Will COROT constrain the turbulent spectrum of solar-like oscillating stars ?

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ABSTRACT

Solar-like oscillations are believed to be excited stochastically by turbulent convection. The stochastic excitation depends on the details of the turbulent spectrum. In Samadi & Goupil (2001) a generalized formulation for the oscillation power was derived. This formulation first calibrated on a solar model allows one to investigate different assumptions about the stellar turbulent spectrum. We thus explore consequences of the assumed turbulent description for solar-like oscillating stars with different effective temperatures and luminosities. Large differences are found in the amplitude spectrum of a given star when using different turbulent spectra as well as in a star-to-star comparison. We conclude that COROT's performances will be able to discriminate between several turbulent models.

1. Introduction

Attempts to model the acoustic power injected into the p modes by turbulent convection has been made by several authors (Balmforth, 1992; Goldreich et al., 1994; Goldreich & Keeley, 1977). In Samadi & Goupil (2001, Paper I hereafter) a general formulation is proposed which allows to investigate more consistently different assumptions about the stellar turbulence such as its turbulent energy spectrum.

In Samadi et al. (2000) , the formulation, viewed as a diagnostic tool of stellar turbulent spectra, was used to compute oscillations power of several solar-like stars. Results in Samadi et al. (2000) are presented here in terms of relative luminosity oscillation amplitudes.

The space seismic experiment COROT (Baglin & The Corot Team, 1998) will provide highly accurate photometric measurements. According to the low noise level of COROT we conclude that it will allow us to constrain the turbulent spectrum of properly chosen solar-like oscillating stars.

2. Amplitudes of solar-like oscillations

2.1. Stochastic excitation

The acoustic power injected into the oscillations is defined (e.g. Goldreich et al., 1994) in terms of the damping rate η, the mean-square amplitude $\langle A^2 \rangle$, the mode inertia I and oscillation frequency ω :

$$P(\omega) = \eta \, \langle A^2 \rangle \; I \; \omega^2 \tag{1}$$

The mean-square amplitude accounts for both the excitation by turbulent convection and the damping processes. A theoretical expression for the mean-square amplitude of p-modes stochastically excited by turbulent convection was presented in Paper I. This expression can be written in a simplified expression as :

$$\left\langle A^2 \right\rangle \propto \eta^{-1} \int_0^M dm \; \rho_0 \; w^4 \; \left(\frac{\partial \xi_r}{\partial r} \right)^2 \; \mathcal{S}(\omega, m) \tag{2}$$

where ξ_r is the radial displacement eigenfunction, ρ_0 the density, w the vertical rms velocity of the convective elements and $\mathcal{S}$ the turbulent source function accounting for both the Reynolds and the entropy fluctuations. Detailed expressions for $\langle A^2 \rangle$ and $\mathcal{S}$ are given in Paper I. The source function involves the turbulent kinetic energy spectrum $E(k)$ and the turbulent spectrum $E_s(k)$ of the entropy fluctuations which can be related to $E(k)$ (e.g. Samadi et al., 2001a, Paper II hereafter). The turbulent spectra in $\mathcal{S}$ are integrated over all eddy wavenumbers k and $\mathcal{S}$ is in turn integrated in Eq.(2) over the stellar mass M.

We considered here for $E_s(k)$ the different turbulent spectra introduced in Paper II. These spectra were used in Samadi et al. (2000) to compute the acoustic power of several oscillating stars. The spectra called "Nesis Kolmogorov Spectrum" (NKS hereafter), "Raised Kolmogorov Spectrum " (RKS hereafter) and "Broad Kolmogorov Spectrum" (BKS hereafter) were suggested by observations of the solar granulation perfomed by Espagnet et al. (1993) and Nesis et al. (1993). They are presented in Figure 1. All the spectra present the well-known Kolmogorov spectrum shape which corresponds to a power law $E(k) \propto k^p$ with the slope $p = -5/3$. They differ in the injection region i.e., in the range $k < k_0$ range where k_0 is the wavenumber at which the turbulent cascade (Kolmogorov spectrum) begins.

