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What can we learn about convection from asteroseismology?

Hans Kjeldsen[1] **and Timothy R. Bedding**[2]

[1]Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark
email: hans@phys.au.dk

[2]School of Physics A28, University of Sydney, NSW 2006, Australia
email: bedding@Physics.usyd.edu.au

Abstract. Asteroseismology—using stellar oscillations to study the interiors of stars—is a relatively new and growing research field in astrophysics. Oscillations are found in stars of most masses and essentially all stages of evolution. Their frequencies are determined by the internal sound speed and density structure of the star, as well as rotation, convection processes and possibly effects of magnetic fields. Recent developments have led to a breakthrough in our ability to study the details of cores of solar-like stars and it is foreseen that a number of key science questions will be addressed through the analysis of frequencies and other properties of stellar oscillations. In this paper we review some of the latest results from asteroseismology of solar-like stars, with the focus on properties of convection.

Keywords. Convection, stars: oscillations (including pulsations), methods: data analysis

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1. Introduction

Oscillation frequencies are the most accurate properties one can measure for a star. With a relative frequency precision well below 0.1%, the oscillations allow a detailed test of models for stars. Solar-like p-mode oscillations are especially interesting because they show a multi-mode oscillation spectrum and because their frequency structure allows identification of the oscillation modes. This property allows observed frequencies to be compared with theoretical models. The most challenging problem for observing solar-like oscillations arises from their extremely tiny amplitudes. Detection of those oscillations therefore requires very sophisticated techniques, such as high-precision Doppler measurements or space-based photometry.

There has been tremendous recent progress in observing oscillations in solar-type stars lying on or just above the Main Sequence. In a few short years we have moved from ambiguous detections to firm measurements. Most of the results have come from high-precision Doppler measurements using spectrographs such as CORALIE, HARPS, UCLES and UVES. For a recent summary of these observations, see Bedding & Kjeldsen (2007). The best data have been obtained from two-site campaigns, although single-site observations are also being carried out. Meanwhile, photometry from space gives a much better observing window than is usually achieved from the ground but the signal-to-noise is poorer. The WIRE and MOST space missions have reported oscillations in several stars, although not without controversy, as discussed below.

The oscillation frequencies depend to first order on the size of the star (the radius) and the sound speed. The sound speed is proportional to the square root of the ratio between pressure and density which, through the equation of state, is (to first order) proportional to the ratio between temperature and mean molecular weight. We may therefore use the frequencies to get information on the pressure, density, temperature and chemical

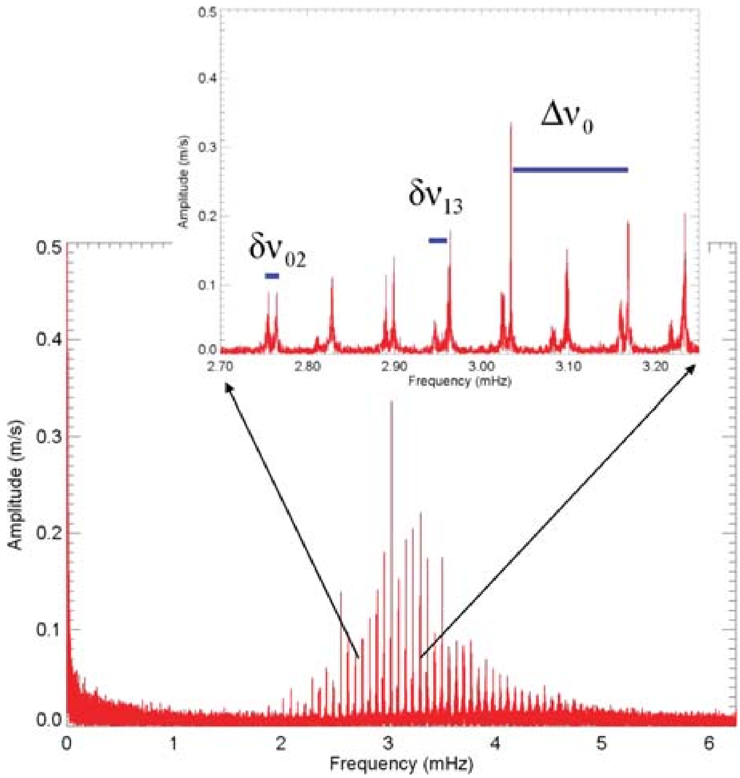

Figure 1. The solar p-mode amplitude spectrum, as measured in velocity by the GOLF instrument on board the SoHO spacecraft. The Fourier spectrum was calculated from a 30-day time series downloaded from the GOLF Web site (http://www.medoc-ias.u-psud.fr/golf). The spectrum shows a clear excess of power centred at 3 mHz, which is about 0.55 times the acoustic cut-off frequency in the solar atmosphere (5.5 mHz). The zoom shows the detailed frequency structure, and we indicate the large and small frequency separations.

