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Using seismic targets as benchmarks for spectroscopic analyses of cool stars

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Abstract. The frequency of maximum oscillation power measured in dwarfs and giants exhibiting solar-like pulsations provides a precise, and potentially accurate, inference of the stellar surface gravity. An extensive comparison for about 40 well-studied pulsating stars with gravities derived by traditional means (ionization balance, pressure-sensitive spectral features or location with respect to evolutionary tracks) supports the validity of this technique and reveals an overall remarkable agreement with mean differences not exceeding 0.05 dex (although with a dispersion of up to ~0.2 dex). It is argued that interpolation in theoretical isochrones may be the most precise way of estimating the gravity by traditional means in nearby dwarfs. The use of seismic targets as benchmarks in the context of forthcoming large-scale surveys (such as the follow up of the *Gaia* mission) is briefly discussed.

1. Solar-like oscillations as a powerful gravity indicator

It is notoriously difficult to accurately estimate the stellar surface gravity in late-type stars, with systematic differences of the order of 0.2 dex being commonplace depending on the technique used and its exact implementation. This large uncertainty surrounding $\log g$ limits the accuracy with which elemental abundances can be determined. This is especially the case for purely spectroscopic analyses where the determinations of the stellar parameters are intimately coupled. In that case, the use of a model atmosphere with an inappropriate gravity adversely impacts on the estimation of the other parameters (i.e., effective temperature and microturbulence) and, ultimately, chemical abundances.

However, the properties of the p-mode pulsations exhibited by cool stars on the main sequence and during the red-giant phase can be used to derive values that are precise to a level rivaling that obtained for eclipsing binaries. In this study, we consider the frequency of maximum oscillation power, $\nu_{\rm max}$, as a surface gravity indicator (see, e.g., Kallinger et al. 2010a for definition and further details on how this quantity can be derived). As first suggested by Brown et al. (1991), $\nu_{\rm max}$ is expected to scale as the acoustic cut-off frequency:

$$\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} = \left(\frac{M}{{\rm M}_\odot}\right)\left(\frac{R}{{\rm R}_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{{\rm T}_{\rm eff,\odot}}\right)^{-1/2}. \quad (1)$$

This leads to:

$$\log g = \log g_\odot + \log\left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) + \frac{1}{2}\log\left(\frac{T_{\rm eff}}{{\rm T}_{\rm eff,\odot}}\right). \quad (2)$$

This relation is largely insensitive to the $T_{\rm eff}$ assumed ($\Delta T_{\rm eff}$ = 100 K leads to $\Delta \log g \sim 0.004$ dex only for Sun-like stars). On the other hand, $\nu_{\rm max}$ can usually be measured with an error below 5% from high-quality time series (e.g., Kallinger et al. 2010a). It follows that $\log g$ can be precise to better than 0.03 dex. If confirmed in terms of accuracy, this would be far better than what can be achieved by other means in single stars. Indeed, seismic gravities are beginning to be adopted in spectroscopic analyses as an alternative to values derived from traditional methods in order to narrow down the uncertainties in the other fundamental stellar parameters and chemical abundances (e.g., Batalha et al. 2011).

The high accuracy of the gravities obtained from asteroseismology is supported by a comparison with values obtained using completely independent techniques (e.g., as shown in the case of a few binaries by Bruntt et al. 2010). However, the validity of the scalings relating the stellar parameters (mass, radius) and the seismic observables has yet to be thoroughly investigated for stars occupying different parts of the H-R diagram and having various properties in terms of metallicity and activity level, for instance. This work is an effort towards this goal (see also Miglio 2011) and also aims at drawing attention to the usefulness of seismic targets for validation purposes in the context of large-scale stellar surveys.