Observations of the solar surface by Espagnet et al. (1993) and Nesis et al. (1993) suggest different values for k_0. Therefore due to this controversy we consider k_0 unknown and we relate it to the mixing length Λ as $k_0 = \pi \, / \, (\beta \Lambda)$ where β is a free parameter introduced for the arbitrariness of such definition (Samadi & Goupil, 2001). Moreover the definition of the eddy time correlation, which enters the description of the turbulent excitation, is somewhat arbitrary and is therefore gauged by introducing an additional free parameter λ. It is shown in Paper II that the oscillation power computed for the Sun is very sensitive to the values of the free parameters λ and β.

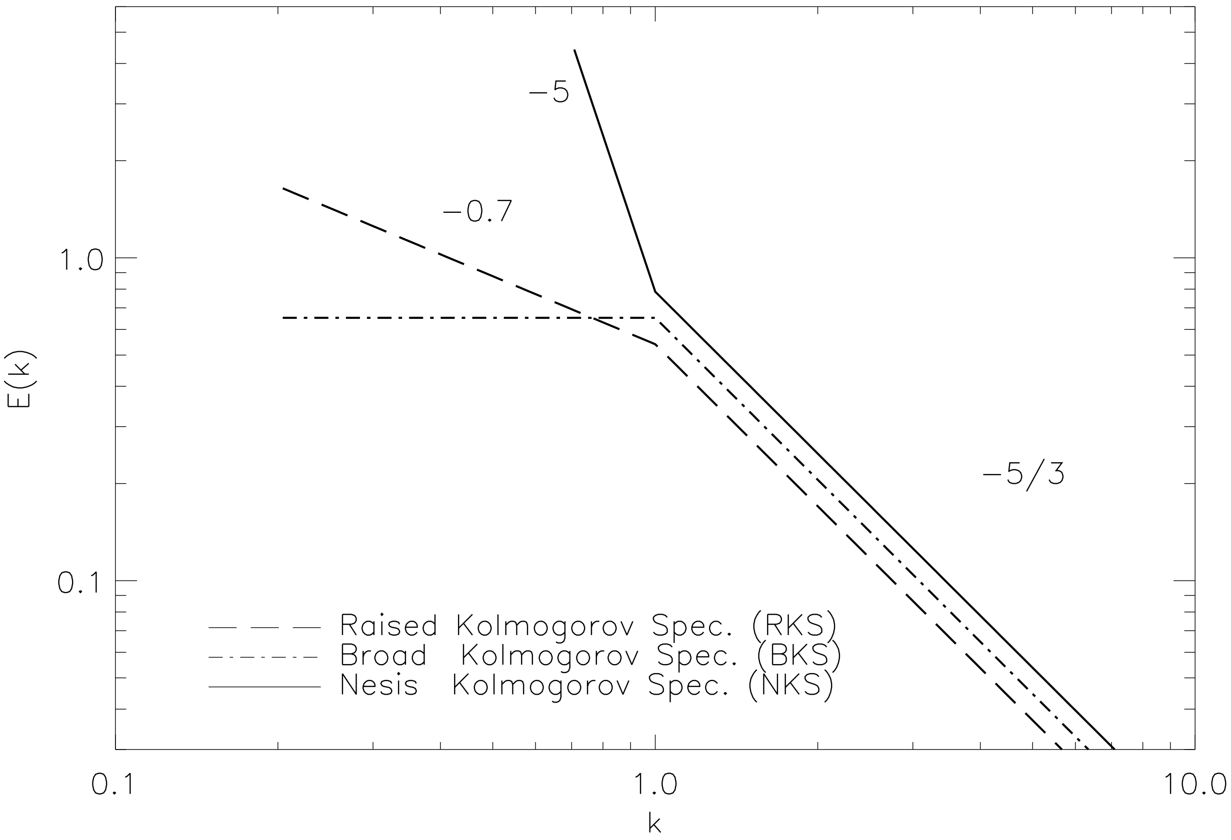

Fig. 1.— Kinetic turbulent spectra versus wavenumber k.

