# 9. STELLAR OSCILLATIONS AND PULSATIONS

# OBSERVING SOLAR-LIKE OSCILLATIONS

HANS KJELDSEN
*Teoretisk Astrofysik Center, Danmarks Grundforskningsfond, Aarhus University, DK-8000 Aarhus C, Denmark*

AND

TIMOTHY R. BEDDING
*School of Physics, University of Sydney 2006, Australia*

**Abstract.** We review techniques for measuring stellar oscillations in solar-type stars. Despite great efforts, no unambiguous detections have been made. A new method, based on monitoring the equivalent widths of strong lines, shows promise but is yet to be confirmed. We also discuss several subtleties, such as the need to correct for CCD non-linearities and the importance of data weighting.

## 1. Why search for solar-like oscillations?

Given the tiny amplitudes of oscillations in the Sun and the obvious problems in detecting similar oscillations in other stars, we should first ask whether the effort is justified. Oscillation frequencies give information about the sound speed in different parts of the stellar interior. They can be measured much more precisely than can any of the other fundamental parameters which have been discussed at this meeting. Accuracies of $10^{-3}$–$10^{-4}$ have been achieved for "classical" multi-periodic pulsators stars such as $\delta$ Scuti stars, rapidly oscillating Ap (roAp) stars and $\beta$ Cephei stars. These stars pulsate with amplitudes typically 1000 times greater than seen in the Sun, so why are we not satisfied with observing them?

One reason is that the classical pulsating stars are only found in restricted areas of the HR diagram (the instability strips). Since oscillations in the Sun are thought to be excited by convective turbulence near the surface, all stars with an outer convective zone should undergo similar oscillations. This makes it possible, at least in principle, to perform seismic studies on *all* stars with spectral type later than about F5.
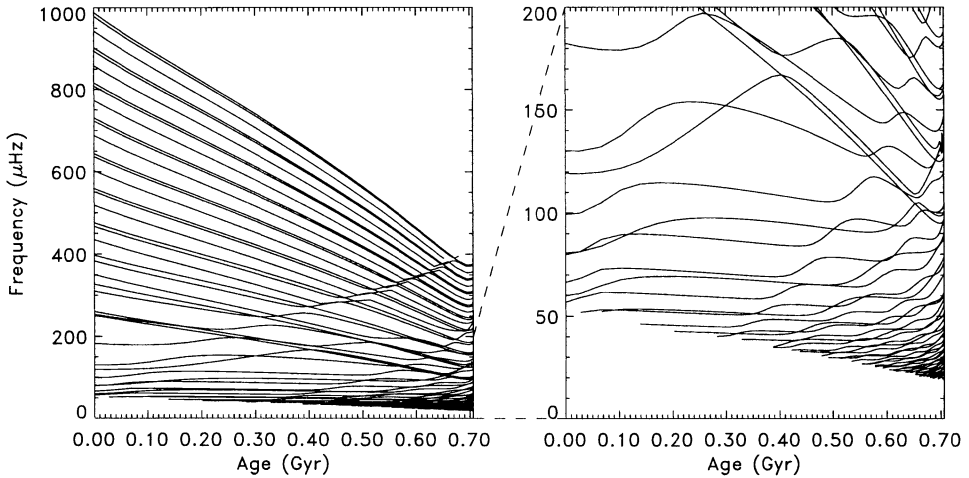
*Figure 1.* Evolution of oscillation frequencies in a $2.2\,M_\odot$ star, from model calculations by J. Christensen-Dalsgaard. Only modes with $\ell = 0, 1, 2$ and $n \le 10$ are shown.

A second reason for studying solar-like oscillations is that the modes are easy to identify. There is little point in knowing the frequency of an oscillation mode unless you also know in which part of the star that mode is trapped. An oscillation mode is characterized by three integers: $n$ (the radial order), $\ell$ (the angular degree) and $m$ (the azimuthal order)[1]. These specify the shape of the eigenfunction, which in turn determines the sensitivity of the oscillation frequency to the internal structure of the star.

Figure 1 shows the oscillation frequencies of a non-rotating star (mass $2.2\,M_\odot$) as it evolves. At any instant during the star's evolution, a vertical cross-section through this figure shows the frequencies of oscillation modes with $\ell = 0$, 1 and 2 (which are most easily observed in an unresolved star). However, in multi-periodic $\delta$ Scuti and $\beta$ Cephei stars, only the lowest frequency modes are found to be excited to an observable level, presumably due to the details of the excitation process (the so-called $\kappa$ mechanism). We are therefore forced to identify modes in the crowded lower region of the diagram. To further complicate matters, these stars tend to be rapid rotators, which causes a splitting of frequencies (analogous to Zeeman splitting). Finally, a given star is only observed to oscillate in a seemingly random subset of possible modes. Until reliable mode identification is achieved, it will be impossible to apply asteroseismology to these "classical" pulsating stars.

In contrast, it is easy to identify the modes of solar-like oscillations. At least in the Sun, all modes in a broad frequency range are excited.

