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L ETTER TO THE E DITOR

Mode lifetimes of stellar oscillations

Implications for asteroseismology

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ABSTRACT

Context. Successful inference from asteroseismology relies on at least two factors: that the oscillations in the stars have amplitudes large enough to be clearly observable, and that the oscillations themselves be stable enough to enable precise measurements of mode frequencies and other parameters. Solar-like p modes are damped by convection, and hence the stability of the modes depends on the lifetime.
Aims. We seek a simple scaling relation between the mean lifetime of the most prominent solar-like p modes in stars, and the fundamental stellar parameters.
Methods. We base our search for a relation on the use of stellar equilibrium and pulsation computations of a grid of stellar models, and the first asteroseismic results on lifetimes of main-sequence, sub-giant and red-giant stars.
Results. We find that the mean lifetimes of all three classes of solar-like stars scale like $T_{\rm eff}^{-4}$ (where $T_{\rm eff}$ is the effective temperature). When this relation is combined with the well-known scaling relation of Kjeldsen & Bedding for mode amplitudes observed in narrow-band intensity observations, we obtain the unexpected result that the height (the maximum power spectral density) of mode peaks in the frequency power spectrum scales as g^{-2} (where g is the surface gravity). As it is the mode height (and not the amplitude) that fixes the S/N at which the modes can be measured, and as g changes only slowly along the main sequence, this suggests that stars cooler than the Sun might be as good targets for asteroseismology as their hotter counterparts. When observations are instead made in Doppler velocity, our results imply that mode height does increase with increasing effective temperature.

Key words. convection – stars: oscillations – methods: data analysis

1. Introduction

Asteroseismology is now opening new windows on the interiors of solar-like stars, and allowing inferences to be made on the masses, sizes, and ages to levels of precision that would not otherwise be possible. These results have come from ground-based campaigns (Bedding & Kjeldsen 2006) and from spacecraft observations, e.g., WIRE (Bruntt 2007), MOST (Matthews et al. 2007) and SMEI (Tarrant et al. 2007). CoRoT (Baglin et al. 2006) is now producing exciting results on hot solar-like main-sequence stars (Michel et al. 2008); while NASA's Kepler mission (Basri et al. 2005) will increase by more than two orders of magnitude the number of solar-like stars we can observe by seismology (Christensen-Dalsgaard et al. 2007).

A first detailed attempt to predict amplitudes and hence the detectability of solar-like p-mode oscillations in stars other than the Sun was presented by Christensen-Dalsgaard & Frandsen (1983). They made computations for a grid of stellar models in the colour-magnitude diagram, and concluded that both velocity and intensity oscillation amplitudes generally increased with increasing age and with increasing mass along the main sequence. Kjeldsen & Bedding (1995) used the same model data as Christensen-Dalsgaard & Frandsen, and found that the p-mode velocity amplitudes in the models scaled as $v_{\rm osc} \propto (L/M)^s$ where $s = 1$. Kjeldsen & Bedding (1995) also used linear theory

and observational data to obtain a relation between the velocity and intensity amplitudes, i.e., $(\delta L/L)_\lambda \propto v_{\rm osc}/T_{\rm eff}^2$ (assuming the amplitudes in intensity were inferred from narrow-band observations).

The scaling relations of Kjeldsen & Bedding (1995) have been used extensively within the field of asteroseismology. However, several studies have since suggested modifications to the relations. Houdek et al. (1999) calculated a new grid of stellar models, and included the perturbations to the convective heat and momentum fluxes in the mode stability computations. From this improved grid of stellar models Houdek et al. (1999) still obtained the same scaling relation as Kjeldsen & Bedding (1995) for L/M less than three times the solar value, but found that $s = 1.29$ for $M/M_\odot \gtrsim 1.4$. Samadi et al. (2005), on the other hand, used numerical 3D simulations of near-surface convection to obtain $s \approx 0.7$, a result which has been supported to some extent by a number of ground-based observations of oscillations in solar-like stars. Very recently, Michel et al. (2008) concluded from the first solar-like oscillation observations made by CoRoT that intensity amplitudes were about 25% lower than the predictions of Samadi et al. (2005).