2.2. *Amplitudes*

The mean square surface velocity v_s is related to the power $P(\omega)$ injected into the solar oscillations and the damping rates η as :

$$v_s^2 = \xi_r^2(r_s)\ P(\omega)\ /\ 2\eta I \tag{3}$$

where r_s is the radius at which oscillations are measured. In the adiabatic assumption v_s is in turn simply related to the luminosity fluctuation δL approximately as (Kjeldsen & Bedding, 1995)

$$\delta L/L \propto v_s\, T_{\text{eff}}^{-1/2} \tag{4}$$

where L is the star luminosity and T_{eff} its effective temperature.

Except for the Sun, measurements of the damping rates η are not available. However, Goldreich & Kumar (1991) derived a simplified equation for η, which allows us to relate η to the damping rates $\eta_\odot$ of solar acoustic modes as (see Houdek, 1996, section 3.4.4)

$$\eta = \frac{L\,(H\,c_s^{-2}\,\omega\,R)^2\,I^{-1}}{L_\odot\,(H\,c_s^{-2}\,\omega\,R)^2_\odot\,I_\odot^{-1}}\ \eta_\odot \tag{5}$$

where c_s and H are the sound speed and the pressure scale height respectively, evaluated at the top of the convection zone, and R is the star radius.

2.3. Solar calibration of the free parameters

The power $P(\omega)$ has been computed for a calibrated solar model obtained with the CESAM code (Morel, 1997) using Eq.(1) and Eq.(2). Convection is described according to the classical mixing-length theory (Böhm - Vitense, 1958). The oscillation properties were obtained from the adiabatic FILOU pulsation code of Tran Minh & Leon (1995). The physical ingredients of the model are detailed in Paper II.

Using the observed linewidths of Libbrecht (1988) we compute the mean surface velocitites $v_s(\omega_0)$ according to Eq.(3). For each of the considered spectra the free parameters β and λ have been adjusted in Paper II in order to match the estimated values of $v_s(\omega_0)$ to the solar observations of Libbrecht (1988). All spectra of Fig 1 fit well (not shown here) the solar observations at low frequency ($\nu \lesssim 3.5$ mHz) while the main differences are observed at high frequency. The overall best agreement is obtained with the NKS. Details of the resulting adjustments are given in Paper II.

3. Scanning the HR diagram

3.1. The models

We consider the stellar models defined in Samadi et al. (2000). Table 1 gives the fundamental parameters of these stars. These models correspond to low intermediate mass stars ($1 \lesssim M \lesssim 2M_\odot$) where the existence of an outer convective shell enables stochastic excitation. The six models are well-distributed in the solar-like oscillation region in order to sample different star luminosity (L) and effective temperature ($T_{\rm eff}$). Positions of these stars in the HR diagram are given in the enclosed window of Figure 3. The equilibrium models and the associated eigenfunctions of these stars are obtained in the same way as for the solar model.

Models	L $[L_\odot]$	$T_{\rm eff}$ [K]	M $[M_\odot]$	ν_c [mHz]	Age [Gyr]
A	12.1	6350	1.68	1.0	1.79
B	9.0	6050	1.44	1.0	3.05
C	6.6	6400	1.46	1.5	2.40
D	3.7	5740	1.08	1.5	7.33
E	3.5	6120	1.25	2.3	4.10
F	2.6	6420	1.25	3.6	1.76

Table 1: Parameters of the stellar models. ν_c is the cut-off frequency.

3.2. Star-to-star comparison

The acoustic power spectra were computed in Samadi et al. (2000) for each selected star and for each of the three turbulent spectra of Figure 1. We present here for each star the relative luminosity fluctuation $\delta L(\omega)/L$ with the help of Eq.(4) and Eq.(3) and using the crude estimate of the damping rates η (Eq. 5). The result is presented in Figure 2.

As expected, the behavior of the oscillation amplitude spectrum $\delta L(\omega)/L$ is analogous to the one of the power spectrum $P(\omega)$ as plotted in Samadi et al. (2000) : the oscillation amplitude spectrum of model E shows a small sensitivity to the properties of the turbulent spectrum whereas the frequency dependence of $\delta L(\omega)/L$ for models A and C is very dependent on the turbulent spectrum.