2. A sample of well-studied stars with a precise seismic gravity

About 40 bright, well-studied solar-like and red-giant stars have an accurate estimate of the frequency of maximum power, either from ground-based radial-velocity monitoring or from ultra-precise photometric observations from space (Table 1). These have been used, along with mean literature $T_{\rm eff}$ values (see Section 3) and assuming $\nu_{\rm max,\odot}$ = 3100 μHz, to compute the seismic gravities (the exact choice of $\nu_{\rm max,\odot}$, which has an uncertainty of ∼50 μHz, has a negligible impact on our results). The temperatures adopted are marginally higher than those derived from angular diameter and bolometric flux measurements (Bruntt et al. 2010): $<\Delta T_{\rm eff}>=+44\pm56$ K (1σ, 10 stars). Adopting these values would lead to negligible differences in the seismic $\log g$ (well below 0.01 dex). The uncertainty in $\nu_{\rm max}$, which is the main source of error, is often not quoted in the original literature source or its estimation relies on widely different criteria and assumptions. It is therefore impossible to properly account for the star-to-star differences in the data quality and provide a homogeneous set of uncertainties. Adopting various procedures for the determination of $\nu_{\rm max}$ and taking into account the different signal realizations arising from the stochastic nature of the oscillations, Hekker et al. (2011) inferred an uncertainty in the range 1–10% for stars observed by the *Kepler* mission. Based on the type of data collected for the stars in our sample, we estimate a typical uncertainty of 5%. This translates into an error in the seismic gravities of ∼0.03 dex only. These figures are supported by a comparison with the values for the three stars in binaries with dynamical masses and interferometric radii (Bruntt et al. 2010): the gravities agree to within 0.02 dex.

3. The classical gravity diagnostics used in late-type stars put to the test

As the stars in Table 1 are amongst the brightest in the sky and are even sometimes regarded as standards (e.g., α Boo or Procyon A), a large number of independent determinations from classical techniques can be found in the literature. This offers an opportunity to empirically assess the reliability of the most popular gravity diagnostics used in cool stars: ionization balance of a given chemical species (usually iron), fitting the wings of strong, pressure-sensitive metal lines or interpolation in theoretical isochrones. These three approaches suffer to different extents from drawbacks. First, non-LTE effects can bias the values obtained from ionization equilibrium, the problem becoming more acute for stars with extended atmospheres and/or metal poor (e.g., Allende Prieto et al. 1999). Another caveat is the neglect of granulation in 1-D model atmospheres. On the other hand, values obtained from fitting the wings of pressure-sensitive lines are generally affected by quite large uncertainties related, for instance, to

Table 1. Values of the frequency of maximum power, $\nu_{\rm max}$, for the stars in our sample. The typical uncertainty is 5% (see text). The original references for the seismic data are given. When not explicitly quoted in these papers, the $\nu_{\rm max}$ values were taken from Bruntt et al. (2010), Kallinger et al. (2010a) or Mosser et al. (2010). The value for 18 Sco was computed from the original data by A.-M. Broomhall (personal comm.).

	Name	$\nu_{\rm max}$ [μHz]	Ref.		Name	$\nu_{\rm max}$ [μHz]	Ref.
	Dwarfs			HD 165341	70 Oph A	4500	17
HD 2151	β Hyi	1000	1	HD 170987		930	18
HD 10700	τ Cet	4490	2	HD 175726		2000	19
HD 17051	ι Hor	2700	3	HD 181420		1500	20
HD 20010	α For	1100	1	HD 181906		1912	21
HD 23249	δ Eri	700	4	HD 190248	δ Pav	2300	1
HD 49385		1013	5	HD 203608	γ Pav	2600	22
HD 49933		1657	6	HD 210302	τ Psa	1950	9
HD 52265		2090	7				
HD 61421	Procyon A	1000	8		**Subgiants and giants**		
HD 63077	171 Pup	2050	9	HD 71878	β Vol	51	23
HD 102870	β Vir	1400	10	HD 100407	ξ Hya	92.3	24
HD 121370	η Boo	750	11	HD 124897	α Boo	3.47	25
HD 128620	α Cen A	2400	1	HD 146791	ϵ Oph	53.5	26
HD 128621	α Cen B	4100	1	HD 153210	κ Oph	35	23
HD 139211	HR 5803	2800	12	HD 161096	β Oph	46	27
HD 142860	γ Ser	1600	1	HD 163588	ξ Dra	36	23
HD 146233	18 Sco	3170	13	HD 168723	η Ser	125	28
HD 150680	ζ Her A	700	14	HD 188512	β Aql	410	1
HD 160691	μ Ara	2000	15	HD 211998	ν Ind	313	29
HD 161797	μ Her	1200	16		M67 S1305	208.9	27