composition throughout the stellar interior. Convection in the core or in the envelope will affect the profiles of pressure, temperature and density and we may therefore use the oscillation frequencies of a star to examine the properties of the convection.

Frequencies for high-order and low-degree solar-like oscillation modes can be approximated by a simple asymptotic relation (see, e.g., Tassoul 1980), which may be expressed as

$$\nu_{n,l} = \Delta\nu(n + l/2 + \epsilon_0) - D_0 l(l+1). \tag{1.1}$$

Here, n is the radial order and l is the mode degree, and "low-degree" means $l \ll n$. For an unresolved star, cancellation over the surface means that only modes with $l = 0$, 1, 2 and 3 are observable. Fortunately, these are also the modes that penetrate most deeply into the stellar interior.

Based on this, one may define a set of frequency separations that characterize the spectrum. Those separations are shown in Fig. 1 and more details can be found in the review by Christensen-Dalsgaard (2004).

As summarised schematically in Fig. 2, there are a number of oscillation properties that provide information on the convection in different parts of the stellar interior. Most of the information on convection is seen as differences between the observed frequencies

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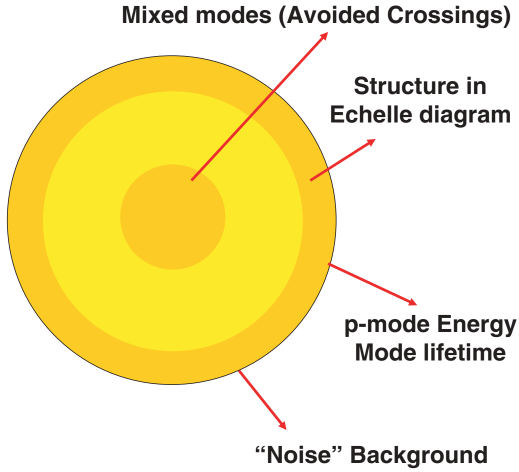

Figure 2. Schematic diagram of a star with two convection zones (core and envelope), summarising the signatures of convection that are expected to be seen in the oscillation properties. A convective core is best visible as frequencies that are not following the simple asymptotic relation, e.g. frequencies for modes that show the effect of so-called avoided crossings. The properties of the outer convection zone are seen as curvature in the échelle diagram. Properties of convection near the surface are seen through the excitation and damping of the p-modes, as well as in the background noise in the power spectrum arising from granulation.

and the simple asymptotic relation (equation 1.1). In the following sections we will show examples of those oscillations properties.

2. Avoided crossings and core convection

An important feature of subgiants is that mode frequencies may be shifted from their usual almost-regular spacing by effects of gravity modes in the stellar core (so-called ‘avoided crossings’). Avoided crossings (also called ‘mixed modes’) provide a very sensitive measure of conditions in the core. There is now good evidence for this phenomenon in two subgiant stars.

The first of these is η Boo, which is the brightest G-type subgiant in the sky. The claimed detection of oscillations almost a decade ago by Kjeldsen *et al.* (1995), based on fluctuations in Balmer-line equivalent-widths, has now been confirmed by further equivalent-width and velocity measurements by the same group (Kjeldsen *et al.* 2003) and also by independent velocity measurements with the CORALIE spectrograph by Carrier *et al.* (2005). With the benefit of hindsight, we can now say that η Boo was the first star for which the large separation and individual frequencies were measured. However, there is still disagreement on some of the individual frequencies, which reflects the subjective way in which genuine oscillation modes must be chosen from noise peaks and corrected for daily aliases. Fortunately, the large separation is $\Delta\nu = 40\,\mu$Hz, which is half way between integral multiples of the 11.57-μHz daily splitting ($40/11.57 = 3.5$). Even so, daily aliases are problematic, but it seems clear that some of the modes in η Boo are shifted by avoided crossings, in general agreement with theoretical models by Christensen-Dalsgaard *et al.* (1995), Guenther & Demarque (1996) and Di Mauro *et al.* (2003a).

