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Letter to the Editor

The universal red-giant oscillation pattern

An automated determination with CoRoT data

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ABSTRACT

Aims. The CoRoT and *Kepler* satellites have provided thousands of red-giant oscillation spectra. The analysis of these spectra requires efficient methods of identifying all eigenmode parameters.

Methods. The assumption of new scaling laws allowed us to construct a theoretical oscillation pattern. We then obtained a highly precise determination of the large separation by correlating the observed patterns with this reference.

Results. We demonstrate that this pattern is universal and are able to unambiguously assign the eigenmode radial orders and angular degrees. This solves one of the remaining problems of asteroseismology, hence allowing precise theoretical investigation of red-giant interiors.

Key words. stars: oscillations – stars: interiors – methods: data analysis – methods: analytical

1. Introduction

Red giants are evolved stars that have depleted the hydrogen in their cores and are no longer able to generate energy from core-hydrogen burning. The physical processes taking place in their interiors are currently fairly poorly understood. Observations with the space-borne mission CoRoT have revealed the oscillation pattern (De Ridder et al. 2009) of many of these stars, which is a crucial step toward probing their internal structure. Before the advent of the CoRoT data, complex oscillation patterns were explained by short-lived modes of oscillation (Stello et al. 2004; Barban et al. 2007). The new era of the space-borne missions CoRoT and *Kepler* has dramatically increased the amount and quality of the available asteroseismic data of red giants (Hekker et al. 2009; Bedding et al. 2010a; Mosser et al. 2010; Huber et al. 2010). Analysis of the oscillation eigenmodes now allows seismic inferences to be drawn about the internal structure.

Identifying the angular degree and radial order of the eigenmodes represents a first and crucial step in asteroseismic analysis. The values of the eigenfrequencies can be related to the order and degree of a mode with the commonly used asymptotic equation:

$$\nu_{n,\ell} = \left[n + \frac{\ell}{2} + \varepsilon \right] \Delta\nu - \delta\nu_{0\ell} \tag{1}$$

where $\nu_{n,\ell}$ is the eigenfrequency of a mode with radial order n and angular degree ℓ; $\Delta\nu$ is the mean value of the large separation ($\Delta\nu \simeq \nu_{n+1,\ell} - \nu_{n,\ell}$), and $\delta\nu_{0\ell}$ a second-order term, or small separation, which depends on the mode degree. This form, which is similar to the original expression developed for the Sun 30 years ago (Tassoul 1980), is useful for analysing the observations and performing the complete mode identification. It assumes that $\delta\nu_{00}$ equals 0. The parameter ε comprises two parts: the offset due to the mode propagation in the uppermost layers of the star, and the second-order term of the asymptotic approximation, which is sensitive to the gradient of sound speed in the stellar interior.

In the absence of accurate determinations of the individual mode frequencies, the global seismic parameters used in the asymptotic expression above are important indicators of the physical parameters of the star. The large separation gives a measure of the mean stellar density; the small separation $\delta\nu_{0\ell}$ describes the stratification of the central regions. Unfortunately, the methods currently used to determine the global oscillation parameters suffer from various sources of uncertainty (Hekker et al. 2009; Huber et al. 2009; Mathur et al. 2010). First, the stochastic excitation of the modes gives rise to variability in the amplitudes, resulting in an apparently irregular comb structure; second, the finite mode lifetime blurs the estimates of the eigenfrequencies; third, estimates are affected by the stellar noise and granulation signal superimposed on the oscillations (Mosser & Appourchaux 2009). In fact, simulations have shown that the impact of realization noise on the measurement of the large separation $\Delta\nu$, can be much stronger than the background noise for red giants (Hekker et al. 2010).

In an analysis of a subsample of *Kepler* red giants, Huber et al. (2010) have shown the regularity of the oscillation spectra of these stars. In this paper, we show that all red giants have a regular pattern, as modelled recently by Montalbán et al. (2010). We propose a method that allows us to tag all the modes with their appropriate radial order and angular degree, regardless of whether there are any of the perturbing effects described above.