In this letter, we continue the work initiated by Christensen-Dalsgaard & Frandsen (1983) and Kjeldsen & Bedding (1995). However, rather than looking at the mode amplitudes we try instead to find a simple scaling relation to describe the *lifetimes*,

τ, of the solar-like oscillations. The solar-like oscillations are damped (and excited) by convection, and so the lifetimes are potentially an extremely useful diagnostic of near-surface convection in stars. Our first motivation in seeking a robust scaling relation is therefore to help elucidate the underlying physics at play. Our second motivation is to enable simple, but robust, lifetime predictions to be made for main-sequence, sub-giant and red-giant stars. As explained below, the lifetimes affect the detectability of the modes, so that lifetime predictions have a rôle to play in target selection.

For a given mode amplitude, strong damping spreads the power of the mode over a large range in frequency, implying a reduction in the height of its peak in a power frequency spectrum compared to a mode with weaker damping. With τ defined as the e-folding lifetime for the amplitude, the mode peak observed in the frequency power spectrum will have a FWHM linewidth of $\Delta = 1/(\pi\tau)$. If a peak is well resolved, its height H may be expressed in terms of the mode amplitude, A (either $v_{\rm osc}$ or $(\delta L/L)_\lambda$) and mode linewidth, Δ, according to

$$H = \frac{2A^2}{\pi\Delta} \propto \frac{A^2}{\Delta}.$$

Hence, when the mode is resolved, it is H that determines the S/N in power, not A^2 alone.

We note that a robust predictor is also desirable to fix the underlying parameters of artificial asteroseismology data. Tests with artificial data (e.g., the hare-and-hounds exercises conducted in support of CoRoT and Kepler) are an important part of developing and validating data analysis codes.

The layout of the rest of our paper is as follows. We begin in Sect. 2 with a description of the theoretically computed mode lifetimes, and measured mode lifetimes, that were used to infer the scaling relation. The measured mode lifetimes come from observations of 12 main-sequence, sub-giant and red-giant stars, made by ground-based telescopes and the CoRoT, WIRE and SMEI spacecraft. We then proceed in Sect. 3 to seek a relation between mode lifetimes and the fundamental stellar parameters. Our main result is that if we average lifetimes over the most prominent modes, the average lifetime scales to a good approximation as $\langle\tau\rangle \propto T_{\rm eff}^{-4}$. We finish in Sect. 4 with a discussion of our scaling result, and its implications for future selection of asteroseismic targets.

2. Data

We consider mode lifetimes computed from the grid of stellar models used by Chaplin et al. (2008) with measured mode lifetimes from 12 solar-like stars, sub-giants and giants.

The grid of stellar models used by Chaplin et al. had masses in the range 0.7 to 1.3 $M_\odot$, and ages in the range from the ZAMS to 9 Gyr. Padova isochrones (Bonatto et al. 2004; Girardi et al. 2002, 2004) were used to specify the primary characteristics of each model, i.e., mass M, radius R, effective temperature $T_{\rm eff}$, and luminosity L. The composition was fixed at $X = 0.7$ and $Z = 0.019$ for all models. In order to estimate mode lifetimes for each model Chaplin et al. (2008) then performed stellar equilibrium and pulsation computations, as described in Balmforth (1992), Houdek et al. (1999), and Chaplin et al. (2005). The pulsation computations required estimates of M, $T_{\rm eff}$, L and the composition as input. The computations gave as output estimates of the powers and lifetimes of the radial p modes of each stellar model. We used the powers and lifetimes to compute the implied heights of the modes, and then estimated an average lifetime $\langle\tau\rangle$

for each model by averaging lifetimes (and linewidths) over the five most prominent radial modes, i.e., those with the largest heights. More details may be found in Chaplin et al. (2008).

We also use measurements of mode lifetimes of solar-like oscillations from observations of 12 main-sequence, sub-giant and red-giant stars. The measured lifetimes are shown in Table 1, together with estimates of stellar masses, luminosities, and effective temperatures, the measured large frequency separations of the p-mode spectra, and the list of references from which the data were taken.