Key to references: [1] Kjeldsen et al. (2008); [2] Texeira et al. (2009); [3] Vauclair et al. (2008); [4] Bouchy & Carrier (2003); [5] Deheuvels et al. (2010); [6] Kallinger et al. (2010b); [7] Ballot et al. (2011); [8] Arentoft et al. (2008); [9] Bruntt et al. (2010); [10] Carrier et al. (2005a); [11] Carrier et al. (2005b); [12] Carrier et al. (2008); [13] Bazot et al. (2011); [14] Martić et al. (2001); [15] Bouchy et al. (2005); [16] Bonanno et al. (2008); [17] Carrier & Eggenberger (2006); [18] Mathur et al. (2010); [19] Mosser et al. (2009); [20] Barban et al. (2009); [21] García et al. (2009); [22] Mosser et al. (2008); [23] Stello et al. (2009); [24] Frandsen et al. (2002); [25] Tarrant et al. (2007); [26] Kallinger et al. (2008); [27] Kallinger et al. (2010a); [28] Barban et al. (2004); [29] Bedding et al. (2006).

difficulties in continuum placement (e.g., Bruntt et al. 2010). Finally, although for very nearby stars parallaxes and reddening are not a major concern, values estimated from interpolation in theoretical isochrones are strongly model dependent and may suffer from degeneracy problems (as a result, the applicability of this method is limited for stars on the red-giant branch).

The $T_{\rm eff}$, [Fe/H] and $\log g$ literature values for the stars in Table 1 were primarily extracted from the PASTEL catalogue (Soubiran et al. 2010), but were supplemented by data from several missing sources. Only studies published after 1990 were considered, as older ones may be based on poor-quality data or inadequate model atmospheres. Each original reference was inspected to evaluate the method used for the $\log g$ determination. In some instances, a single value was quoted in PASTEL whereas estimates based on different techniques were reported in the original paper (e.g., Santos et al. 2004, 2005 where the gravities estimated from isochrone fitting

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are missing). These values were added. Finally, duplicate entries from the same authors were omitted; only the value in the most recent paper was used. This roughly totals to 360 individual measurements from 80 independent literature sources. The results are presented in Table 2.

Table 2. Mean effective temperature, iron content and mean surface gravities from the four different methods for the stars in Table 1. The error bars are the quadratic sum of the standard deviation of the individual measurements and the typical uncertainty in the parameter determination (80 K for $T_{\rm eff}$, 0.1 dex for [Fe/H], 0.1 dex for the ionization and isochrone gravities, and 0.15 dex for the strong-line gravities). The numbers in brackets are the number of measurements. The typical uncertainty in the seismic $\log g$ is 0.03 dex (see text).