2. Method

The method of mitigating the effects of realization noise uses Eq. (1) in a dimensionless form:

$$\frac{\nu_{n,\ell}}{\Delta\nu} = n + \frac{\ell}{2} + \varepsilon(\Delta\nu) - d_{0\ell}(\Delta\nu). \quad (2)$$

In a departure from the previous practice, we have assumed that ε obeys a scaling law $\varepsilon = A + B \log \Delta\nu$, as derived from the observation of thousands of CoRoT targets (Mosser et al. 2010) and as observed by Huber et al. (2010). This is justified by the observation that scaling laws apparently govern *all* global asteroseismic parameters (Hekker et al. 2009; Stello et al. 2009; Bedding et al. 2010a; Mosser et al. 2010) and is equivalent to assuming that the underlying physics of ε varies with the global stellar parameters. As the mixed nature of dipole modes ($\ell = 1$) is more pronounced, we did not include them in the template, but only those doublets that correspond to the eigenmodes with even degrees ($\nu_{n-1,2}$ and $\nu_{n,0}$), with equal amplitudes. As a first guess, we set the small separation d_{02} at -0.14 and then allowed it to vary with the value of $\Delta\nu$ according to the same relationship as given for ε. For constructing the peaks of the template, we also used the scaling laws of the Gaussian excess power derived by Mosser et al. (2010). We assumed that the mode lifetime varies as $\Delta\nu^{-1}$ and used mode widths equal to about a few percent of $\Delta\nu$. Finally, we stress that no background model is needed.

The measurement of the large separation is performed in two steps. First, an initial-guess value $\Delta\nu_{\rm guess}$ of the large separation is computed by an automated pipeline (Mosser & Appourchaux 2009). This is used to form the initial synthetic template to correlate with the real spectrum. The best correlation between the observed and synthetic spectra then provides the corrected value of the large separation. The template was iteratively adjusted by varying its parameters to maximize the correlation.

In Fig. 1, we show the results with all high signal-to-noise CoRoT data (Mosser et al. 2010). In both cases the graphs show the spectra arranged in strips with the colour representing the strength of the signal, as in Gilliland et al. (2010). The spectra are sorted by increasing large separation with the smallest large separation at the top of the plots: in the upper plot we use the output from a conventional pipeline and in the lower one the corrected value. The remarkably regular structure within the oscillation spectra in the lower plot reveals the signature of comb-like structure of the asymptotic relationship in Eq. (2) already reported in De Ridder et al. (2009), Carrier et al. (2010), Bedding et al. (2010a), and Huber et al. (2010). Furthermore, it validates the scaling law in ε included in the reference template. The global agreement of all high signal-to-noise spectra of bright targets with the synthetic pattern (Fig. 2) shows that these oscillation patterns are homologous and that the red-giant oscillation pattern is universal.

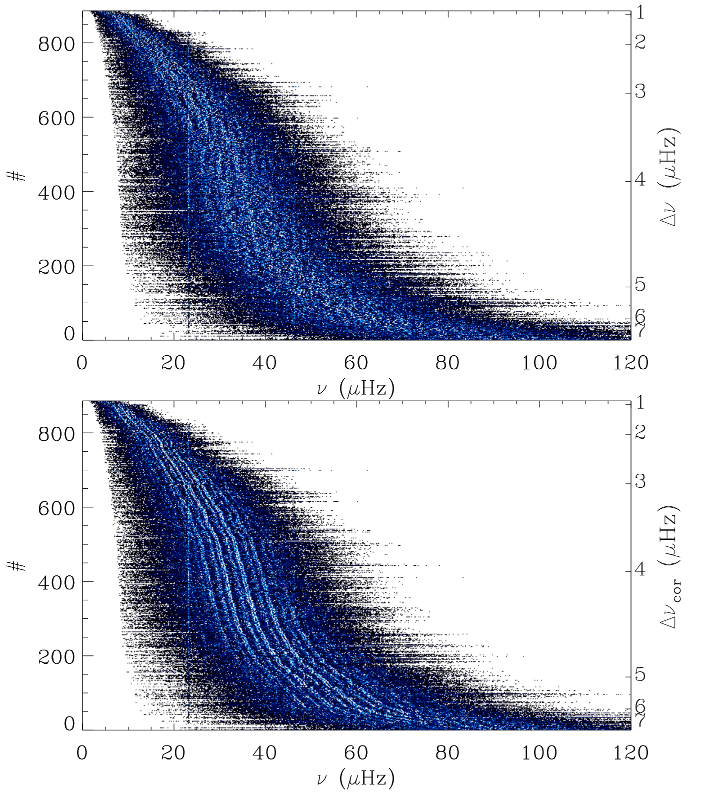

Fig. 1. CoRoT red giant power spectra stacked into an image after sorting on the large separation. One line corresponds to one star. **a)** The first sorting is based on the large separation before any correction. **b)** The blurred aspect disappears once the correction has been performed and reveals the clear comb structure common to all red giants. The vertical lines at 23.2 μHz are the signature of the low-Earth orbit (Auvergne et al. 2009).