Spaced-based observations of η Boo, made with the MOST satellite, have generated considerable controversy. Guenther *et al.* (2005) showed an amplitude spectrum (their Fig. 1) that rises towards low frequencies in a fashion that is typical of noise from

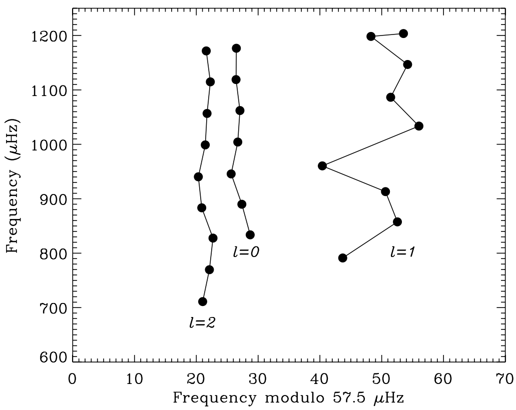

Figure 3. Échelle diagram of oscillations in β Hyi. The avoided crossings are clearly visible as a departure from regularity in the $l = 1$ modes (Bedding *et al.*, in prep.).

instrumental and stellar sources. However, they assessed the significance of individual peaks by their strength relative to a fixed horizontal threshold, which naturally led them to assign high significance to peaks at low frequency. They did find a few peaks around $600\,\mu$Hz that agreed with the ground-based data, but they also identified eight of the many peaks at much lower frequency (130–500 μHz), in the region of rising power, as being due to low-overtone p-modes. Those peaks do line up quite well with the regular $40\,\mu$Hz spacing, but extreme caution is needed before these peaks are accepted as genuine. This is especially true given that the orbital frequency of the spacecraft ($164.3\,\mu$Hz) is, by bad luck, close to four times the large separation of η Boo ($164.3/40 = 4.1$).

The other subgiant to show avoided crossings is β Hyi, as shown in Fig. 3. This figure shows the measured frequencies in so-called échelle format, where each frequency is plotted modulo the large separation $\Delta\nu$. For precisely regular peaks that exactly follow (1.1), the points would align vertically. The avoided crossings in β Hyi are clearly visible as a departure from regularity in the $l = 1$ modes, and they show a close resemblance to theoretical models made earlier by Fernandes & Monteiro (2003) and Di Mauro *et al.* (2003b). It is to be hoped that detailed comparison between observations of avoided crossings in subgiants and theoretical models will allow us to test models of convective cores.

3. Outer convection zone and curvature in the échelle diagram

One may directly measure the depth of the outer convection zone by measuring the global structure of the échelle diagram. In Fig. 4 we show one example of an observed échelle diagram, for the main-sequence star α Cen B. The scatter of the measurements about the ridges is due to the finite lifetime of the modes, which tells us about the damping by convection in the near-surface layers (see Sec. 4). Of particular interest here is the curvature of the ridges, which arises from the internal structure of the star and is sensitive to the outer convection zone. In fact, the depth of the convection zone can in principle be determined from the details of the curvature in the échelle diagram.

4. Near-surface convection, excitation and damping

The excitation of the p-mode oscillations arise from near-surface turbulence (convective motions). The convection also plays an important role in mode damping, and so a study

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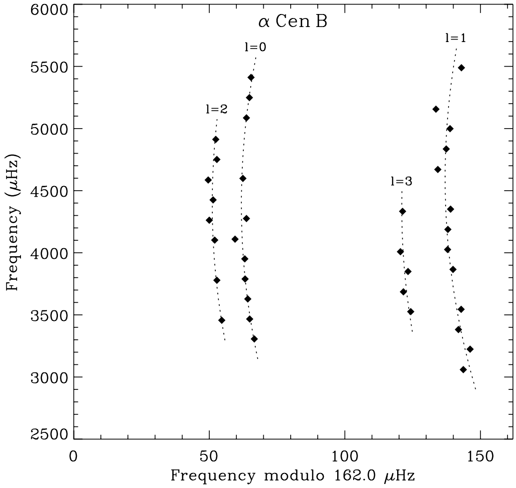

Figure 4. Échelle diagram of oscillation frequencies in α Cen B, from Kjeldsen *et al.* (2005).

of the p-mode amplitude, mode lifetime and the frequency of peak power may be used to check the convective properties of the outer part of the convection zone. As mentioned above, the scatter of measured frequencies about the ridges in échelle diagrams such as Fig. 4 is due to the finite lifetime of the modes. Measuring the mode lifetime tells us about the damping by convection in the near-surface layers. This is being done for a growing number of stars.