---

[1] In a star with no rotation or magnetic field, frequencies do not depend on $m$.

Furthermore, these modes approximately satisfy an asymptotic relation, with modes of fixed $\ell$ and differing $n$ having regularly spaced frequencies separated by the so-called large separation, $\Delta\nu$. The resulting comb-like structure is clearly seen in the upper part of Figure 1 and allows modes to be identified directly from the oscillation spectrum.

Measuring $\Delta\nu$ provides an estimate of the stellar density. Moreover, the small differences between observed frequencies and those predicted by the asymptotic relation give crucial information about the sound speed deep inside the star.

## 2.  Sensitivities of detection methods

*Velocity*   In the Sun, the strongest modes have velocity amplitudes of about 25 cm/s, which corresponds to a wavelength variation $(\delta\lambda/\lambda)$ of less than $10^{-9}$, or $4.2\,\mu$Å at 5000 Å. Detecting such miniscule Doppler shifts in other stars is extremely difficult. Spectrographs cannot be made with absolute stabilities of $10^{-9}$, so one must simultaneously monitor the wavelength of a stable reference (e.g., a Na or K resonance cell, an $I_2$ absorption cell or telluric absorption features). The noise levels at present are down to about 0.5 m/s, which is a factor of two higher than the solar signal.

*Radius*   Given that solar periods are around 5 min, the change in radius is only about 12 m or 17 microarcseconds. Astrometry of the solar limb using SoHO/MDI has recently revealed the oscillations (J. Kuhn et al., Proc. IAU Symp. 181, in press), but such observations will surely be impossible for other solar-like stars.

*Intensity*   The solar oscillations have been observed as variations in total intensity, with amplitudes of about 4 ppm (parts per million). Open clusters are a natural target for differential CCD photometry and the lowest noise level so far achieved is 5–7 ppm, from observations by Gilliland et al. (1993) of twelve stars in M 67 using six telescopes (2.5 m to 5 m) during one week. This is an interesting noise level, less than a factor of two away from solar photometric amplitude.

Ground-based photometric observations are severely hampered by atmospheric scintillation. Several space missions have been proposed, but only one has so far been launched: the EVRIS experiment, on board the Russian Mars96 probe, which ended in the Pacific Ocean.

*Temperature*   Since the change in radius during solar oscillations is insignificant, the intensity fluctuations observed in the Sun must result from local temperature changes in the atmosphere of about 6 mK $(\delta T_{\text{eff}}/T_{\text{eff}} \approx 10^{-6})$. It has been suggested that these temperature changes can be measured by their effect on spectral absorption lines (Kjeldsen et al. 1995;

Bedding et al. 1996). For example, the Balmer lines in the Sun should show variations in equivalent width of about 6 ppm. As discussed below, the equivalent-width method has so far attained noise levels in other stars of 2–3 times the solar peak amplitude.

## 3.  Some subtleties

Achieving low noise levels demands care during both observing and data analysis. One major requirement is high efficiency, in order to get as many photons as possible (photon counting statistics are a fundamental limitation). This requires optical systems with high transmissions, detectors with high Q.E. (i.e., CCDs) and observations with a high duty cycle. This may force one to observe under quite unusual conditions. For example, in the case of photometry these requirements mean observing defocussed stars in order to avoid saturating the CCD.

Linearity of the system is another important issue. Measuring oscillations at the ppm level requires that the detector be linear to the level of $10^{-3}$ or better. This is certainly not trivial and our tests of different CCDs and controllers often reveal deviations from linearity of up to a few per cent. Unless correction is made for these effects, the extra noise will destroy any possibility of detecting oscillations.

Each step in the data reduction procedure must be tested to establish how much noise it adds to the time series. It also helps if, as well as measuring the parameter which is expected to contain the oscillation signal (magnitude, velocity or the line strength), one also monitor extra parameters. For example, by correlating measured magnitudes with seeing variations, one has a chance to remove the influence of seeing simply by subtracting that part of the signal which correlates with seeing. Of course, this assumes that the real oscillations do not correlate with the seeing. This process of decorrelation, which can be repeated for other parameters (total light level, position on detector, etc.), is very powerful but can also be quite dangerous if not done with care.

Once a time series has been extracted, the search for oscillation frequencies is done by calculating the power spectrum. The simplest method is to Fourier transform the time series and take the squared modulus. The resulting spectrum shows power as a function of frequency, and a significant peak in this spectrum implies a periodic signal in the time series data. However, the standard Fourier transform treats all data points as having equal weight. In reality, data quality can vary significantly within a data set, due to variable weather conditions or even because data are being combined from different telescopes. The power spectrum is very sensitive to bad data points – the final noise level will be dominated by the noisiest parts of the time series. One should therefore calculate a weighted power spec-

trum, with each data point being allocated a statistical weight according to its quality (e.g., Frandsen et al. 1995). Unfortunately, this procedure is not widely used and many published power spectra have higher noise than necessary.