				$\log g$			
	Name	$T_{\rm eff}$ [K]	[Fe/H]	seismology	ionization	wings	isochrone
			Dwarfs				
HD 2151	β Hyi	5829±107 (10)	−0.09±0.12 (11)	3.95	4.02±0.18 (6)	3.76±0.15 (1)	3.98±0.10 (8)
HD 10700	τ Cet	5334±103 (14)	−0.53±0.11 (14)	4.58	4.48±0.21 (12)	4.45±0.15 (1)	4.51±0.14 (5)
HD 17051	ι Hor	6136±120 (9)	0.15±0.12 (8)	4.39	4.48±0.15 (6)	4.40±0.15 (1)	4.40±0.13 (5)
HD 20010	α For	6154±141 (7)	−0.26±0.12 (7)	4.00	4.07±0.25 (4)	3.79±0.15 (1)	3.97±0.11 (4)
HD 23249	δ Eri	5060±111 (11)	0.12±0.13 (11)	3.76	3.86±0.18 (5)	3.95±0.27 (2)	3.82±0.21 (5)
HD 49385		6131±94 (2)	0.09±0.10 (1)	3.97	4.00±0.10 (1)	4.03±0.15 (1)	4.08±0.10 (1)
HD 49933		6580±120 (7)	−0.44±0.10 (5)	4.20	4.24±0.19 (4)	4.00±0.15 (1)	4.23±0.14 (3)
HD 52265		6097±92 (12)	0.19±0.11 (11)	4.28	4.31±0.16 (9)		4.29±0.11 (6)
HD 61421	Procyon A	6590±131 (13)	−0.03±0.11 (15)	3.98	4.06±0.32 (9)	3.92±0.20 (2)	4.01±0.11 (8)
HD 63077	171 Pup	5783±135 (8)	−0.86±0.14 (6)	4.26	4.16±0.19 (3)	4.00±0.15 (1)	4.22±0.15 (5)
HD 102870	β Vir	6131±107 (11)	0.13±0.11 (11)	4.11	4.11±0.16 (7)	3.97±0.15 (1)	4.13±0.11 (7)
HD 121370	η Boo	6059±143 (9)	0.23±0.11 (9)	3.83	3.83±0.29 (7)	3.90±0.15 (1)	3.80±0.11 (4)
HD 128620	α Cen A	5745±138 (14)	0.21±0.13 (14)	4.33	4.21±0.21 (9)	4.32±0.15 (1)	4.31±0.11 (6)
HD 128621	α Cen B	5191±126 (9)	0.24±0.11 (9)	4.54	4.46±0.12 (5)	4.52±0.15 (1)	4.54±0.11 (5)
HD 139211		6296±161 (3)	−0.15±0.18 (2)	4.41	4.05±0.10 (1)	4.10±0.15 (1)	4.20±0.15 (2)
HD 142860	γ Ser	6253±108 (10)	−0.19±0.12 (10)	4.17	4.05±0.17 (6)	4.02±0.15 (1)	4.20±0.12 (6)
HD 146233	18 Sco	5783±92 (13)	0.03±0.11 (13)	4.45	4.40±0.13 (10)		4.43±0.11 (7)
HD 150680	ζ Her A	5762±110 (6)	0.01±0.12 (6)	3.79	3.85±0.18 (3)		3.71±0.11 (5)
HD 160691	μ Ara	5732±104 (12)	0.26±0.11 (11)	4.25	4.20±0.20 (6)	4.07±0.15 (1)	4.23±0.11 (9)
HD 161797	μ Her	5532±105 (7)	0.23±0.13 (7)	4.02	3.98±0.10 (3)		3.94±0.17 (5)
HD 165341	70 Oph A	5221±135 (7)	0.00±0.15 (7)	4.58	4.38±0.19 (5)	4.56±0.15 (1)	4.52±0.11 (3)
HD 170987		6540±80 (1)	−0.15±0.10 (1)	3.94		4.35±0.15 (1)	
HD 175726		6031±88 (3)	−0.07±0.10 (2)	4.26	4.53±0.10 (1)		4.38±0.10 (2)
HD 181420		6671±151 (2)	0.00±0.10 (1)	4.15	4.26±0.10 (1)		4.23±0.10 (1)
HD 181906		6607±80 (1)		4.26			4.24±0.10 (1)
HD 190248	δ Pav	5558±129 (9)	0.30±0.16 (9)	4.30	4.23±0.15 (5)	4.32±0.15 (1)	4.32±0.12 (6)
HD 203608	γ Pav	6065±109 (11)	−0.73±0.13 (10)	4.37	4.22±0.35 (4)	4.15±0.15 (1)	4.33±0.12 (7)
HD 210302	τ Psa	6295±96 (3)	0.05±0.11 (2)	4.26	4.09±0.10 (1)	4.11±0.15 (1)	4.25±0.12 (2)
			Subgiants and giants				
HD 71878	β Vol	4736±246 (2)	−0.01±0.10 (1)	2.61	3.00±0.10 (1)		2.42±0.10 (1)
HD 100407	ξ Hya	5002±106 (5)	0.11±0.15 (4)	2.88	2.86±0.17 (2)	2.88±0.15 (1)	2.69±0.23 (3)
HD 124897	α Boo	4292±97 (17)	−0.58±0.11 (17)	1.42	1.61±0.25 (11)		1.84±0.29 (7)
HD 146791	ϵ Oph	4921±98 (8)	−0.09±0.13 (7)	2.64	2.82±0.20 (4)		2.73±0.23 (5)
HD 153210	κ Oph	4559±116 (4)	0.06±0.13 (3)	2.44	2.50±0.30 (2)		2.47±0.24 (2)
HD 161096	β Oph	4580±112 (6)	0.14±0.13 (5)	2.56	2.67±0.26 (3)		2.38±0.24 (3)
HD 163588	ξ Dra	4464±123 (3)	−0.05±0.11 (2)	2.45	2.40±0.10 (1)		2.46±0.24 (2)
HD 168723	η Ser	4927±89 (10)	−0.18±0.14 (9)	3.01	3.06±0.15 (7)	2.95±0.15 (1)	3.09±0.13 (6)
HD 188512	β Aql	5100±93 (8)	−0.20±0.12 (8)	3.53	3.58±0.14 (3)	3.69±0.15 (1)	3.55±0.11 (5)
HD 211998	ν Ind	5244±101 (7)	−1.54±0.14 (6)	3.42	3.31±0.18 (3)	3.70±0.15 (1)	3.40±0.11 (4)
	M67 S1305	4940±80 (1)	−0.08±0.10 (1)	3.23	3.20±0.10 (1)		