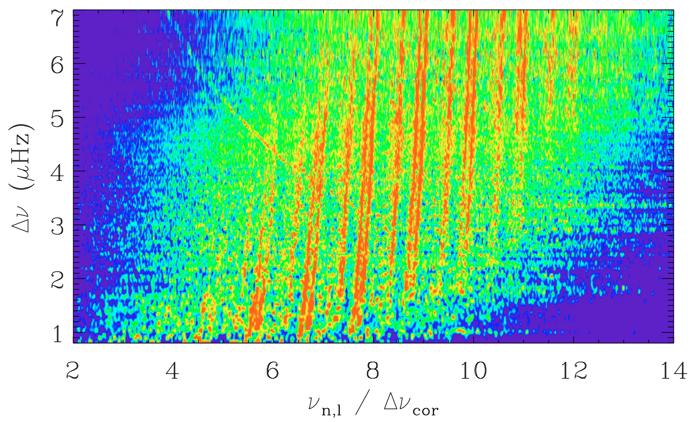

Fig. 2. Spectra presented in Fig. 1b rearranged to have the dimensionless frequency on the abscissa and the mean large separation on the ordinate. The hyperbolic branch is here the signature of the low-Earth orbit.

We further found that the template is significantly improved if it takes account of the linear dependence of the large separation in frequency, expressed by the degree-dependent gradient $\alpha_\ell = (\mathrm{d}\log\Delta\nu/\mathrm{d}n)_\ell$:

$$\frac{\nu_{n,\ell}}{\Delta\nu} = n + \frac{\ell}{2} + \varepsilon(\Delta\nu) - d_{0\ell}(\Delta\nu) + \frac{\alpha_\ell}{2}\left(n - \frac{\nu_{\max}}{\Delta\nu}\right)^2 \quad (3)$$

with $\nu_{\max}$ the frequency of maximum oscillation amplitude. The corrected values of $\Delta\nu$ are derived from this template. The values of the 12 free parameters that account for the variations in

Table 1. Fits of the ridges.

ℓ		Fit $A_\ell + B_\ell \log \Delta\nu$		Gradient of $\Delta\nu_\ell$
		A_ℓ	B_ℓ	α_ℓ
0	ε	0.634 ± 0.008	0.546 ± 0.008	0.008 ± 0.001
1	d_{01}	−0.056 ± 0.012	−0.002 ± 0.010	0.003 ± 0.002
2	d_{02}	0.131 ± 0.008	−0.033 ± 0.009	0.005 ± 0.001
3	d_{03}	0.280 ± 0.012	0	0.005 ± 0.002

Notes. for $\Delta\nu$ expressed in μHz, in the range [0.6, 10] μHz.

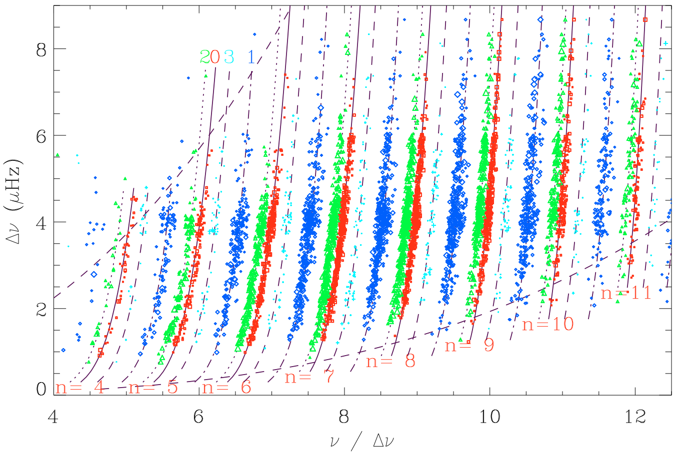

Fig. 3. Complete identification of the ridges, automatically derived from the eigenfrequencies extracted with a height-to-background ratio greater than 3. Each colour corresponds to a different mode degree (radial modes in red, dipole modes in dark blue, $\ell = 2$ modes in green, $\ell = 3$ modes in light blue). The solid grey lines superimposed on the ridges indicate the fits of ε for each radial order (with indication of the radial order n). The fits of d_{01}, d_{02} and d_{03} are superimposed on the respective ridges (respectively dash-dot, dot, and dash lines for ℓ =1, 2, and 3). The dark dashed lines, derived from the scaling law dealing with the oscillation excess power, delineate the region where the modes have noticeable amplitudes (Mosser et al. 2010).