These observed differences were related in Samadi et al. (2000) to the effective temperature of the stars : for the other hotter stars, the relative smaller size of their convection zone (CZ, hereafter) causes the excitation region to be localized in a thinner domain where changes in the properties of ξ_r are large. Moreover at a given frequency the extension of the excitation region changes with the considered turbulent spectra. Therefore the shape of $\delta L(\omega)/L$ is very sensitive to both the properties of ξ_r - thus to ω - and the behavior of the turbulent spectrum. As a result, significant differences in term of $\delta L(\omega)/L$ are observed when using different turbulent spectra (see also Samadi et al., 2000, 2001b). As these differences are generally larger than the accuracy to be reached by COROT on the measurements of the amplitudes (Fig. 2), this experiment will allow to constrain the stellar turbulent spectrum of each observed star.

For the cooler model E (equivalently the Sun), the more extended outer CZ causes the excitation region to be deeper in the interior. Therefore as for the Sun the power injected into low frequency oscillations is mainly governed by the eigenfunction behavior ($\partial\xi_r/\partial r$ and I) and not by the behavior of turbulence (see Samadi et al., 2000, for more details).

Besides a temperature effect, there is also a luminosity (or mass) effect, although much smaller. This is illustrated with model F which is much hotter than model E but shows only a very weak sensitivity to the choice of the turbulent spectrum (not shown here). Model F is an intermediate case as it is less massive than for instance model C. Therefore the excitation region for this star extends deeper down compared to that of model C. As a consequence, the oscillation amplitude spectrum of model F is mainly governed by the eigenfunction behavior and thus it is less sensitive to the turbulence model.

Figure 3 presents a star to star comparison of the oscillation amplitudes computed assuming the NKS. As the star becomes hotter and more luminous the frequency domain where $\delta L(\omega)/L$ takes significant values becomes smaller. This is due to the decrease of the cut-off frequency with increasing values of $T_{\rm eff}$ and L. Moreover the oscillation amplitude spectra of the hotter and more luminous stars (models A, B, and C) present more structures than those of cooler and less massive stars (models D, E, and F).

3.3. Observational constraints

Clear evidencies of solar-like oscillations have been produced for Procyon by Martic et al. (1999) and Barban et al. (1999) and for β Hydri by Bedding et al. (2001).

Ground-based observations are strongly limited by the daily aliases. Measurements of the growth rates η are thus not currently possible and the power injected into the observed solar-like oscillations cannot be evaluated from current observations. Thus we need observations performed in such a way as to avoid the daily aliases.

Space experiments are particularly adapted for asteroseismology: the forthcoming space project COROT (Baglin & the Corot team, 1998) based on photometric measurements will reach a noise level of 0.7 ppm (Auvergne & the COROT Team, 2000) and will thus detect oscillation amplitudes comparable to the solar ones (~ 2 ppm). Furthermore, the instrument will continuously monitor several stars during ~ 150 days giving a frequency precision of $\sim 0.1\,\mu$Hz, such that accurate measurements of η will be available.

Will this high accuracy enable us to constrain the theory of stochastic excitation and stellar turbulence ? In Figure 2 we have plotted the error bars assuming COROT noise level $\Delta\delta L \sim 0.7$ ppm. We conclude that the differences between the spectra for the hotter stars (models A and C) are sufficiently large compared to the error bars to identify the best turbulent spectrum.

Conclusion

The computed oscillation amplitudes of the hotter stars considered here clearly show a large sensitivity to the model of turbulence (Figure 2). According to COROT's high performances it will be thus possible to constrain the turbulent spectrum of stars properly chosen in the solar-like oscillation region.

Moreover, for a given turbulent spectrum, large differences are observed between the oscillation amplitudes computed for different stars (Figure 3). This suggest that a comparaison between oscillation amplitudes of different stars observed with COROT will provide valuable additional constraints.

