GRANULATION IN RED GIANTS: OBSERVATIONS BY THE KEPLER MISSION
AND THREE-DIMENSIONAL CONVECTION SIMULATIONS

S. Mathur1, S. Hekker2,3, R. Trampedach4, J. Ballot5,6, T. Kallinger7,8, D. Buzasi9, R. A. García10, D. Huber11, A. Jiménez12,13, B. Mosser14, T. R. Bedding11, Y. Elsworth13, C. Régulo13, D. Stello11, W. J. Chaplin3, J. De Ridder3, S. J. Hale3, K. Kinemuchi15, H. Kieldsen16, F. Mullally17, and S. E. Thompson17

1 High Altitude Observatory, NCAR, P.O. Box 3000, Boulder, CO 80307, USA
2 Astronomical Institute “Anton Pannekoek,” University of Amsterdam, P.O. Box 94249, 1090 GE Amsterdam, The Netherlands
3 School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
4 JILA, University of Colorado and National Institute of Standards and Technology, 440 UCB, Boulder, CO 80309, USA
5 Institut de Recherche en Astrophysique et Planétologie, CNRS, 14 avenue E. Belin, 31400 Toulouse, France
6 Université de Toulouse, UPS-OMP, IRAP, 31040 Toulouse, France
7 Institute for Astronomy (IfA), University of Vienna, Türkenschanzstraße 17, 1180 Vienna, Austria
8 Institut voor Sterrenkunde, K.U. Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
9 Eureka Scientific, 2452 Delmer Street Suite 100, Oakland, CA 94602-3017, USA
10 Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot–IRFU/SAp, 9191 Gil-sur-Yvette Cedex, France
11 Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia
12 Dpto de Astrofísica, Universidad de La Laguna, 38206, Tenerife, Spain
13 Instituto de Astrofísica de Canarias, 38205, La Laguna, Tenerife, Spain
14 LESIA, UMR8109, Université Pierre et Marie Curie, Université Denis Diderot, Obs. de Paris, 92195 Meudon Cedex, France
15 Bay Area Environmental Research Inst./NASA Ames Research Center, Moffett Field, CA 94035, USA
16 Danish AsteroSeismology Centre, Department of Physics and Astronomy, University of Aarhus, 8000 Aarhus C, Denmark
17 SETI Institute/NASA Ames Research Center, Moffett Field, CA 94035, USA

ABSTRACT

The granulation pattern that we observe on the surface of the Sun is due to hot plasma rising to the photosphere where it cools down and descends back into the interior at the edges of granules. This is the visible manifestation of convection taking place in the outer part of the solar convection zone. Because red giants have deeper convection zones than the Sun, we cannot a priori assume that their granulation is a scaled version of solar granulation. Until now, neither observations nor one-dimensional analytical convection models could put constraints on granulation in red giants. With asteroseismology, this study can now be performed. We analyze ∼1000 red giants that have been observed by Kepler during 13 months. We fit the power spectra with Harvey-like profiles to retrieve the characteristics of the granulation (timescale $t_{\text{gran}}$ and power $P_{\text{gran}}$). We search for a correlation between these parameters and the global acoustic-mode parameter (the position of maximum power, $v_{\text{max}}$) as well as with stellar parameters (mass, radius, surface gravity ($\log g$), and effective temperature ($T_{\text{eff}}$)). We show that $T_{\text{eff}} \propto v_{\text{max}}^{-0.89}$ and $P_{\text{gran}} \propto v_{\text{max}}^{-1.90}$, which is consistent with the theoretical predictions. We find that the granulation timescales of stars that belong to the red clump have similar values while the timescales of stars in the red giant branch are spread in a wider range. Finally, we show that realistic three-dimensional simulations of the surface convection in stars, spanning the ($T_{\text{eff}}$, $\log g$) range of our sample of red giants, match the Kepler observations well in terms of trends.

Key words: methods: data analysis – stars: late-type

Online-only material: color figures

1. INTRODUCTION

Granulation was first observed by Herschel (1801) on the Sun and is widely known as the surface signature of convection, where bright cells of ascending hot gas are visible as the granules and the darker descending cool gas are the so-called intergranular lanes. These solar granules have typical sizes of about 1 Mm. The study of granulation is tightly related to the analysis of convection quantities, being the most important manifestation of convection at the surface of the Sun in terms of energy. Other phenomena related to convection are the acoustic (p-mode) oscillations that reveal the internal structure of the Sun. These oscillations are stochastically excited in the convective atmosphere.

Red giants are cool, bright, and evolved stars. They have a surface gravity, $\log g$, between 2 and 4 and an effective temperature, $T_{\text{eff}}$, in the range ~4000 to ~6000 K, as defined by Ciardi et al. (2011). For these stars, the mass is roughly in the range $0.7-4 \ M_\odot$ and $\log (L/L_\odot)$ varies from 0.3 to 3 (Miglio et al. 2009; Hekker et al. 2011a). They are interesting not only because they provide constraints on distance, age, and chemical evolution of stars, galaxies, and the extragalactic medium (e.g., Girardi & Salaris 2001) but they also serve as laboratories for studying convection, granulation, and p-mode oscillations. As in the Sun, the inefficient, super-adiabatic convection in the upper few pressure scale heights is host to sonic, turbulent flows that stochastically excite sound waves—these stochastic oscillations are also known as solar-like oscillations. The unambiguous detection of non-radial oscillations in red giants (De Ridder et al. 2009) from photometric time series of several hundreds of red giants obtained with the CoRoT satellite (Convection, Rotation and planetary Transits, Baglin et al. 2006) was a significant step forward in red giant seismology. These observations also allowed the study of p-mode global parameters and their scaling laws (Hekker et al. 2009; Mosser et al. 2010; Mosser 2010) to estimate their masses and radii (Kallinger et al. 2010b), and to
even retrieve evidence of sharp features in their internal structure (Miglio et al. 2010) from, for instance, the second ionization zone of helium.

The launch of NASA’s Kepler mission (Borucki et al. 2010) in 2009 March took the next big step in asteroseismology. The Kepler field of view is 105 deg² in the direction of Cygnus and Lyra and the filter of the photometer ranges from 4300 to 8800 Å, with a broad peak at 5900 Å. In total about 150,000 stars are observed with high-precision photometry throughout the nominal lifetime (3.5 years) of the mission. While for ~17,000 red giants only a few months of data have been released to the public domain (Ciardi et al. 2011; Hekker et al. 2011a), around 1500 red giants with time series longer than a year are at our disposal within the Kepler Asteroseismic Science Consortium (KASC; Bedding et al. 2010; Hekker et al. 2011b; Huber et al. 2010; Kallinger et al. 2010a; Mosser et al. 2011c). We thus have exquisite data for studying not only the acoustic modes and their dependence on stellar parameters, but we can also, for the first time, study properties of surface convection of a large sample of red giants. The observations and data processing that we have used are described in Section 2.

When studying the p modes of stars, granulation is normally considered a “noise” term and referred to as “background.” In the present paper, however, we use this background signal to investigate the surface manifestation of convection and the source of p-mode excitation. In Section 3, different methods used to extract characteristic granulation parameters from the power spectra are described and compared. In Section 4, we investigate the correlations between granulation properties, stellar parameters (mass, radius, surface gravity, and $T_{\text{eff}}$), and the frequency of maximum power, $v_{\text{max}}$.