frequency of the parameter ε, of the small separations $d_{0\ell}$, and of the gradients α_ℓ as derived from the fits to more than 6000 eigenmodes (Fig. 3) are given in Table 1. The value of ε, defined modulo 1, is fixed thanks to the extrapolation to the solar case. As noted by Carrier et al. (2010) and Huber et al. (2010), the small separation d_{01} is negative. All these fits are consistent with *Kepler* results.

The average value of the correction from $\Delta\nu_{\text{guess}}$ to $\Delta\nu$ is of the order of 2.5%. For the largest giants, with the lowest values of $\Delta\nu$ and the lowest ratio $\nu_{\max}/\Delta\nu$, the correction can be as high as 6%. The absolute difference $|\Delta\nu_{\text{guess}} - \Delta\nu|$ can be 10 times the estimate of the stellar noise contribution. At low frequency, with an observing run not much longer than the mode lifetimes (Baudin et al. 2010), the realization noise dominates the background noise and the mean accuracy of the determination of $\Delta\nu$ is uniform, at about 0.015 μHz. We are aware that any bias in the $\varepsilon(\Delta\nu)$ input relation will induce a bias in the results. We therefore took care to insure that the iterative process is unbiased. Analysis of synthetic data indicates that the precision gained with this method is about 10 times better than obtained with conventional methods (Hekker et al. 2010).

3. Discussion

This new method based on a simple hypothesis and an automated procedure removes any ambiguity in the identification of the modes (Fig. 3), despite the complexity induced by mixed modes. Mode identification is derived by looking at the closest ridge. In particular, we provide a straightforward determination of the mode radial orders, which were previously unknown. Radial eigenfrequencies are located at

$$\nu_{n,0} = [n + \varepsilon(\Delta\nu)]\ \Delta\nu. \tag{4}$$

Ridges have already been shown in previous works. While De Ridder et al. (2009) and Carrier et al. (2010) looked at single stars separately, Bedding et al. (2010a) and Huber et al. (2010) used manual fine-tuning of the large separation to align the radial modes of a large sample of stars. However, the radial modes were identified in only one third of the spectra by Huber et al. (2010), but they also showed the ridges with varying ε in the folded and collapsed power spectrum.

In most regions of the oscillation spectra, we observe the presence of both radial and non-radial modes. Realization noise causes the height of the individual modes to show considerable variability, but on average, the ratio between the dipole and radial mode height is almost independent of $\nu_{\max}$, although there is some reduction in the strength of the dipole mode at very low $\nu_{\max}$. We also make it clear that the larger spread of the ridges corresponding to dipole modes (Fig. 3) comes from the presence of many mixed modes, as already noticed (Dupret et al. 2009; Bedding et al. 2010a). The universal pattern makes it easier to identify them, opening up the possibility of exploring the conditions in the inner layers of the red giants.

Despite their low amplitudes and the resulting poor signal, $\ell = 3$ modes have been detected in *Kepler* data on red giants (Bedding et al. 2010a; Huber et al. 2010). Our results represent the first such detection in CoRoT data. This identification gives access to the fine structure of the oscillation spectra, because modes of different angular degree probe different depths within the star. Their detection and complete characterization will first be derived from the universal pattern, then the small differences to this pattern will be exploited to characterize a given object in detail (Miglio et al. 2010).

More than 75% of the red-giant candidates with brighter magnitudes than $m_{\text{R}} = 13$ observed with CoRoT show solar-like oscillations. In the remainder, we observe a high proportion of classical pulsators or of giants with such a large radius that the oscillations occur at too low a frequency for positive detection. In a very limited number of cases at very low frequency, the possible confusion between radial and dipole modes is not clearly solved. This confusion increases toward dimmer targets with lower quality time series. Among the positive detections of bright stars, we did not observe any outliers when performing the correlation with the universal pattern. For this procedure to be effective, we require that the modes have a significant height-to-background ratio. Hence, for all high signal-to-noise targets (Mosser et al. 2010) we are able to derive corrected values for the large frequency spacing.