In Fig. 5 we compare the p-mode spectra for α Cen A, the Sun and α Cen B. The spacings of the modes (the large separation, $\Delta\nu$) reflect the mean density, with α Cen A having the lowest density. The envelopes are also very different, with strongest modes in α Cen B having the lowest amplitudes and the highest frequencies. The difference in these properties for the three stars are mainly due to differences in mean density, surface gravity and surface temperature, which give rise to different properties in surface convection. As more and more stars are added to the picture, we expect to place constraints on models of near-surface convection (e.g., Samadi *et al.*, these Proceedings).

5. Granulation background in the power spectrum

Intensity measurements are dominated by temperature fluctuations and so are sensitive to the stellar background that arises from granulation. This is well known from intensity observations of the Sun, appearing as a background in the power spectrum that rises towards low frequencies. Such power has been reported in observations of α Cen A by Kjeldsen *et al.* (1999) and more recently by Bruntt *et al.* (2005) in the star Procyon A. The latter result was based on two photometric time series from the star tracker on the WIRE satellite. Those power spectra, shown in Fig. 6, show a slight excess around 1 mHz that is consistent with the detection of p-modes. In addition, there is a significant rise in the noise level below 0.3 mHz, which these authors interpreted as the granulation signal. Both the shape of the background power signal and the size of the power density spectrum are important values for understanding the granulation properties in solar-like stars.

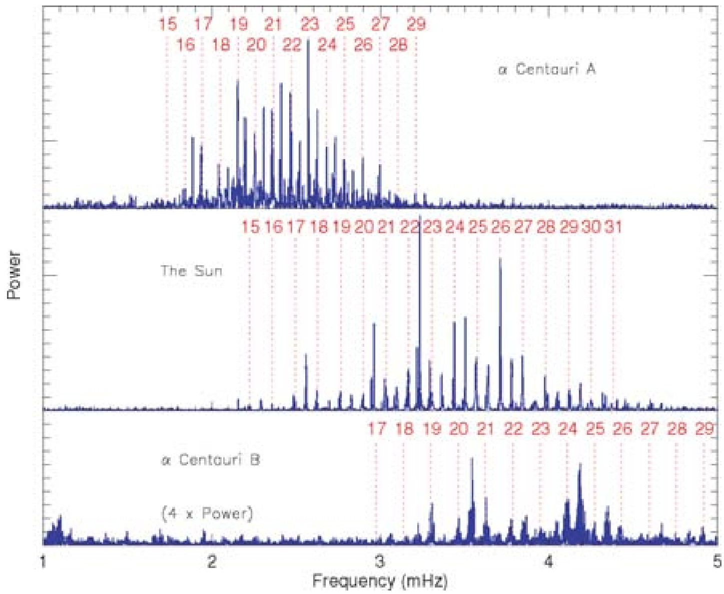

Figure 5. Comparison between the power spectra for α Centauri A, the Sun and α Centauri B. The data for α Centauri B has been multiplied by a factor of 4 in power (2 in amplitude). The data for α Cen A and B are taken from Bedding *et al.* (2004) and Kjeldsen *et al.* (2005), while the solar data are from GOLF (see Fig. 1). In each case we have marked the positions of the radial ($l = 0$) modes, which are labelled with the radial order (n).

6. Future prospects

In the future, we expect further ground-based observations using Doppler techniques (for example, a multi-site campaign on Procyon has been organized for January 2007). The new spectrograph SOPHIE at l'Observatoire de Haute-Provence in France should be operating very soon (`http://www.obs-hp.fr/`).

From space, the WIRE and MOST satellites continue to return data and we look forward with excitement to the expected launches of COROT (December 2006) and Kepler (2008). The major improvements that one expects from those projects are the capability to produce long uninterrupted time series data for a very large number of stars covering the HR diagram.