From a modeling point of view, convection can be treated either by one-dimensional analytical models, or by two-dimensional or three-dimensional hydrodynamical simulations. The three most employed analytical models of convection are the mixing-length theory (MLT; Bohm-Vitense 1958), non-local MLT formulations (e.g., Unno 1967; Gough 1977a, 1977b; Dupret et al. 2006), and the Canuto and Mazzitelli model (CM; Canuto & Mazzitelli 1991, 1992). All of these formulations of convection are employed in stellar-structure modeling, but have severe shortcomings in the surface layers, where most of the approximations they are built on break down (for more details, see Trampedach 2010). In addition to these shortcomings, the free parameters of the analytical models suffer from large uncertainties. As a result, the analytical models have only limited predictive power. None of the analytical models deal with granulation, and estimates of sizes, contrasts and flow speeds rely on a number of additional assumptions.

Contrary to one-dimensional analytical models, realistic numerical simulations of convection are based on the quantum mechanics of the equation of state (EOS) and opacities and the fundamental physics of radiative transfer and hydrodynamics. However, the simulations are also limited by the available computational power and hence employ various approximations to make them tractable. Most of these approximations, such as the effect of a limited numerical resolution can be quantified (Asplund et al. 2000).

Although two-dimensional simulations can be run at much higher resolution, the topology of convection is fundamentally altered by the lack of a third dimension, and the properties of the two-dimensional simulations cannot be directly related to observations of stars. Since the top boundary of convective envelopes occurs in the photosphere, a realistic treatment of radiative transfer is also necessary when the aim is to produce simulations that can be directly compared to observations (Nordlund et al. 2009, and references therein). The surface layers are, of course, the very layers we observe, which is the reason why we turn to more realistic, three-dimensional convection simulations for guidance in the interpretation of the Kepler observations.

Previously, Collet et al. (2007) used three-dimensional red giant simulations for abundance analysis for $[\text{Fe/H}] = 0 \rightarrow -3$, using the same code and atomic physics as presented here (Stein & Nordlund 2000). They find metallicity effects on the granulation with increased size of the granules for increased metallicity values. Some three-dimensional radiative-hydrodynamics simulations are also done for subgiant stars (Robinson et al. 2004). Ludwig et al. (2009) compared their three-dimensional radiative-hydrodynamics simulation carried out with CO5BOLD code with the CoRoT observations of the F-type dwarf, HD 49933. They found a significant overestimation of the theoretical signal by a factor of two to three in total power.

In this work, we use the simulations performed with the Stein & Nordlund (2000) code and compare them to observations of ~1000 red giants. The simulations are introduced in Section 5, where we also explain the synthetic Kepler data of these simulations and compare the results of the simulations with the observations.

2. OBSERVATIONS

2.1. Sample Selection

In the present investigation we used Kepler observations of red giants showing solar-like oscillations, which were pre-selected for asteroseismic or astrometric purposes before launch of the spacecraft. While the asteroseismic sample is composed of subsamples with different selection criteria, the astrometric sample, which consists of the majority of our total sample, has been selected coherently. These ~1000 stars are selected to be (1) as distant as possible, to ensure small parallaxes and proper motions, (2) as bright as possible, but with very small chances of saturating the detector in any season, (3) located in fields as uncrowded as possible, and (4) uniformly distributed over the focal plane and not close to the edge of a CCD. This resulted in the following criteria:

1. $T_{\text{eff}} < 5400 \text{ K},$
2. $\log g < 3.8 \text{ c.g.s.},$
3. 11.0 mag < Kepler magnitude < 12.5 mag,
4. crowding > 0.95 (i.e., very low probability of having light from another source).

$T_{\text{eff}}$ and log g from the Kepler Input Catalog (KIC; Batalha et al. 2010; Koch et al. 2010; Brown et al. 2011) have been used.

Long-cadence (~29.4 minute sampling) data of the first 10 days (Q0), the initial one-month roll (Q1), and each of the following three-month rolls (Q2, Q3, Q4, and Q5) have been used to obtain long time series of more than one year of data (Jenkins et al. 2010). We have used data processed as described in García et al. (2011) in which instrumental effects, such as satellite safe-mode events or attitude adjustments, have been removed. These effects can affect the high-frequency range when jumps happen in the light curve or the low-frequency range when a safe-mode event is observed. Long-term variations have been preserved, which could contain signal of stellar origin, e.g., granulation, but also from instrumental effects. The latter are filtered out with a procedure described below (Section 2.2).
Among the 1283 stars for which we have Q012345 data, we have selected a sample of ~1000 red giants (900–1100 depending on the method used to analyze them), corresponding to the ones where different teams returned values in agreement for the mean large separation, \((\Delta
u)\), and the position of maximum power, \(\nu_{\text{max}}\). See Hekker et al. (2011b) and references therein for descriptions and comparisons of the different methods and results.

2.2. Removing Instrumental Long-Term Variation

From the long-term variations preserved in the data (García et al. 2011), we need to remove the instrumental signal without affecting the granulation signal. We assume that the characteristic granulation timescale \(\tau_{\text{gran}}\) is of the same order as the timescale of the oscillations, as is the case for the Sun (see, e.g., Vázquez Ramió et al. 2005). For red giants we therefore expect \(\tau_{\text{gran}}\) to be of the order of hours up to a few days for the largest stars of our sample. Note that these equivalent timescales differ by roughly a factor of \(\pi\) in the frequency domain as an \(e\)-folding time of \(\tau\) in power equates to a position in the frequency domain of \(1/(\pi \tau)\), while a wave of period \(T\) has a frequency of \(1/T\).

We have investigated effects of different high-pass filters used to remove the signature of signals with periods longer than the expected \(\tau_{\text{gran}}\) for red giants, which we assume to be (partly) due to instrumental effects. We tested different filter shapes and decided to use a triangular smooth filter as it introduces fewer ripples due to sharp edges compared to boxcar filters. Additionally, we tested different filter widths of 10, 20, and 30 days. It showed that the wider filters result in increasingly different \(\tau_{\text{gran}}\) values obtained from the data, i.e., introducing a bias as well as additional scatter. From these results we concluded that a triangular smooth filter with a full width at half-maximum of 10 days applied to an interpolated time series provides most robust results. Note that the filter with a width of 10 days limits our sensitivity of \(\tau_{\text{gran}}\) to periods <10 days, which is sufficiently long to study the granulation in red giants under the aforementioned assumption that these are of the order of hours up to a few days.

3. GRANULATION PARAMETERS

Granulation parameters were first modeled in the Sun by Harvey (1985). He approximated the autocovariance of the time evolution of the granulation by an exponential decay function with a characteristic time \(\tau_{\text{gran}}\). This results in a power spectrum with a Lorentzian profile:

\[
P_{\text{H}}(\nu) = \frac{4\sigma^2 \tau_{\text{gran}}}{1 + (2\pi \nu \tau_{\text{gran}})^2}
\]

in which \(P_{\text{H}}(\nu)\) is the total power of the signal at frequency \(\nu\), \(\sigma\) is the characteristic amplitude of the granulation, and \(\alpha\) is a positive parameter characterizing the slope of the decay. We also define the amplitude of the granulation power, \(P_{\text{gran}} = 4\sigma^2 \tau_{\text{gran}}\). This approach has been successfully applied to the solar measurements by several instruments in both velocity and intensity (e.g., Lefebvre et al. 2008).