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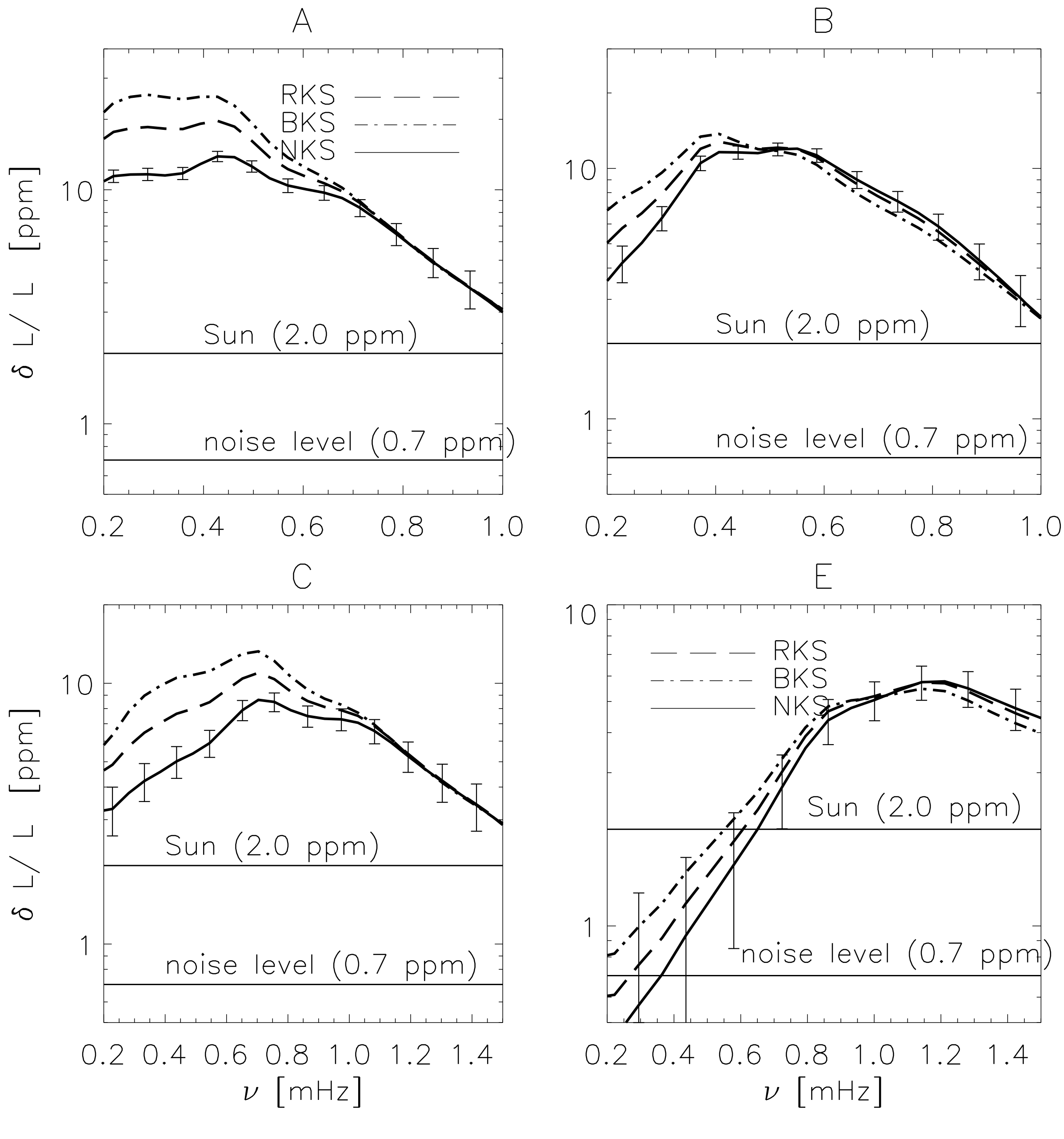

Fig. 2.— Oscillation amplitudes $\delta L/L$ versus frequency ($\nu = \omega/2\pi$), assuming the different spectra of Fig.1, are computed for the stars : A, B, C and E. Vertical error bars corresponds to COROT noise level of 0.7 ppm.