On the theoretical side, we need improvements in the general stellar modelling, to include rotation, mixing, fluid motions, turbulent convection and deviation from spherical symmetry in the calculations.

Asteroseismology is observationally driven and one should therefore identify the limiting factors in the observing techniques, in order to progress further. The velocity of the stellar surface can be determined with high accuracy and with little contamination from the granulation background that affects intensity measurements (see Sec. 5). However, we still suffer from false peaks (aliases) in the Fourier spectrum caused by gaps in the observations. We should therefore concentrate on setting up multi-site campaigns and ultimately we should work on establishing a ground-based network of dedicated telescopes that may provide nearly 100% duty cycle. Such a network could beat future space projects in precision, since those will be dominated by the granulation background. One such network is SONG (Stellar Oscillation Network Group). For a detailed description see Grundahl *et al.* (2006) or http://astro.phys.au.dk/SONG. The plan is to design and

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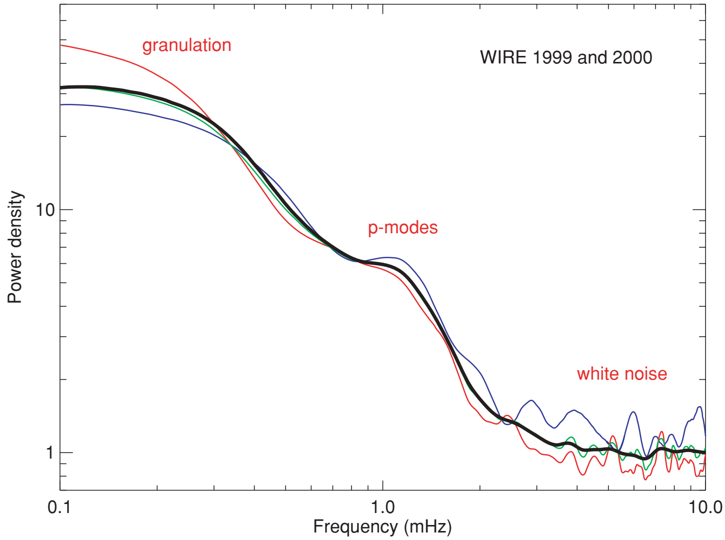

Figure 6. The smoothed curves shown here are the Procyon power density observed by Bruntt *et al.* (2005) using the WIRE satellite. The red (medium grey) curve is the 1999 WIRE data series and the blue (dark grey) is the 2000 WIRE series. The green (light grey) curve is the weighted average of the two, while the black curve is the smoothed version of the weighted average, where the smoothing has been done in logarithmic units. In this figure it is evident that Procyon shows power from granulation, p-modes and white noise (instrumental).

build a global network of small telescopes located at 6–8 existing observatories around the world, dedicated to carry out highly precise measurements of stellar velocities. SONG would out-perform existing and planned ground- and space-based instrumentation, including that available at the largest telescopes, and provides the next logical step forward in asteroseismology, as well as exoplanet searches.

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Discussion

RUEDIGER: Did you find similar lineshifts due to the turbulent convection in stars, similar to those known for the solar p-modes?

HANS KJELDSEN: We are able to measure lineshifts in a similar way as is done for the Sun, where low- and high-degree modes are used to measure the size of the lineshifts, since they are independent of frequency. In stars we only observe low-degree modes. However, we hope to be able to estimate the lineshifts from the overall structure of the frequencies (e.g., the curvature in the échelle diagram).

I.W. ROXBURGH: Just to add that the oscillations contain signatures of the boundary of convective zones: the base of a convective envelope and the boundary of a convective core.

MARTIN ASPLUND: Could you please comment on the possibility of determining stellar ages using asteroseismology – what kind of accuracy can be expected and when will it be achieved?

HANS KJELDSEN: Stellar ages are measured through a measurement of the core helium content of the star. There is a simple relation between the small and large separations and the core helium content, and this is not difficult to measure, if one resolves the p-mode structure, i.e., measuring frequencies for different degrees and orders of the modes. The accuracy is at present about 5–10 % of the total main sequence lifetime for a given star. Space missions like COROT and Kepler will provide age measurements for a large number of stars.