Other signals such as mesogranulation, supergranulation, and active regions can be modeled with similar functions, and act at much longer timescales. We note here that it is mentioned in Harvey (1985) that the declining slopes of the functions may well be different from two. Different modified Harvey functions have indeed been used by for instance Aigrain et al. (2004), Hekker et al. (2010), Huber et al. (2009), Kallinger et al. (2010a), and in several methods used in this work, which are explained below in more detail. The use of values different from \(\alpha = 2\) was established empirically, but the physical meaning of the function with \(\alpha = 2\) has not been deeply investigated previously.

Recalling that the autocorrelation of a signal is nothing but the Fourier transform of its power spectrum, we can easily investigate the influence of \(\alpha\) on the autocorrelation function (ACF) of the temporal signal of the granulation component. We note that, for a given \(\tau\), an increasing value for \(\alpha\) indicates an increase in the temporal correlation. For \(\alpha = 2\), the ACF is obviously an exponential function decaying over a timescale \(\tau\). When \(\alpha\) tends to zero, the power spectrum becomes flatter and flatter, i.e., tends to white noise. The ACF does then decrease faster and faster and tends to a Dirac function, typical for the ACF of white noise. With increasing \(\alpha\), the ACF broadens and converges to the sinc function for \(\alpha \rightarrow \infty\).

To be able to compare characteristic timescales \(\tau\) obtained with different \(\alpha\) values or even with different expressions of the granulation spectrum, we define an effective timescale \(\tau_{\text{eff}}\) as the \(e\)-folding time of the ACF. For \(\alpha = 2\), we thus recover \(\tau = \tau_{\text{eff}}\). In the following, we will study \(\tau_{\text{eff}}\) instead of \(\tau_{\text{gran}}\) to correctly account for slopes that differ from two.

3.1. Methods

Six teams have fitted the granulation background of the red giants and the values of the parameters have been compared to check the validity of the results. For all the methods explained below, except CAN (Kallinger et al. 2010a), the fit is performed by not taking into account the frequency region in which the solar-like oscillations are present. CAN fits the p-mode bump together with the background. The methods are all summarized in Tables 1 and 2.

The OCT method fits the background of the power density spectrum (PDS) using one Harvey-like model:

\[
P(\nu) = W + P_{\text{H}}(\nu).
\]

The initial input parameters are \([P_{\text{gran}}, 0, \tau_{\text{gran}}, 0, \alpha_0, W_0] = [P, 0.01, 2, \text{noise}],\) in which \(P\) is the maximum power of the binned power spectrum (bins vary with frequency and are \(2\Delta\nu\) wide) and noise is the minimum power of the binned power spectrum. All four parameters are left free in the nonlinear least-squares fit. When 100 iterations are done, the model with the lowest \(\chi^2\) is chosen. The standard deviations of the fitted parameters are used as the uncertainties. More details can be found in Hekker et al. (2010).

The method adopted by SYD (see Huber et al. 2009, for details) consists of fitting the background with two modified Harvey functions (Karoff 2008):

\[
P(\nu) = W + \sum_{i=1}^{2} \frac{4\sigma_i^2 \tau_i}{1 + (2\pi \nu \tau_i)^2 + (2\pi \nu \tau_i)^4}
\]

with \(\sigma_i\) the root-mean-square (rms) intensity in power density, \(\tau_i\) corresponds to the granulation timescale and \(\tau_2\) might correspond to another feature with no physical meaning so far. This method uses a Levenberg–Marquardt least-squares algorithm to fit the background and to estimate \(\sigma_i\) and \(\tau_i\). The initial guess value for the granulation timescale is scaled from the Sun using the relation \(\tau_{\text{gran}} \propto 1/\nu_{\text{max}},\) where \(\nu_{\text{max}}\) is the frequency of maximum oscillation power and is determined before the background model is fitted. To stabilize the fit, only
The likelihood function is based on a $\chi^2$ power at the high frequency end of the spectrum. The adopted frequency, $1/\tau$, is currently under investigation. The granulation width $\sigma$ is set by a Gaussian function $\sigma_i, \tau_i, W$. The COR method (B. Mosser 2011, private communication) focuses on the frequency range around the break of the Harvey function. The CAN method uses a Bayesian Markov Chain Monte Carlo (MCMC) algorithm.

The initial guess for $W$ is derived from a general relation between the stellar magnitude obtained from the KIC and the noise in the time series. This relation was determined from a larger sample of solar-like stars observed in short cadence by *Kepler*. The initial guess of the exponent $\alpha$ is 2, while that of $\tau_{\mathrm{gran}}$ is set to $2.1 \times 10^4$ s. Assuming a $\chi^2$ distribution with 2 dof and the uncertainties are determined from the marginalized posterior probability density distributions.

The DLB method (D. Buzasi 2011, private communication) fits a single-component Harvey model plus white noise as indicated in Equation (2) with $\alpha = 2$ as a fixed parameter. This method uses a linear least-squares fit over the frequency range $[2/T, \nu_{\mathrm{Nyquist}}]$, where $T$ is the length of the time series. Initial guesses for the fit $[W, \nu_{\mathrm{gran}}, \tau_{\mathrm{gran}}]$ are given by $[P_{\min}, P_{\max}, 3 \times 10^4]$, where $P_{\min}$ and $P_{\max}$ are respectively the minimum and maximum power found in the region considered in the PDS. No uncertainties have been estimated with this method.

The COR method (B. Mosser 2011, private communication) focuses on the frequency range around the break of the Harvey functions, just below the identified oscillation power. The fit of the background at $\nu_{\mathrm{max}}$ (Mosser et al. 2011b, 2011c) and at low frequency (in the plateau region; Mosser et al. 2010). The exponent of the Harvey component (Equation (1)) is a free parameter.

With the $A2Z$ method, the background is fitted with one Harvey-like model and a power law as described in Mathur et al. (2010):

$$P(\nu) = W + \frac{\alpha^2 t_{\mathrm{gran}}^2}{1 + (2\pi \nu t_{\mathrm{gran}})^2} + P_g \exp\left(-\frac{(\nu_{\max} - \nu)^2}{2\sigma_g^2}\right)$$

(4)

with the condition $\tau_1 < \tau_2 < \tau_3$, where the indices indicate consecutive background components. The Gaussian p-mode component has amplitude $P_g$, central frequency $\nu_{\max}$, and width $\sigma_g$. This method uses a Bayesian Markov Chain Monte Carlo (MCMC) algorithm.

The parameter $\tau_2$ corresponds to the granulation timescale. For now, a physical explanation of the other timescales, $\tau_1$ and $\tau_3$, is lacking. The latter could be related to a different scale of granulation and is currently under investigation. The granulation frequency, $1/\tau_{\mathrm{gran}} = 1/\tau_2$, was allowed to vary from 0 to 10 times $\nu_{\max}$. $P_g$ was allowed to vary from 0 to 10 times the average power in the spectrum around the initial guess for $\nu_{\max}$, and $W$ was kept between 0.5 and 2 times the average power at the high frequency end of the spectrum. The adopted likelihood function is based on a $\chi^2$ distribution with 2 dof and the uncertainties are taken as the standard deviations of the distributions derived from typically 1000 simulations.