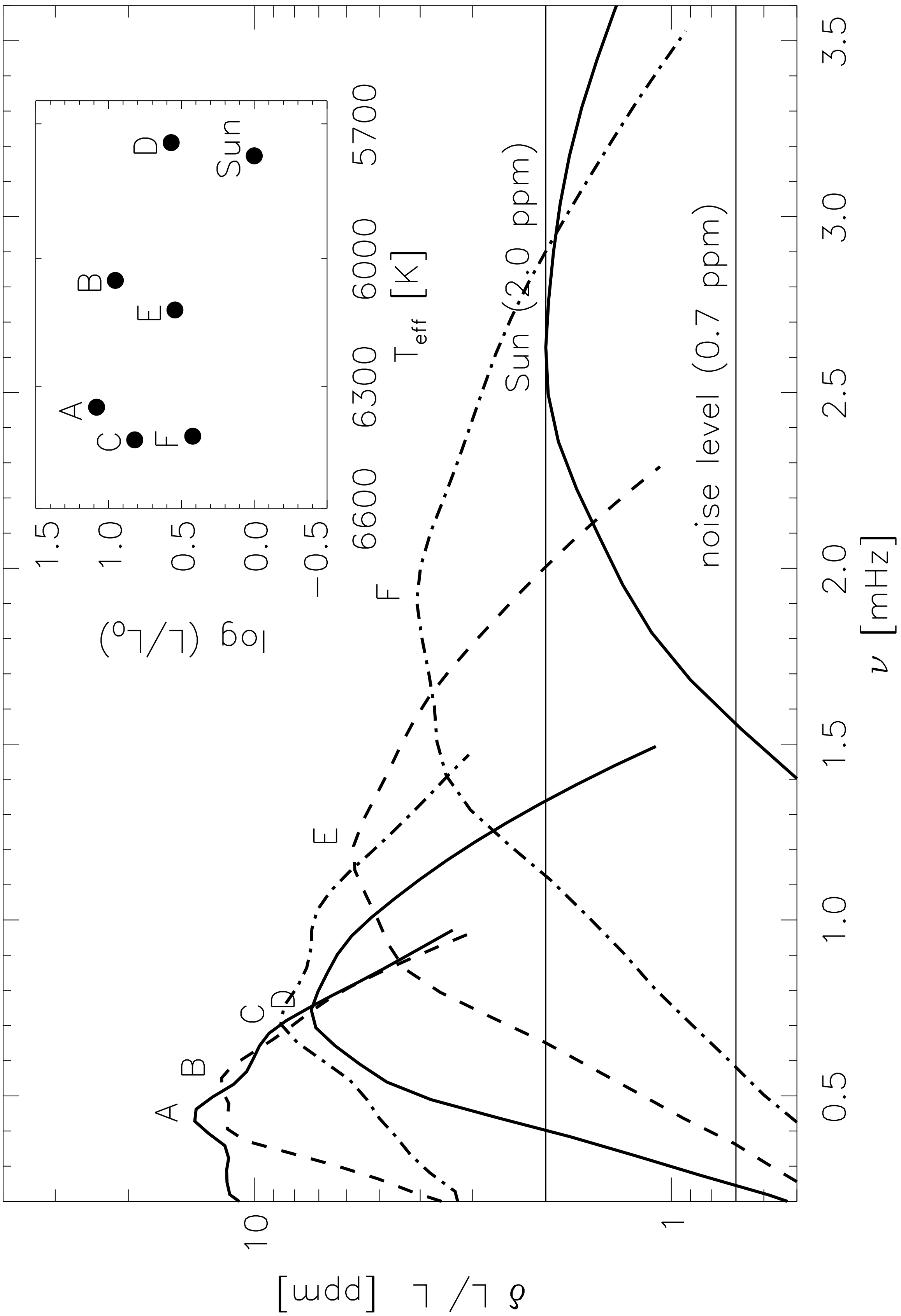

Fig. 3.— For each star the oscillation amplitude $\delta L/L$ is computed assuming the NKS. Positions of the stellar models in the HR diagram is shown in the enclosed window.