It is important to point out that the mode lifetimes were not measured in the same way on all 12 stars, and the quoted averages are not entirely self consistent; nor do the quoted values necessarily correspond precisely to an average over the five strongest radial modes (the datum chosen for the model data). However, given the level of precision in the measurements, and given that, in many cases, it was only possible to estimate the lifetimes of a small number of modes in the vicinity of the highest amplitude, we feel this is not a major cause for concern.

The mismatch between the measured lifetimes of the different stars will no doubt introduce some extra scatter into the lifetime-stellar parameter relations we seek to constrain. We also note that for the stars observed by the Kjeldsen & Bedding group (ν Indi, α Cen B, β Hydri, Procyon and τ Ceti), lifetimes were evaluated from frequency scatter of mode frequency ridges in the Echelle diagram without including the effects of rotation, which are known to artificially lower the value of the mode lifetime (see Bazot et al. 2007, for discussion). We comment in Sect. 3 below on the impact of this bias on our results.

3. Results

Following Kjeldsen & Bedding (1995), we first sought to obtain a power-law relation between the average lifetimes and L/M. The left-hand panel of Fig. 1 plots, as a function of L/M, the average lifetimes from the stellar equilibrium and pulsation computations (diamond symbols), and the average lifetimes from the observations (crosses with error bars). The average lifetimes from the pulsation computations – which we recall do not include evolved stars – follow a well-constrained power-law relation of the form

$$\langle\tau\rangle \propto (L/M)^{-0.51\pm0.05}. \tag{1}$$

The solid line shows the best-fitting power law. The average lifetimes of the observed main-sequence stars show a rough match to this power law; however, the more evolved stars with large L/M depart significantly from the prediction. We conclude that a power law in L/M fails to provide an adequate scaling relation for main-sequence, sub-giant and giant stars.

It struck us that in order to get the observed lifetimes to follow a single curve, we needed an independent variable which reversed the order on the abscissa of the main-sequence points and giant points. Use of $T_{\rm eff}$ as the independent variable would fulfill this requirement. The right-hand panel of Fig. 1 therefore plots the lifetime data as a function of $T_{\rm eff}$. The pulsation computations again follow a well-constrained power law, described by

$$\langle\tau\rangle \propto T_{\rm eff}^{-3.7\pm0.3}, \tag{2}$$

but this time the observational data on the main-sequence stars, sub-giants *and* giants also show a good match to the best-fitting curve. We add that the model prediction for ξ Hydrae presented by Houdek & Gough (2002) is not inconsistent with this power law. However, Houdek & Gough did make different assumptions

Table 1. Mode lifetimes and fundamental stellar parameters for 12 solar-like stars, sub-giants and giants.

Name	$M/M_\odot$	$L/L_\odot$	T_{eff}	$\Delta\nu$	τ
ξ Hydrae	3.07^a	61.1 ± 6.2^a	5000 ± 100 K^a	$7.11 \pm 6.14\ \mu$Hz^a	2 days^b
ν Indi	0.847 ± 0.043^c	6.21 ± 0.23^c	$5291 \pm 34K^c$	$24.25 \pm 0.25\ \mu$Hz^c	$16.2^{+44.6}_{-7.5}$ days^d
α Cen A	1.105 ± 0.007^e	1.522 ± 0.03^e	5810 ± 50 K^e	106.2^f	3.9 ± 1.4 days^g
α Cen B	0.934 ± 0.006^e	0.503 ± 0.02^e	5260 ± 50 K^e	$161.38 \pm 0.06\ \mu$Hz^h	$3.3^{+1.8}_{-0.9}$ days^h
β Hydri	1.07 ± 0.03^i	3.51 ± 0.09^i	5872 ± 44 K^i	$57.24 \pm 0.16\ \mu$Hz^j	$2.3^{+0.6}_{-0.5}$ days^j
HD 49 933	1.2^k	0.53 ± 0.01^k	6780 ± 130 K^k	$85.9 \pm 0.15\ \mu$Hz^k	$2.3^{+0.5}_{-0.3}$ days^k
Procyon	1.48^l	6.9^l	6500 K^l	$55.90 \pm 0.08\ \mu$Hz^l	$1.5^{+1.9}_{-0.8}$ days^m
τ Ceti	0.783 ± 0.012^n	0.488 ± 0.01^n	5264 K^o	$169 \pm 0.2\ \mu$Hz^n	1.7 ± 0.5 days^n
ϵ Oph	2.4 ± 0.4^p	59^p	4887 ± 100 K^p	$5.3 \pm 0.1\ \mu$Hz^q	$2.7^{+0.6}_{-0.8}$ days^q
Arcturus	0.8 ± 0.3^r	200 ± 10^r	4290 ± 30 K^r	$0.8\ \mu$Hz^r	24.1 days^r
β Ursae Minoris	1.3 ± 0.3^s	475 ± 30^s	4040 ± 100 K^s	$0.7 \pm 0.1\ \mu$Hz^s	18 ± 9 days^s
Sun	1	1	5780 K	$134\ \mu$Hz	3.2 ± 0.2 days^t