### Table 1

Summary of the Background Fitting Methods (Part 1)

| ID  | OCT \textsuperscript{a} | SYD \textsuperscript{b} | CAN \textsuperscript{c} |
|-----|-----------------|-----------------|-----------------|
| Model | $W + \frac{4\sigma^2 t_{\mathrm{gran}}^2}{1 + (2\pi \nu t_{\mathrm{gran}})^2}$ | $W + \sum_{i=1}^{\nu_{\max}} 4\sigma^2 t_i$ | $W + \sum_{i=1}^{\nu_{\max}} 4\sigma^2 t_i$ |
| Additional component | | $1 + (2\pi \nu t_i)^2 + (2\pi \nu t_j)^2$ | Gaussian function |
| Free parameters | $\alpha, \sigma, \nu_{\mathrm{gran}}$ | $\sigma, \tau_i, W$ | $\sigma, \tau_i, W$ |
| Minimization method | Nonlinear | Levenberg–Marquardt | Monte Carlo |
| Uncertainties | Std dev. of parameters | Std dev. of distributions from simulations | Posterior probability of density distribution |

**Notes.**

\textsuperscript{a} Hekker et al. (2010).
\textsuperscript{b} Huber et al. (2009).
\textsuperscript{c} Kallinger et al. (2010a).

### Table 2

Summary of the Background Fitting Methods (Part 2)

| ID  | DLB | COR | A2Z \textsuperscript{a} |
|-----|-----|-----|-----------------|
| Model | $W + \frac{4\sigma^2 t_{\mathrm{gran}}^2}{1 + (2\pi \nu t_{\mathrm{gran}})^2}$ | $W + \frac{4\sigma^2 t_{\mathrm{gran}}^2}{1 + (2\pi \nu t_{\mathrm{gran}})^2}$ | $W + \frac{4\sigma^2 t_{\mathrm{gran}}^2}{1 + (2\pi \nu t_{\mathrm{gran}})^2}$ |
| Additional component | | | Power law |
| Free parameters | $\sigma, \nu_{\mathrm{gran}}$ | $\alpha, \sigma, \nu_{\mathrm{gran}}$ | $\alpha, \sigma, \nu_{\mathrm{gran}}$ |
| Minimization method | Linear | Least squares | Maximum likelihood estimator |
| Uncertainties | Std dev. of parameters | | Inversion of Hessian matrix |

**Note.** \textsuperscript{a} Mathur et al. (2010).
fit is performed using a maximum likelihood estimator. The uncertainties are estimated by inverting the Hessian matrix. For each method, we have computed $\tau_{\text{eff}}$ converted from $\tau_{\text{gran}}$ and $P_{\text{gran}}$ as defined in Equation (1).

3.2. Comparison of the Results

Figure 1 shows a typical PDS of a red giant observed by Kepler. The results of each method listed above are shown and all of them provide the same qualitative results around the break of the granulation profile with small differences at very low frequency or at very high frequency. We note that one method can work well for one star while another method might work better for another star.

Figures 2 and 3 show the results of $\tau_{\text{eff}}$ and $P_{\text{gran}}$ for the methods described in Section 3.1. For the methods where more than one Harvey-like functions were fitted, the one with the smallest timescale has been interpreted as belonging to the granulation for the SYD method and the middle timescale was used for the CAN method. The trends in the results from different methods are consistent, although they are not always the same. Interestingly the correlation between $\tau_{\text{eff}}$ and $P_{\text{gran}}$ as shown in Figure 4 is more coherent for the different methods.

This could indicate a degeneracy in the fitted parameters coming from the use of different methods with different free parameters, models, data, and number of components, as can be seen in Figure 1. However, for a given method, the results and the trends are consistent.

For the different methods, the average uncertainties on $1/\tau_{\text{eff}}$ are 3%, 9%, 9%, 1%, and 6% for A2Z, CAN, SYD, OCT, and COR, respectively. Some of these uncertainties (in particular for A2Z, OCT, and COR) seem rather small and might be underestimated so we assume that the uncertainty should rather be around 10%. If we look at the dispersion between the methods for a given $v_{\text{max}}$, $1/\tau_{\text{eff}}$ varies by $\sim30\%$ around the average value. The dispersion between the stars can be related to the different metallicities of the stars.

One thing that is apparent is the existence of a “jump” in the $\tau_{\text{gran}}$ results at $v_{\text{max}} \sim 40 \mu$Hz for two of the methods using a single power law, an initial guess for $\tau_{\text{gran}}$ independent of $v_{\text{max}}$, and $\alpha$ as a free parameter. This second branch is most likely due to the fact that the fit converges to a second feature in the power spectrum. The absence of the second branch in the results of DLB (guess of $\tau_{\text{gran}}$ independent of $v_{\text{max}}$ but fixed $\alpha$) indicates that the convergence is at least partly due to the fact...
that $\alpha$ is a free parameter. We also performed tests with different initial guesses for $\tau_{\text{gran}}$ (again independent of $\nu_{\text{max}}$) and that reduces the second branch but the fit does not converge for high values of $\nu_{\text{max}}$. Additionally, to investigate further the number of components, we performed tests with one method, A2Z in this case, in which we fitted either one or two Harvey components with several initial parameters to investigate how these affect the results (see the Appendix for more details). It appears that by using two Harvey-like functions, we obtain only one branch instead of two branches (see discussion in Section 6). For all of these reasons, we think that on the one hand, the minimization algorithm of the fit could go to a local minimum instead of a global minimum, which can lead to the second branch. On the other hand, this second branch could be related to the initial guesses, for which we converge to a background component with lower $\tau_{\text{gran}}$, which is likely to be something different from granulation. From the fact that the second branch also shows a strong correlation with $\nu_{\text{max}}$, we expect it to be of stellar origin and it could correspond for instance to a phenomenon similar to bright points or stellar spots whose appearance is modulated by the stellar rotation.

As the results of the methods are qualitatively similar, we use one method for the representations of our results in the remainder of this work.

4. GRANULATION AND OTHER STELLAR PARAMETERS

4.1. Granulation Scaling Relations and Observations

From some basic physical assumptions, it is possible to predict the behavior of granulation with respect to stellar parameters. As argued by Huber et al. (2009) and Kjeldsen & Bedding (2011), the convection cells travel a vertical distance that is proportional to the pressure scale height, $H_p$, at a speed that is approximately proportional to the sound speed, $c_s$. Since $H_p \propto T_{\text{eff}}/g$ and $c_s \propto \sqrt{T_{\text{eff}}}$, the characteristic timescale of the granulation can be expressed as $\tau_{\text{gran}} \propto H_p/c_s \propto \sqrt{T_{\text{eff}}}/g \propto \sqrt{T_{\text{eff}}^2 R^2/M} \propto L/(MT_{\text{eff}}^3) \propto 1/\nu_{\text{max}}$, where $g$ is surface gravity, $T_{\text{eff}}$ is effective temperature, $R$ is stellar radius, and $M$ is stellar mass. This result indicates that we should expect longer characteristic granulation timescales on larger stars, i.e., stars with lower surface gravity. Support for the argument is given by the three-dimensional simulations by Trampedach et al. (2011) carried out with the Stein & Nordlund (2000) code. These simulations indicate that red giants have granulation cells that are roughly 15 $H_p$ wide.

The proportionality of the horizontal size of a granule, $d$, to the pressure scale height, $H_p$ (e.g., Schwarzschild 1975; Antia et al. 1984), implies the following: $d \propto H_p \propto T_{\text{eff}}/g \propto T_{\text{eff}} R^2/M \propto \sqrt{T_{\text{eff}}}/\nu_{\text{max}}$. Thus, the linear size of the granules is inversely proportional to the gravity, and since $T_{\text{eff}}$ and the mass of the star vary less than the radii of red giants, it indicates that the size of the granules should increase with the radius of the star. For the number of granules on the surface, $N$, we derive the following: $N \propto R^2/d^2 \propto M^2/(T_{\text{eff}}^2 R^2) \propto M g/T_{\text{eff}}^2$. This indicates that the number of granulation cells decreases with increasing stellar radius or equivalently decreasing surface gravity. So, larger stars have a relatively small number of large granulation cells on their surfaces compared to smaller stars with a relatively higher number of smaller cells. These results are in line with earlier work by, e.g., Schwarzschild (1975) and Antia et al. (1984). Evidence for large granulation features has been observed on red supergiants such as Betelgeuse using interferometry (for a review see Monnier 2003; for recent observations see Haubois et al. 2009 and Ohnaka et al. 2009, 2011; and for their interpretation with three-dimensional simulations, see Chiavassa et al. 2010 and Kiss et al. 2010). We can test this hypothesis here also for red giants.