The comparison between the seismic $\log g$ values and those obtained through traditional techniques is shown in Fig. 1. Overall, there is a remarkably good agreement with systematic differences not exceeding 0.04 dex. The significant 1-σ dispersion of up to 0.19 dex with respect to the reference seismic values may have been expected considering the heterogeneous nature of the data and the diversity of analyses performed. By averaging results from a large number of

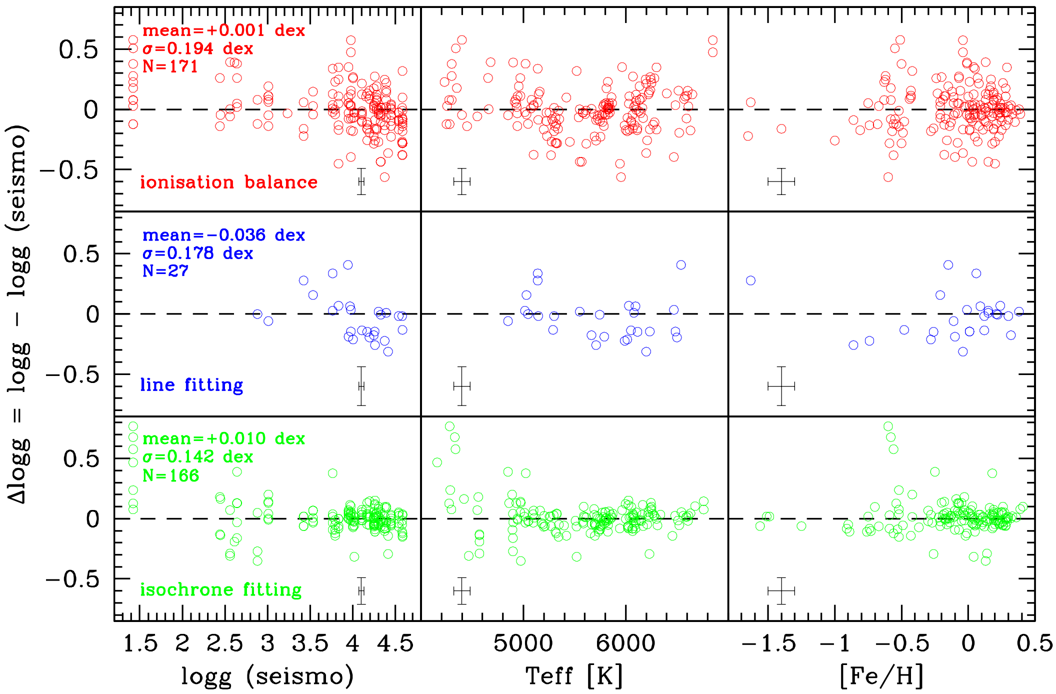

Figure 1. Difference between the seismic $\log g$ values and those obtained through ionization balance of iron (*top panels*), fitting of the wings of pressure-sensitive lines (*middle panels*) and isochrone fitting (*bottom panels*), as a function of the seismic gravities, effective temperature and metallicity. Representative error bars are shown.

independent studies (as is the case here for the ionization and isochrone gravities, but *not* for the strong-line ones), one can hope that the systematic errors partly cancel out and that the mean offset with respect to the seismic values provides a better appraisal of the true accuracy of the method. It should be kept in mind that the systematic differences which may exist between the various studies (discussed in Morel & Miglio 2011) might not be completely related to the method used, but instead to other assumptions in the modeling (e.g., $T_{\rm eff}$ scale). As a matter of fact, the $\log g$ values from the literature were associated to different temperatures than those adopted here. It can readily be seen that the scatter is lower for the gravities estimated from isochrone fitting. The same conclusion holds when considering for each star the average of the measurements obtained using a given method (Fig. 2), especially when one excludes the evolved objects ($\log g < 3.2$) for which the determination through the position of the star with respect to evolutionary tracks is ill defined. In that case, the difference scatter is a mere ∼15%: $<\Delta \log g>=-0.006\pm0.065$ dex (1σ, 29 stars). Although this method is generally the most precise, it must be stressed that the mean difference with respect to the seismic gravities is less than 0.05 dex irrespective of the technique used.