References: [a] Frandsen et al. (2002); [b] Stello et al. (2006); [c] Bedding et al. (2006); [d] Carrier et al. (2007); [e] Miglio & Montalbán (2005); [f] Bedding et al. (2004); [g] Fletcher et al. (2006); [h] Kjeldsen et al. (2005); [i] North et al. (2007); [j] Bedding et al. (2007); [k] Appourchaux et al. (2008); [l] Leccia et al. (2007); [m] Arentoft et al. (2008); [n] Teixeira et al. (2009); [o] Pijpers (2003); [p] de Ridder et al. (2006); [q] Barban et al. (2007); [r] Tarrant et al. (2007); [s] Tarrant et al. (2008); [t] Chaplin et al. (2005).
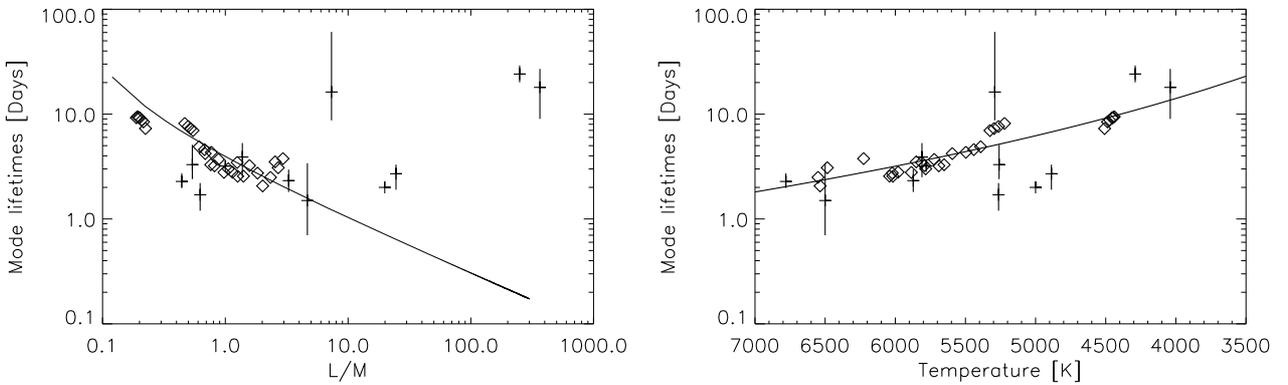

Fig. 1. Average mode lifetimes $\langle\tau\rangle$ from the stellar equilibrium and pulsation computations (diamonds) and from observations of 12 stars (crosses), plotted as a function of: the L/M of each star (*left-hand panel*); and the effective temperature, T_{eff}, of each star.

about the "non-locality" of the convection to those adopted in the models used here. We are currently working on new models for a selection of red giant stars, which will provide a consistent treatment of the convection parameters.

We therefore propose that a power law of the form

$$\langle\tau\rangle \propto T_{\mathrm{eff}}^{-4}$$

does provide an adequate scaling relation for main-sequence, sub-giant and giant stars.

Some of the measured lifetimes, close to $T_{\mathrm{eff}} \sim 5000$ K, are noticeably shorter than the lifetimes implied by the best-fitting power law. These measurements were made by the Kjeldsen & Bedding group, and we suggest that the results for these stars may have been affected by not including rotation in the analysis (cf. Sect. 2).