As already pointed out by the original Harvey models, the power of the granulation $P_{\text{gran}}$ is proportional to $\sigma^2 T_{\text{gran}}$, $\sigma$ being the rms intensity fluctuation. The proportionality with $T_{\text{gran}}$ also means that $P_{\text{gran}} \propto d$, i.e., fewer larger cells result in higher granulation power, and thus each cell has a larger influence on the total luminosity fluctuations of the star, and hence a larger influence on its variability. This has some similarity with the oscillations, i.e., the amplitudes of oscillation modes also increase with lower $\nu_{\text{max}}$ (Mossel et al. 2010; Huber et al. 2010).

In Figures 2 and 3, we fitted a power law for each parameter and for each method. The values of the slopes are listed in Table 3. By taking the results of all the methods together, we find that $\tau_{\text{eff}} \propto \nu_{\text{max}}^{-0.89}$ while $P_{\text{gran}} \propto \nu_{\text{max}}^{-1.90}$, which is close to the relation derived above ($\tau_{\text{gran}} \propto \nu_{\text{max}}^{-1}$) and to the relations obtained by Kjeldsen & Bedding (2011) ($P_{\text{gran}} \propto \nu_{\text{max}}^{-2}$). Finally, it also agrees with analytical models of convection where a coefficient $-1$ is found for the $\tau_{\text{gran}}$-$\nu_{\text{max}}$ relation (R. Samadi 2011, private communication). Given that both $p$ modes and granulation are driven by convection, this correlation is not surprising.

Figure 4 shows the variation of $P_{\text{gran}}$ with $\tau_{\text{eff}}$. The fit of a power law (see Table 3) gives a slope of 2.18 for all the methods together, which agrees with the scaling laws.

### Table 3

| Method | $\tau_{\text{eff}} \propto (\nu_{\text{max}})^\gamma$ | $P_{\text{gran}} \propto (\nu_{\text{max}})^\delta$ | $P_{\text{gran}} \propto (\tau_{\text{eff}})^\beta$ |
|--------|----------------|----------------|----------------|
| OCT    | $-0.82 \pm 0.02$ | $-1.2 \pm 0.02$ | $2.11 \pm 0.03$ |
| SYD    | $-0.90 \pm 0.004$ | $-2.12 \pm 0.01$ | $2.37 \pm 0.01$ |
| CAN    | $-0.86 \pm 0.005$ | $-1.73 \pm 0.02$ | $1.99 \pm 0.02$ |
| DLB    | $-0.86 \pm 0.01$ | $-2.06 \pm 0.02$ | $2.34 \pm 0.02$ |
| COR    | $-0.90 \pm 0.005$ | $-2.15 \pm 0.12$ | $2.34 \pm 0.01$ |
| A2Z    | $-0.79 \pm 0.008$ | $-2.09 \pm 0.16$ | $2.39 \pm 0.02$ |
| All    | $-0.89 \pm 0.005$ | $-1.90 \pm 0.01$ | $2.19 \pm 0.01$ |

Note. The fits for OCT, A2Z, and all the methods together do not take into account the second branch.
It is interesting to study the variation of the ratio between $P_{\text{gran}}$ and $\tau_{\text{eff}}$, which is proportional to the variance of the intensity variations. This quantity varies as a function of log $g$. This is illustrated in Figure 5, where we used the granulation parameters obtained by A2Z as an example, but this tendency is qualitatively similar for the other methods. Stars that have smaller log $g$ and thus larger radii present a higher intensity contrast compared to stars with a higher log $g$. This anticorrelation between $P_{\text{gran}}/\tau_{\text{eff}}$ and log $g$ seen in Figure 5 is mostly due to the fact that $P_{\text{gran}}$ scales with $N^{-1}$ (Kjeldsen & Bedding 2011), which arises from the averaging of fluctuations over many (unresolved) granules, diminishing the power for large $N$, i.e., having fewer granules leads to less averaging over the stellar surface and the effect on luminosity from each granule is higher.

4.2. Granulation and Global Stellar Parameters

We investigate the dependence of the granulation parameters of the red giant stars on stellar fundamental parameters $R$, $M$, $T_{\text{eff}}$, and log $g$. These parameters have been computed with the method described by Kallinger et al. (2010a) using 13 month long time series for a sample of 1035 red giants. Figure 6 shows how $\tau_{\text{eff}}$ computed with method CAN varies with $R$, log $g$, $M$, and $T_{\text{eff}}$. The results from the CAN method are shown here because this method provides results of a large sample of stars. As predicted from scaling relations (see Section 4.1, $\tau_{\text{gran}} \propto \sqrt{T_{\text{eff}} R^2 / M}$) for bigger stars, the granulation timescales are larger and we can fit a power law showing the correlation between $\tau_{\text{eff}}$ and $R$ as $R \propto \tau_{\text{eff}}^{1.6}$. This is also consistent with the predicted anti-correlation between $\tau_{\text{gran}}$ and log $g$. Correlations of granulation parameters with mass and radius are not as tight as with $g = GM/R^2$, since the latter is the underlying independent variable (see also Gai et al. 2011). The correlation with $T_{\text{eff}}$ seems much less tight than with log $g$. However, the plot of $\tau_{\text{eff}}$ versus $T_{\text{eff}}$ is dominated by stellar evolution effects and hence shows a similar behavior as seen in the H-R diagram (Figure 8) including the spread in points intrinsically linked to the distribution of stars in the H-R diagram. From the fact that $P_{\text{gran}} \propto \tau_{\text{gran}}$, we would expect similar correlations for the granulation power. These are indeed observed and shown in Figure 7.

We note a bump around $10 R_{\odot}$, log $g = 2.5$, and $T_{\text{eff}} = 4700$ K in Figures 6 and 7. It corresponds to the so-called red clump, corresponding to red giants that have gone through a helium flash and are now in their He-core burning phase. In the plot showing $\tau_{\text{eff}}$ as a function of $T_{\text{eff}}$, we also clearly see the red giant branch.

4.3. Granulation in the H-R Diagram

Having a large number of red giants that are at different stages of their evolution allows us to study the distribution of the granulation parameters in this part of the H-R diagram.

The left panel of Figure 8 shows the distribution of $1/\tau_{\text{eff}}$ in our sample of red giants. As previously, the values of $T_{\text{eff}}$ and $L$ have been computed as described by Kallinger et al. (2010a). For stars with increasing luminosity, $1/\tau_{\text{eff}}$ decreases, thus $\tau_{\text{eff}}$ is larger, which also correlates with larger granulation cells. There is a large concentration of points at log $(L/L_{\odot}) \sim 1.7$. These stars belong to the red clump.
The distribution of the granulation power, $P_{\text{gran}}$, is shown in the right panel of Figure 8. We note that low-luminosity stars have low $P_{\text{gran}}$ values, which is once again similar to what we observe for the mode amplitudes (Mosser et al. 2010, 2011c). This is not surprising as the p modes are excited in the convection zone so the same order of magnitude of energy would be involved in both granulation and p-mode excitation. This is in agreement with the study of the height-to-background ratio by Mosser et al. (2011c).