There is no evidence for trends as a function of $\log g$, $T_{\rm eff}$ or [Fe/H]. An underestimation of $\log g$ through ionization balance may be expected for very metal-poor stars ([Fe/H] < -1) because of non-LTE effects (Allende Prieto et al. 1999). We only have one such star in our sample (ν Ind), but the ionization gravity does not appear discrepant. The $\log g$ values are systematically underestimated in the dwarfs by up to 0.3 dex when fitting the wings of strong metal lines. However, the bulk of the data comes from a single source (Bruntt et al. 2010) and large line-to-line differences are observed (a weighted mean has been used here). Some of these results have recently been criticized by Fossati et al. (2011).

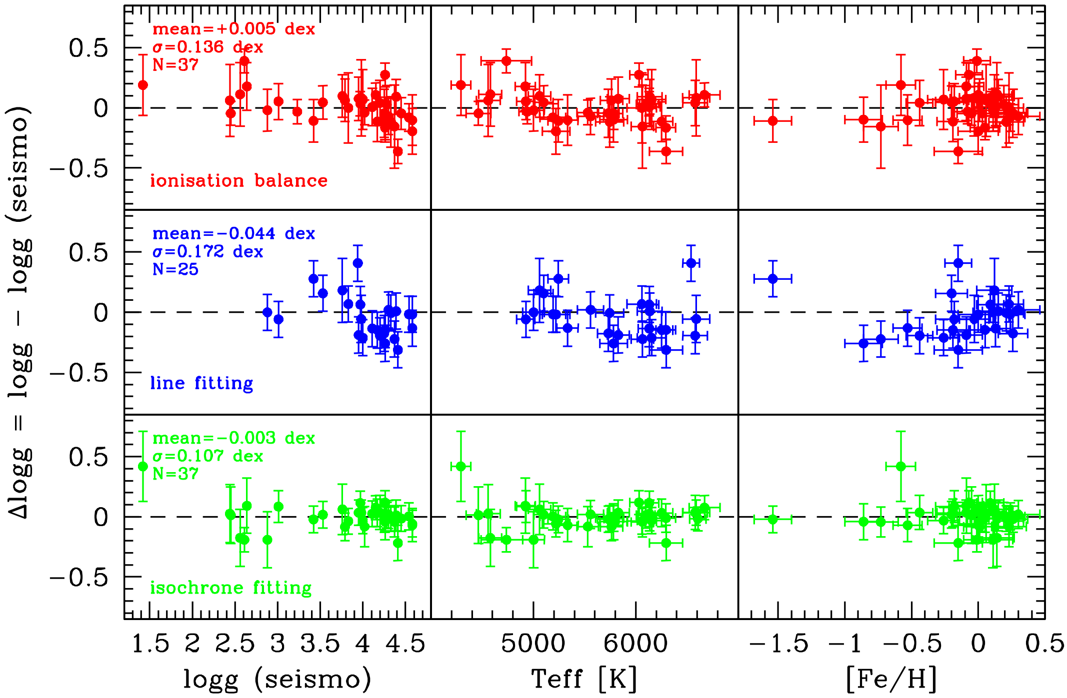

Figure 2. As Fig. 1, but with the data averaged on a star-to-star basis.

4. The case of the red-giant *CoRoT* targets

The *CoRoT* satellite has detected solar-like pulsations in hundreds of red giants in the so-called exoplanet fields (e.g., De Ridder et al. 2009). These stars are relatively faint ($11 < V < 16$) and a determination of their fundamental parameters from spectroscopic analyses is usually not available. However, a spectral analysis of some of these stars has recently been presented by Gazzano et al. (2010) based on GIRAFFE spectra and the automated software MATISSE. To assess the reliability of these results, we have determined the seismic gravities using the $\nu_{\rm max}$ values from Mosser et al. (2011) and temperatures computed from dereddened 2MASS (J–K_s) colors (Alonso et al. 1999). As can be seen in Fig. 3, the gravities appear largely overestimated with respect to the seismic ones, especially for stars in the Galactic centre direction (the LRc01 field) with the poorest signal-to-noise ratio (in the range 10–55). An independent analysis using the software developed by Valentini & Munari (2010) is underway. The benefit of a manual analysis of high-quality FEROS or HARPS spectra can clearly be seen in Fig. 3 for red giants in the seismology fields (Morel et al. 2011). The agreement is much better in that case.