## 4. Recent reults

Attempts to detect solar-like oscillations have been reviewed by Brown & Gilliland (1994) and Kjeldsen & Bedding (1995), and here we only discuss more recent results. Most efforts have concentrated on subgiants, since these are expected to have higher oscillations amplitudes than the Sun.

*η Boo* is the brightest G-type subgiant. We observed this star over six nights with the 2.5-m Nordic Optical Telescope (Kjeldsen et al. 1995). Using the equivalent-width method, we claimed a detection of solar-like oscillations with amplitudes at the expected level and frequencies that were subsequently shown to be consistent with models (Christensen-Dalsgaard et al. 1995; Guenther & Demarque 1996). However, a search for velocity oscillations in η Boo by Brown et al. (1997) has failed to detect a signal, setting limits level below the value expected on the basis of the Kjeldsen et al. result.

Some support for the equivalent-width method was given by Keller et al. (1997), who detected the 5-minute oscillations in the Sun from measurements of H-beta equivalent widths. However, they have subsequently had difficulties in reproducing these results (Keller, priv. comm.).

*α Cen A* is the brightest G-type main-sequence star. We obtained Hα spectra over six nights in April 1995 using the 3.9-m AAT (UCLES) and the 3.6-m ESO (CASPEC). Data reduction using the equivalent-width method was hampered by a variability of the continuum, which seems to be due to some kind of colour term in scintillation at a level of about $10^{-4}$ per minute (well below the normal photometric scintillation).

*Procyon* is the brightest F-type subgiant. Recent results from Doppler-shift measurements are: (i) Bedford et al. (1995), using a narrow-band filter, have retracted an earlier possible detection; and (ii) Brown et al. (1996), using an echelle spectrograph, have not detected a signal. We observed Procyon for several hours per night during the 1995 run mentioned above. Preliminary analysis reveals excess power at the expected amplitude and frequency, but sparse sampling prevents a definite measurement of the frequency splitting. A recent campaign on Procyon in Jan–Feb 1997 by several members of SONG (see below) should produce results soon.

*Arcturus* and similar red giants are variable in both velocity (e.g., Hatzes & Cochran 1996 and references within; Merline 1996) and intensity (e.g., Edmonds & Gilliland 1996), but the presence of solar-like oscillations has not yet been established.

## 5. Conclusion

In the last few years, the precision in velocity and photometric measurements has not been significantly improved. The new equivalent-width method is far from being fully developed and no confirmation of the claimed signal in $\eta$ Boo has been made. Hopefully, the formation of SONG (Stellar Oscillations Network Group; see `http://www.noao.edu/noao/song/`), which aims to do joint research in this field, will soon produce robust detections of oscillation signals.

Space would be a wonderful place to do photometry. Although COROT has been selected, for now we will have to continue using ground-based facilities. It is important to remember that we are only about a factor of two from producing noise levels equal to the solar oscillation signal, and that some stars are expected to oscillate with higher amplitudes than our own Sun. A network of 10-m class telescopes should provide scintillation levels low enough for detection of oscillations in M 67 (Gilliland et al. 1993), but getting a week on each of these big telescopes will not be easy.

We still await real asteroseismic results for solar-type stars. However, twenty-five years ago we were in a similar situation concerning oscillations in the Sun. First, people had to believe that these oscillations actually existed. Next, they had to measure their frequencies accurately. Finally, we have reached a stage where we truly see the Sun as a physics laboratory. The same will one day be true for other stars. It might take longer than twenty-five years, but it could also happen much faster.

## References

Bedding, T. R., Kjeldsen, H., Reetz, J., Barbuy, B., 1996, MNRAS 280, 1155
Bedford, D. K., Chaplin, W. J., Coates, D. W., et al., 1995, MNRAS 273, 367
Brown, T. M., Gilliland, R. L., 1994, ARA&A 33, 37
Brown, T. M., Kennelly, E. J., Noyes, R. W., et al., 1996, BAAS 188, 5902
Brown, T. M., Kennelly, E. J., Korzennik, S. G., et al., 1997, ApJ 475, 322
Christensen-Dalsgaard, J., Bedding, T. R., Kjeldsen, H., 1995, ApJ 443, L29
Edmonds, P. D., Gilliland, R. L., 1996, ApJ 464, L157
Frandsen, S., Jones, A., Kjeldsen, H., et al., 1995, A&A 301, 123
Gilliland, R. L., Brown, T. M., Kjeldsen, H., et al., 1993, AJ 106, 2441
Guenther, D. B., Demarque, P., 1996, ApJ 456, 798
Hatzes, A. P., Cochran, W. D., 1996, ApJ 468, 391
Keller, C. U., Harvey, J. W., Barden, S. C., et al., 1997, PASP (submitted)
Kjeldsen, H., Bedding, T. R., 1995, A&A 293, 87
Kjeldsen, H., Bedding, T. R., Viskum, M., Frandsen, S., 1995, AJ 109, 1313
Merline, W. J., 1996, BAAS 28, 860

Discussion of this paper appears at the end of these Proceedings.