Recently, Beck et al. (2011), Bedding et al. (2011), and Mosser et al. (2011a) detected for the first time mixed modes in the red giants. They showed that the period spacings between the mixed modes make it possible to distinguish between stars ascending the red giant branch, i.e., H-shell burning stars and stars in the red clump, i.e., He-core burning stars. Using this information, we investigated whether the stars show differences in granulation parameters related to their evolutionary phase. Due to the uncertainties in the granulation parameters a firm
conclusion cannot yet be drawn, although some indications of different granulation parameters with evolutionary state are present. It is at least clear that the red-clump stars have granulation values in a specific range, and the red giant branch stars have their values spread over a larger range. This is not surprising as the structure of red-clump stars is very similar, which would lead to similar granulation characteristics.

5. THREE-DIMENSIONAL SIMULATIONS OF CONVECTIVE RED GIANT ATMOSPHERES

To help us interpret the Kepler observations, we have turned to three-dimensional hydrodynamic simulations of convection in stellar surface layers. These simulations, described in more detail in Trampedach et al. (2011), were constructed for direct comparison with observations and are therefore based on the state-of-the-art atomic physics. The thermodynamics is provided by tables of the so-called MHD EOS (Hummer & Mihalas 1988; Mihalas et al. 1988), which is based on explicit accounting for all excited states in all ions of the 16 most abundant elements, and a physical model of the (non-ideal) effect of interactions between particles. The opacities are based on the Marcs stellar atmosphere package (Gustafsson 1973), but with several updates of the opacity sources and line opacities from the Atlas stellar atmosphere package (Kurucz 1992a, 1992b), as detailed in Trampedach et al. (2011). The three main processes governing the surface layers (i.e., what we can observe) of late-type stars are hydrodynamics, thermodynamics, and radiative transfer. These processes interact in very complicated ways, hence the need for realistic first-principles simulations. The surface layers (by definition) straddle the photospheric transition from the optically deep interior and the optically thin atmosphere, which means the radiative transfer cannot be treated in any known approximation. The full wavelength- and ray-direction-dependent problem has to be considered and the simulations are based on the opacity binning formulation introduced by Nordlund (1982). The simulations are each performed on a grid of $150 \times 150 \times 82$ points, spanning about 13 pressure scale heights in the vertical direction (with 7 below the photosphere) and reaching up to an optical depth of $\log \tau_{\text{Ross}} = -4.5$. The horizontal extent primarily scales with gravity, with only a slight increase with $T_{\text{eff}}$, and is large enough to cover about 10 major granules. Each simulation was relaxed to a statistically steady state, with no systematic drifts in fluxes or mean structure over time. Surplus energy was extracted by artificially damping radial $p$ modes during the relaxation. After this relaxation, production runs were carried out, covering at least 10 periods of the fundamental $p$ mode. The resonant modes of the box (the bottom is a node) are excited and damped by the convection in the box and saturate at an amplitude given by the balance between the damping and driving. With these fairly short time series ranging from 14h55 for the coolest subgiant to 5 days 17h30 for the hottest giant, we see two to three radial modes and similar for the non-radial modes that have the box width as horizontal wavelength. All 37 simulations of the grid were performed for solar metallicity as in Anders & Grevesse (1989) with He and Fe adjusted to mimic Grevesse & Noels (1993) and cover the zero-age main sequence from $T_{\text{eff}} = 4300 \text{ K}$ to $6900 \text{ K}$ and up to giants of $\log g = 2.2$ between $T_{\text{eff}} = 5000 \text{ K}$ and $4200 \text{ K}$. Our sample of 1035 Kepler red giants is spanned by seven of the 37 simulations of the grid. About 11% of the stars, however, fall outside the simulation grid and are therefore not included in the comparisons of Section 5.2.

Similar simulations that are not part of the grid have been widely applied to solar and stellar observations. A study of solar Fe i and II lines by Asplund et al. (2000) showed remarkable agreement with the shape, asymmetry, and wavelength shift (without adjustable parameters to match these profiles to the observations). Note that one-dimensional solar atmosphere models cannot reproduce these observations. A similar analysis was carried out for Procyon with a similar level of success. This agreement with detailed line shapes leads to a recognition of the Ni i blend with the [O i] line, leading to agreement between the oxygen abundances from [O i] and O i lines (Prieto et al. 2001). The center-to-limb variation of Na and O lines in the Sun also matches observations (Prieto et al. 2004). Even earlier simulations could reproduce the observed sizes, shapes, and contrast of granules (Nordlund & Stein 1991) and Rosenthal et al. (1999) showed how the change in stratification from a realistic three-dimensional convective atmosphere accounts for most of the so-called surface term in helioseismology. Together, these disparate observational tests probe a large range of depths in the atmosphere of the simulation, giving us confidence that they are a better representation of stellar atmospheres than are one-dimensional models. Hence, the three-dimensional simulations have a larger predictive power.

5.1. “Observing” the Simulations

For each simulation, radiative transfer was performed for the full set of wavelengths in the opacity distribution functions (ODFs). The ODFs that were used are defined for 1100 wavelength regions, with 12 points in each of these distribution functions. We have artificially assigned wavelengths to these 12 points within their respective wavelength regions, in a way that gives them the appropriate integration weight. The resulting spectra are saw-tooth shaped with 20 Å wide bins in the optical. This is obviously not adequate for monochromatic studies, but this wavelength re-ordering of opacity on a 20 Å scale has very little effect on broadband colors. Figure 9 shows such an ODF spectrum together with the Kepler filter. Having computed complete spectra for each snapshot of each simulation, and for eight $\mu$-angles ($\mu = \cos \theta$ of the position angle on the stellar disk) and four azimuthal $\phi$-angles, we then proceeded to average over $\phi$ and convolve with the transmission curve of the Kepler filter.
filter. This results in Kepler intensities as a function of $\mu$-angle and time, $I(\mu, t)$.

The subsequent transformation from specific intensities to power spectra of observable fluxes was performed as described by Trampedach et al. (1998) and later described in great detail by Ludwig (2006). Following the derivations of Ludwig (2006) we write

$$P(v) = \frac{l^2}{2\pi R^2 F^2} \sum_{ij} w_i \mu_i^2 w_j \hat{I}_{ij} \hat{I}_{ij}^*$$  \hspace{1cm} (6)

where $l$ is the horizontal extent of the simulation domain, $\hat{I}$ is the Fourier transform of $I$, $\hat{I}^*$ indicates the complex conjugate, $R$ is the radius of the star, and $2\pi R^2/l^2$ is the number of simulation domains that fit over the visible half of the stellar surface. Division by the Kepler flux of the simulation, $F = \sum w_i \mu_i \sum \hat{I}_{ij}$, provides for the relative power spectra of the flux in Equation (6). The weights, $w_i$, and angles, $\mu_i$, of the angular quadrature are chosen according to the method of Radau (1880), which gives an optimal set of quadrature points, with the vertical direction included. The $\phi$-angles that have index $j$ are equidistant and therefore have weights $1/N_{\phi} \hat{I}_{ij} \hat{I}_{ij}^*$ is the power of intensity in a particular direction, $\mu_i$ and $\phi_j$.

