with a good precision. Thanks to the very precise measurements that the space mission Gaia will soon provide, we can plan to derive others parameters using the seismic indices. Indeed, it would be possible to derive a seismic effective temperature or the seismic interstellar extinction A_{m}.

[4]http://ssi.lesia.obspm.fr/

Acknowledgements

This paper is based on data from the CoRoT Archive.The CoRoT space mission has been developed and operated by CNES, with contributions from Austria, Belgium, Brazil, ESA (RSSD and Science Program), Germany, and Spain. This paper also includes data collected by the *Kepler* mission. Funding for the *Kepler* mission is provided by the NASA Science Mission directorate. The authors acknowledge the entire *Kepler* and CoRoT team, whose efforts made these results possible. We acknowledge financial support from the SPACEInn FP7 project (SPACEInn.eu) and from the "Programme National de Physique Stellaire" (PNPS, INSU, France) of CNRS/INSU.

Annexe: Detailed calculation of the "seismic" effective temperature T_{eff}

We detail in this annexe the calculation of the seismic effective temperature T_{eff}.

The Stefan-Boltzmann law, normalised with the solar values, gives:

$$\frac{L}{\mathrm{L}_{\odot}} = \left(\frac{R}{\mathrm{R}_{\odot}}\right)^2 \left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^4 , \qquad (3)$$

with L, the star luminosity (W) and R, its radius (m). The constants $\mathrm{L}_{\odot}$, $\mathrm{R}_{\odot}$ and $\mathrm{T}_{\mathrm{eff},\odot}$ correspond to the solar values.

The radius R can be expressed using the seismic indices ν_{max} and $\Delta\nu$ via the following theoretical relation:

$$\frac{R}{\mathrm{R}_{\odot}} = \left(\frac{\nu_{\mathrm{max}}}{\nu_{\mathrm{ref}}}\right) \left(\frac{\Delta\nu}{\Delta\nu_{\mathrm{ref}}}\right)^{-2} \left(\frac{T_{\mathrm{eff}}}{\mathrm{T}_{\mathrm{eff},\odot}}\right)^{1/2} , \qquad (4)$$

with ν_{max}, the frequency of the maximum height in the oscillation spectrum (μHz) and $\Delta\nu$, the large separation (μHz). The constants $\Delta\nu_{\mathrm{ref}}$ and ν_{ref} correspond to the reference values defined by [7].

Concerning the luminosity L, it can be expressed as a function of the stellar absolute magnitude $\mathcal{M}$ (mag):

$$\frac{L}{\mathrm{L}_\odot} = 10^{\left(\frac{\mathcal{M}_\odot - \mathcal{M}}{2.5}\right)}, \quad (5)$$

with the constant $\mathcal{M}_\odot$ corresponding to the solar values.

And given that $\mathcal{M}$ is dependant of the apparent magnitude m (mag), the distance d (pc) and the extinction A_m (mag), as:

$$\mathcal{M} = m - 5\log(d) + 5 - A_\mathrm{m}\,. \quad (6)$$

One can finally deduce the seismic effective temperature as a function of A_m, m, d, ν_max and $\Delta\nu$, as:

$$\frac{T_\mathrm{eff}}{\mathrm{T}_{\mathrm{eff},\odot}} = 10^{\frac{(\mathcal{M}_\odot - 5 + A_\mathrm{m} - m)}{12,5}} d^{2/5} \left(\frac{\Delta\nu}{\Delta\nu_\mathrm{ref}}\right)^{4/5} \left(\frac{\nu_\mathrm{max}}{\nu_\mathrm{ref}}\right)^{-2/5}, \quad (7)$$

with $\mathrm{T}_{\mathrm{eff},\odot} = 5777$ K, $\mathcal{M}_\odot = 4.8$ mag, $\Delta\nu_\mathrm{ref} = 138.8\,\mu$Hz, $\nu_\mathrm{ref} = 3104\,\mu$Hz.

Furthermore, the stellar parallax p being small, one can approximate the distance d by $1/p$. Thus, the seismic T_eff can also be expressed with the parallax p (arcsec):

$$\frac{T_\mathrm{eff}}{\mathrm{T}_{\mathrm{eff},\odot}} = 10^{\frac{(\mathcal{M}_\odot - 5 + A_\mathrm{m} - m)}{12.5}} p^{-2/5} \left(\frac{\Delta\nu}{\Delta\nu_\mathrm{ref}}\right)^{4/5} \left(\frac{\nu_\mathrm{max}}{\nu_\mathrm{ref}}\right)^{-2/5}. \quad (8)$$

The associated relative error of this seismic T_eff is then:

$$\frac{\delta T_\mathrm{eff}}{T_\mathrm{eff}} = \sqrt{\left(\frac{\ln 10}{12.5}\delta A_\mathrm{m}\right)^2 + \left(\frac{\ln 10}{12.5}\delta m\right)^2 + \left(\frac{2}{5}\frac{\delta p}{p}\right)^2 + \left(\frac{2}{5}\frac{\delta\nu_\mathrm{max}}{\nu_\mathrm{max}}\right)^2 + \left(\frac{4}{5}\frac{\delta\Delta\nu}{\Delta\nu}\right)^2}. \quad (9)$$

Note that the bolometric correction have to be taken into account in the calculation of the seismic effective temperature.

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