It is recognized that the majority of the red giants in the CoRoT field of view are in their post-flash helium-burning phase (Miglio et al. 2009). In terms of stellar evolution, demonstration of the universal regular pattern of red giants proves that these red giants have similar and homologous interior structures. On the other hand, despite the agreement of the fit in ε with the solar value, we have verified that the method does not work with

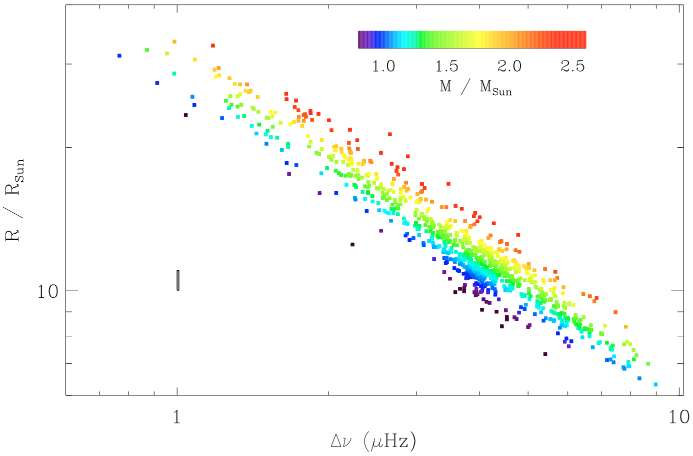

Fig. 4. Variation in stellar mass and radius as a function of the large separation $\Delta\nu$. The vertical line corresponds to the error box in large separation and radius.

subgiants or main-sequence stars (Barban et al. 2009; Benomar et al. 2009; Bedding et al. 2010b; Deheuvels et al. 2010). We explain this by the wide range of evolutionary phases that pertain outside the red clump, which certainly will cause a complex dependence of ε on more parameters than just the large separation. This disagreement reinforces the homogenous properties of red-giant stars. The clearly observed pattern confirms that, on average, the linewidths of the modes are significantly smaller than the separation of the even mode pairs and hence makes short mode lifetimes unlikely (Stello et al. 2004). From the quasi-uniform width of the ridges (Fig. 3), we can see that the lifetimes of the modes increase significantly with decreasing large separation, contrary to Huber et al. (2010). It also suggests that very complex previously observed oscillation spectra may be an artefact of noise.

Finally, the better determination of the large separation $\Delta\nu$ helps us to enhance the accuracy of the estimates of the stellar mass and radius as done in Mosser et al. (2010), with typical error bars of 12 and 5%, respectively, instead of 20 and 8% (Fig. 4). This accuracy, achieved without the need of stellar modelling (Kallinger et al. 2010), constitutes an important progress compared to the current photometric determination and demonstrates the power of asteroseismology.

4. Conclusion

We have shown with CoRoT observations that the red-giant oscillation spectrum is very regular and can be described by its underlying universal pattern. This was modelled in parallel by Montalbán et al. (2010). As a consequence, the precise measures of the large separation and the scaling relation of the parameter ε allow us to provide an unambiguous detection of the radial orders and angular degrees of the modes. Since the method is able to mitigate the realization noise, we consider it to give the most precise determination of the large separation available.

It remains important to interpret the physical meaning of the scaling law for the term ε in the Tassoul expression. We will have to disentangle the contributions of the surface and of the inner region. This will require investigating the term ε in the context of the second-order corrections of the Tassoul development. Very long-duration observations with *Kepler* will help for this task.

Despite the uniform aspect of the oscillation spectra, many differences invisible in the global approach are revealed by a detailed analysis of each individual spectrum, as, for example, the modulation with frequency of the large separation (Mosser et al. 2010). Study of this variation will give access to the most accurate analysis of the red-giant interior structure available so far. This summarizes the power of asteroseismology: first, the regular pattern provides the identification of the individual modes; second, the difference to this regular pattern unveils the detailed interior structure. We are confident that the shifts to the regular pattern will be explained by mass, age, and/or metallicity effects.

Similar analysis can be performed for oscillations in subgiants and solar-like stars (Michel et al. 2008; Appourchaux et al. 2008). Thanks to the wide variety of evolutionary stages among those stars, we expect the Tassoul parameter ε to depend on more than the large separation.

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