The power of the simulation domain is diluted by the factor $2\pi R^2/l^2$ to account for the averaging out of uncorrelated convective fluctuations from different parts of the stellar disk. The underlying assumption of this formulation is that patches on the stellar surface more than the distance $l$ apart are uncorrelated. The simulations are dimensioned such that they each contain about a dozen major granules at any one time, and the assumption is therefore reasonable.

The time series of the simulations are unfortunately not long enough to be sub-divided in order to perform ensemble averaging to reduce the noise. Instead we performed a running Gaussian smoothing of the power spectra and these are then fitted with a Harvey-like model. In the fitting process we also allow for a white noise component and the two strongest $p$ modes. Due to the rather short time series, these modes are very broad, and we fit them with Gaussian profiles. Only two or three modes are visible in each simulation, and they are constrained to have a node at the bottom of the simulation box, which means they do not correspond to real eigenmodes of the star. Their frequencies, however, are still within the $p$-mode bump of real stars.

5.2. Results on the Granulation Characterization

Having fitted the granulation power spectra of the simulations of the grid to the generalized Harvey function of Equation (2), we now have three granulation parameters as a function of $T_{\text{eff}}$ and $\log g$. For comparison with the red giants studied in this paper, we therefore interpolated these parameters between the simulations to the red giants based on their atmospheric parameters, $T_{\text{eff}}$ and $\log g$. Since the simulation grid is irregular, we used linear interpolation on a Delaunay triangulation of the grid (Renka 1984).

Top panels of Figures 10 and 11 show how $\tau_{\text{eff}}$ of the simulations varies with $T_{\text{eff}}$ and $\log g$. The simulations have the same trend as the observations. We observe very tight correlations between $\tau_{\text{eff}}$ and $\log g$. In the correlation between the granulation parameters and $T_{\text{eff}}$ (Figure 10) the stellar evolution effects are again dominant (see also Section 4.2) and these figures show similar structure as seen in the H-R diagrams in Figure 8. For $\tau_{\text{eff}}$, the agreement between the observations and the simulations is better than a factor two. We also compared $P_{\text{gran}}$ from the simulations and the observations (bottom panels of Figures 10 and 11) and we note a discrepancy of an order of magnitude.

6. DISCUSSION AND CONCLUSIONS

For $\sim$1000 red giants we studied 13 months of data obtained by the Kepler mission. These data were processed in order to reduce the instrumental effects while keeping as much information as possible to preserve the granulation signal.

Six teams fitted the power spectra with different methods based on a Harvey model to estimate the granulation parameters. We first checked that the values obtained by the different methods were in general agreement. We note that two branches appear for two of the methods that fitted only one Harvey model. In these cases, the methods are likely to fit for another feature present in the data. Judging from the correlation of the second branch with $v_{\text{max}}$, we think this signal could also be of stellar origin. The comparison of the results of the red giants with the values we have for the Sun suggests that the second branch would correspond to some high-frequency phenomena, such as...
The Astrophysical Journal, 741:119 (12pp), 2011 November 10

Mathur et al.

APPENDIX

INFLUENCE OF THE METHOD AND THE INITIAL GUESSES ON THE FITTING

We did a few tests with one of the methods used in this work (namely A2Z) to investigate the impact of the initial guess of the slope, $\alpha$, for the following values: [1, 2, 3, 4, 5] on six different red giants, ranging in $v_{\text{max}}$ between 40 and 100 $\mu$Hz. To quantitatively compare the fits, we computed $\chi^2$ values as the mean value of the difference between the background fit and the heavily smoothed PDS. The best fits for the stars with $v_{\text{max}} > 40$ $\mu$Hz were obtained for a slope of 2 and 3, with $\chi^2$ values ranging from 0.7 to 3.7, while for other values (1, 4, and 5), we could not reproduce the knee of the Harvey model and obtained only a straight line with a slope (see Figure 12). For stars with $v_{\text{max}} \sim 40$ $\mu$Hz, the best fit is found for an initial guess of 3, 4, and 5 for the slope with $\chi^2$ values around 0.2.

We also note that by fixing the value of the white noise parameter the results were the same except in the case of a slope lower than 3. It seems that by assuming a slope too large and by adding a constraint on the white noise component, the background fit becomes less reliable. Then we added a Gaussian to the fit to incorporate the p-mode bump. These values were close to the ones obtained by not taking into account the bump of the oscillation modes.

We also checked how the fit converged when we decreased the initial guess of $1/\tau_{\text{gran}}$ to 10 $\mu$Hz. Though the code does not converge for high values of $v_{\text{max}}$, the second branch starts to disappear for $v_{\text{max}} < 40$ $\mu$Hz.

In the following, the fit done by A2Z with one Harvey-like model with an initial guess for $1/\tau_{\text{gran}}$ of 15 $\mu$Hz is chosen as the reference fit.

We fitted two Harvey-like models using different initial values for timescale of the second Harvey model: 2, 5, 10, and 15 $\mu$Hz. Depending on the value of $v_{\text{max}}$, the code could converge or not. For all the stars, a result for the fit could be obtained when the timescale value of the second model was 5 or 2 $\mu$Hz. For these stars, the $\chi^2$ between the fit and the PDS is smaller when the guess of the first slope is smaller than three and when we do not fix the value of the white noise parameter (around 3.6 compared to 7.5). We compared the dispersion of the values of $\tau_{\text{eff}}$ and of $P_{\text{gran}}$ with the uncertainties for the fits that reproduced the knee of the granulation and found that the dispersion is related to the way we fit the background. Depending on the initial guess of $1/\tau_{\text{gran}}$, we find that $\tau_{\text{eff}}$ and $P_{\text{gran}}$ vary by $\sim 5\%$ around the value found by the reference fit. The uncertainties on these values are $\sim 6\%$–$10\%$ around the value found by the reference fit. We conclude that the dispersion of these parameters with the initial guess of $1/\tau_{\text{gran}}$ is of the same order of magnitude as the uncertainty.

We also performed some tests on 700 red giants by fitting two Harvey-like models without the white noise component and with a guess for the second $\tau$ of 300 $\mu$Hz. For these tests, a triangular smooth filter over 30 days was used to have enough points for the second Harvey-like model. In Figure 13, we can note that for these cases, $\tau_{\text{eff}}$ is larger compared to the case where we use only one Harvey model. As we fit two Harvey-like models, the code compensates the presence of the second component by increasing the value of $\tau_{\text{eff}}$. Besides, we find the same value of $a$ in the relation $\tau_{\text{eff}} = (v_{\text{max}})^a$ whether we fit one or two Harvey-like function while the second branch below 40 $\mu$Hz starts to disappear and to merge with the first one when we fit two Harvey-like functions.

Figure 12. PDS of KIC 11618103 smoothed over 10 bins with the comparison of the background fitting using one Harvey-like model and different values for $\alpha$. The fits using $\alpha = 1$ and 4 are not visible because they are exactly the same as the fit using $\alpha = 5$.

(A color version of this figure is available in the online journal.)

The authors gratefully acknowledge the Kepler Science Team and all those who have contributed to making the Kepler mission possible. Funding for the Kepler Discovery mission is provided by NASAs Science Mission Directorate. NCAR is supported by the National Science Foundation. S.H. acknowledges financial support from the Netherlands Organisation for Scientific Research (NWO). This research was supported by grant AYA2010-17803 from the Spanish National Research Plan. R.T. was supported by NASA grant NNX08AI57G.
Finally, we checked that the granulation signature in the PDS was not a result of observing some harmonics of the p-mode bump. We removed the p modes from the PDS by applying a pre-whitening and fitted the background with OCT. We obtained the same values for the granulation characteristics confirming that there was no reflection effect.