5. Seismic targets as benchmark stars in the *Gaia* era

An accurate determination of the physical parameters of the sources detected by the forthcoming *Gaia* satellite is required for optimising the scientific return of the mission. These parameters ($T_{\rm eff}$, $\log g$, metallicity) will be derived within the coordination unit CU8 using data acquired with both the BP/RP (down to $V\sim19$) and RVS (down to $V\sim13$) photometric and spectroscopic onboard instruments (for the brightest sources, this will also be achieved through ambitious ground-based observing campaigns, most notably the so-called 'Gaia-ESO Public survey').

The algorithms developed for this purpose by CU8 (GSP-phot and GSP-spec) will be calibrated using a set of well-studied benchmark stars with an accurate determination of the fundamental parameters in the literature. The preliminary list of candidates includes many of

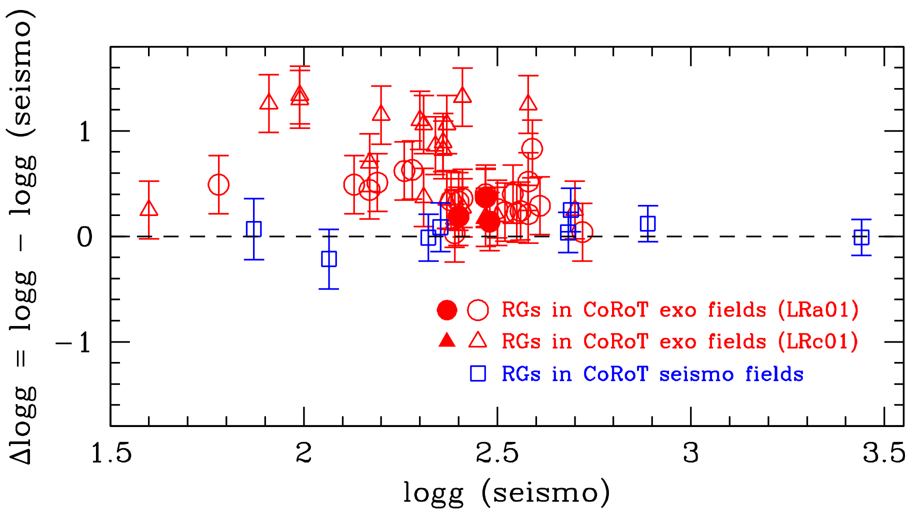

Figure 3. Difference for the red-giant *CoRoT* targets between the seismic $\log g$ values and those derived from spectral synthesis of GIRAFFE spectra with MATISSE (Gazzano et al. 2010; *red*) and from ionization balance of iron using high-resolution spectra (Morel et al. 2011; *blue*). The stars in the exoplanet fields belonging to the red clump (as diagnosed by the $l = 1$ pulsation modes; see Mosser et al. 2011) are indicated with filled symbols.

the solar-like pulsators in Table 1. The seismic gravities can hence constitute a valuable piece of information in this context. Of particular interest in this respect are the stars with an accurate $T_{\rm eff}$ and $\log g$ estimate from interferometric and seismic observations, respectively.

6. Conclusions

The good agreement between the gravities inferred from asteroseismology and from classical methods supports the applicability of the scaling law linking $\log g$ and $\nu_{\rm max}$ for stars spanning a relatively wide range in temperature and evolutionary status (its validity in the low-metallicity and low-gravity regimes cannot, however, be meaningfully investigated here owing to the limited number of objects). In turn, this also suggests that the global seismic properties can be used to retrieve the stellar mass and radius to high accuracy (see, e.g., Miglio 2011). Although the scope of this comparison is limited in some cases by the fundamental difficulties plaguing the classical techniques (e.g., isochrone fitting in giants), seismic gravities may therefore provide a promising alternative in the case of the faint *CoRoT* (see Section 4) or *Kepler* (see, e.g., Bruntt et al. 2011) targets whose spectroscopic gravities may be attached by large uncertainties.

A comparison with data for detached eclipsing binaries has already illustrated the power of isochrone fitting as gravity indicator (Allende Prieto & Lambert 1999), and our study indeed identifies it as being the most precise classical method for nearby dwarfs.

Finally, several large-scale spectroscopic surveys are being planned or are presently conducted. The pipelines developed for that purpose should be able to recover the parameters determined through completely different and, as much as possible, model-independent methods for a set of training stars before embarking on the automatic analysis of large samples of potentially faint objects. Asteroseismic targets may be of interest in this context.

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