The result we obtain when fitting the lifetimes from the stellar equilibrium and pulsation computations to a power law in L/M disagrees somewhat with the result of Chaplin et al. (2007). Chaplin et al. obtained $\Delta \propto (L/M)^{1.6\pm0.3}$, while our result here implies $\Delta \propto (L/M)^{0.5}$. Chaplin et al. used pulsation computations of a sample of models matching 22 solar-like stars in the Mount Wilson Ca II H and K survey (Baliunas et al. 1995). All models had L/M lower than $\sim$1.3-times the solar value. We suggest, with reference to Fig. 1, that this is a too small range in L/M to extract a robust relation.

4. Discussion

The aim of this study was to find a simple scaling relation between the mean lifetimes, $\langle\tau\rangle$, of the most prominent solar-like p modes in stars, and the fundamental stellar parameters. We used predicted lifetimes from stellar equilibrium and pulsation computations, and measured mode lifetimes from observations of 12 main-sequence, sub-giant and red-giant stars. Our study suggests that the lifetimes follow to a good approximation a scaling relation that depends only on effective temperature:

$$\langle\tau\rangle \propto T_{\mathrm{eff}}^{-4}. \tag{3}$$

The fourth-power dependence on effective temperature deserves some comment. The total surface flux radiated by a star is of course by definition proportional to T_{eff}^4, and we would expect that, to first order, this will also correspond approximately to the surface convective heat flux in stars with near-surface convection zones. The total heat flux transported by the convection is clearly an important parameter in fixing the strength of damping of solar-like oscillations. It is perhaps worth noting (see below) that a similar, simple dependence on effective temperature is not seen in the *amplitudes* of the solar-like p modes.

We may combine our scaling relation for average lifetime with the scaling relation of Kjeldsen & Bedding (1995) for the maximum mode amplitude, A, to yield a scaling relation for the maximum mode height, H, in the frequency power spectrum. For

narrow-band intensity observations, Kjeldsen & Bedding proposed:

$$A = (\delta L/L)_\lambda \propto \frac{L}{MT_{\mathrm{eff}}^2} \propto \frac{T_{\mathrm{eff}}^2}{g}.$$

Combining with our prediction for lifetime, we obtain

$$H \propto g^{-2}. \tag{4}$$

We predict that the maximum mode height – which fixes the S/N, and hence the visibility, of peaks when they are resolved in the frequency power spectrum – depends *predominantly* on the surface gravity of stars, when the observations are made in intensity. We use the qualification in the preceding sentence because the above does assume that the Kjeldsen & Bedding scaling for $(\delta L/L)_\lambda$ is accurate. While this scaling is supported to a large extent by observations, there is evidence for some departures from the scaling, most notably for hotter solar-like stars (as noted in Sect. 1 above). When observations are instead made in Doppler velocity – which, using Kjeldsen & Bedding's proposed scaling, implies $A \propto L/M$ – we find

$$H \propto \frac{T_{\mathrm{eff}}^4}{g^2}. \tag{5}$$

Since the surface gravity changes fairly slowly along the main sequence, our new scaling relation for H given by Eq. (4), which assumes narrow-band intensity observations, suggests that stars notably cooler than the Sun might have mode heights that are in fact comparable to those of solar-like stars that are hotter than the Sun. Previously, asteroseismic target selections were based only on the expected amplitudes, mainly because we had no idea about how the mode lifetimes scaled with fundamental stellar parameters. This would lead one to favour hotter stars as targets, while our result here suggests cooler solar-like stars may actually be very good targets as well. When observations are instead made in Doppler velocity (Eq. (5)), our results imply that H increases with increasing effective temperature.

Our prediction that cooler stars show longer lifetimes brings another added benefit: it is easier to estimate stellar rotation rates using asteroseismology, because the ratio between the rotational splittings and the mode linewidths will generally be higher than in hotter stars (see also Chaplin et al. 2008). This is important, because one of the main goals of asteroseismology is to measure surface and internal differential rotation (see also: Gizon & Solanki 2003, 2004; and Ballot et al. 2006).

We therefore suggest that in future our scaling relations for mode height (Eqs. (4) and (5)), and not the previously used relations for mode amplitude, be used when selecting targets for asteroseismology.

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