REFERENCES

Aigrain, S., Favata, F., & Gilmore, G. 2004, A&A, 414, 1139
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Antia, H. M., Chitre, S. M., & Narasimha, D. 1984, ApJ, 282, 574
Asplund, M., Ludwig, H.-G., Nordlund, Å., & Stein, R. F. 2000, A&A, 359, 669
Asplund, M., Nordlund, Å., Trampedach, R., Prieto, C. A., & Stein, R. F. 2000, A&A, 359, 729
Baglin, A., Auvouergne, M., Boisnard, L., et al. 2006, 36th COSPAR Scientific Assembly (Vol. 36 of COSPAR), Plenary Meeting, 3749
Batalha, N. M., Borucki, W. J., Koch, D. G., et al. 2010, ApJ, 713, L109
Beck, P. G., Bedding, T. R., Mosser, B., et al. 2011, Science, 332, 205
Bedding, T. R., Huber, D., Stello, D., et al. 2010, ApJ, 713, L176
Bedding, T. R., Mosser, B., Huber, D., et al. 2011, Nature, 471, 608
Bohm-Vitense, E. 1958, Z. Astrophys., 46, 108
Bonf-Luvene, E. 1958, Z. Astrophys., 46, 108
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 109
Brow, T. M., Latham, D. W., Everett, M. E., & Esquerdo, G. A. 2011, arXiv:1102.0342
Canuto, V. M., & Mazzitelli, I. 1991, ApJ, 370, 295
Canuto, V. M., & Mazzitelli, I. 1992, ApJ, 389, 724
Chiavassa, A., Haubois, X., Young, J. S., et al. 2010, A&A, 515, A12
Ciardi, D. R., von Braun, K., Bryden, G., et al. 2011, ApJ, 141, 108
Collet, R., Asplund, M., & Trampedach, R. 2007, A&A, 469, 687
De Ridder, J., Barban, C., Baudin, F., et al. 2009, Nature, 459, 398
Dupret, M.-A., Goupil, M.-J., Samadi, R., Grigahcène, A., & Gabriel, M. 2006, in Proc. SOHO 18/GONG 2006/HELAS 1, Beyond the Spherical Sun, ed. K. Fletcher (ESA Special Publication, Vol. 624), 781
Gai, N., Basu, S., Chaplin, W. J., & Elsworth, Y. 2011, ApJ, 730, 63
García, R. A., Hekker, S., Stello, D., et al. 2011, MNRAS, 414, L6
Girardi, L., & Salari, M. 2001, MNRAS, 323, 109
Gough, D. 1977b, ApJ, 119, 196
Grevesse, N., & Noels, A. 1993, in Origin and Evolution of the Elements: Proc. Symp. in Honour of H. Reeves, Paris, 1992 June 22–25, ed. N. Prantzos, E. Vangioni-Flam, & M. Casse (Cambridge: Cambridge Univ. Press), 14
Gustafsson, B. 1973, A FORTRAN Program for Calculating Continuous Absorption Coefficients for Stellar Atmospheres, Upsala Astron. Obs. Ann., 5, 6
Harvey, J. 1985, in Future Missions in Solar, Heliospheric & Space Plasma Physics, ed. E. Rolle & B. Battrick (ESA Special Publication, Vol. 235), 199
Haubois, X., Perrin, G., Lacour, S., et al. 2009, A&A, 508, A100
Hekker, S., Broomhall, A.-M., Chaplin, W. J., et al. 2010, MNRAS, 402, 2049
Hekker, S., Elsworth, Y., De Ridder, J., et al. 2011b, A&A, 525, A131
Hekker, S., Kallinger, T., Baudeen, F., et al. 2009, A&A, 506, 465
Herschel, W. 1801, Phil. Trans. R. Soc. L, 91, 265
Huber, D., Bedding, T. R., Stello, D., et al. 2010, ApJ, 723, 1607
Huber, D., Stello, D., Bedding, T. R., et al. 2009, Commun. Asteroseismol., 160, 74
Hummer, D. G., & Mihalas, D. 1988, ApJ, 331, 794
Jenkins, J. M., Caldwell, D. A., Chandrasekharan, K., et al. 2010, ApJ, 713, L87
Kallinger, T., Mosser, B., Hekker, S., et al. 2010a, A&A, 522, A1
Kallinger, T., Weiss, W. W., Barban, C., et al. 2010b, A&A, 509, A77
Karoff, C. 2008, PhD thesis, University of Aarhus, Denmark
Kiss, L. L., Monnier, J. D., Bedding, T. R., et al. 2010, in ASP Conf. Ser. 425, Hot and Cool: Bridging Gaps in Massive Star Evolution, ed. C. Leitherer, P. Bennett, P. Morris, & J. van Loon (San Francisco, CA: ASP), 140
Kjeldsen, H., & Bedding, T. R. 2011, A&A, 529, L8
Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, ApJ, 713, L79
Kurucz, R. L. 1992a, RevMexAA, 23, 1
Kurucz, R. L. 1992b, RevMexAA, 23, 2
Lefebvre, S., García, R. A., Jiménez-Reyes, S. J., Turk-Chèze, S., & Mathur, S. 2008, A&A, 490, 1143
Ludwig, H.-G. 2006, A&A, 454, 661
Ludwig, H.-G., Samadi, R., Steffen, M., et al. 2009, A&A, 506, 167
Mathur, S., García, R. A., Régulo, C., et al. 2010, A&A, 511, A46
Miglio, A., Montalbán, J., Baudin, F., et al. 2009, A&A, 515, L1
Miglio, A., Montalbán, J., Carrier, F., et al. 2010, A&A, 520, L6
Mihalas, D., Düpjen, W., & Hummer, D. G. 1988, ApJ, 331, 815
Monnier, J. D. 2003, Rep. Prog. Phys., 66, 789
Mosser, B. 2010, Astron. Nachr., 331, 944
Mosser, B., Barban, C., Montalbán, J., et al. 2011, A&A, 532, A86
Mosser, B., Belkacem, K., Goupil, M.-J., et al. 2010, A&A, 517, A22
Mosser, B., Belkacem, K., Goupil, M. J., et al. 2011b, A&A, 525, L9
Mosser, B., Elsworth, S., Hekker, S., et al. 2011c, A&A, submitted
Nordlund, Å. 1981, A&A, 101, 543
Nordlund, Å. 1982, A&A, 107, 5
Robinson, F. J., Demarque, P., Li, L. H., et al. 2004, MNRAS, 347, 1208
Rosenthal, C. S., Christensen-Dalsgaard, J., Nordlund, Å., Stein, R. F., & Trampedach, R. 1999, A&A, 351, 689
Schwarzschild, M. 1975, ApJ, 195, 137
Stein, R. F., & Nordlund, Å. 2000, Sol. Phys., 192, 91
Trampedach, R. 1970, Ap&SS, 28, 213
Trampedach, R., Christensen-Dalsgaard, J., Nordlund, Å., Asplund, M., & Stein, R. F. 2011, A&A, submitted
Trampedach, R., Christensen-Dalsgaard, J., Nordlund, Å., & Stein, R. F. 1998, in Workshop on Science with a Small Space Telescope, ed. H. Kjeldsen & T. Bedding (Denmark: Aarhus Universitet), 59
Ueno, W. 1967, PASJ, 19, 140
Vázquez Ramió, H., Régulo, C., & Rocà Cortés, T. 2005, A&A, 443, L11