Solar-like oscillations: the search goes on

Timothy R. Bedding

School of Physics, University of Sydney 2006, Australia

Hans Kjeldsen

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

Abstract.

Despite numerous attempts and many hours of telescope time, there has so far been no confirmed detection of solar-like oscillations in any star except the Sun. We review recent efforts, with particular emphasis on the technique of monitoring equivalent widths of Balmer lines and the steps in data reduction.

1. Introduction

Measuring stellar oscillations is a beautiful physics experiment. A star is a gaseous sphere and will oscillate in one or more modes when suitably excited. The best targets are stars which oscillate in several modes simultaneously. Each mode has a slightly different frequency, reflecting spatial variations of the sound speed within the star, which in turn depends on density, temperature, gas motion and other properties of the stellar interior. The oscillation amplitudes are determined by the excitation and damping processes, which may involve opacity variations, turbulence from convection and magnetic fields. Studying the frequencies and amplitudes of oscillations in different types of stars promises to lead to significant advances in our understanding of stellar structure and evolution (for recent reviews see Brown & Gilliland 1994; Gautschy & Saio 1996).

The best-studied example of an oscillating star is the Sun. Observations of the 5-minute solar oscillations have led to enormous progress in our understanding of solar and stellar theory (Gough & Toomre 1991) and it is widely expected that measuring oscillation frequencies in other Sun-like stars will produce similar advances. Oscillations in the Sun are excited by convective turbulence near the surface, so 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. For our purposes, we define solar-like oscillations to be those which are excited stochastically by convection.

An advantage of 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). These specify the shape of the eigenfunction, which in turn determines the sensitivity of the oscillation frequency to the internal structure of the star. In the Sun, as opposed to classical variables (e.g., \( \delta \) Scuti stars, rapidly oscillating Ap stars and \( \beta \) Cephei stars), all modes in a broad frequency range are excited. 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 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. For example, in the Sun we find that modes with \( \ell = 2 \) are displaced by a few per cent of \( \Delta \nu \) from modes with \( \ell = 0 \). This displacement contains information on the internal properties of the Sun, such as helium content.

### 2. Detection methods

The disadvantage of studying solar-like oscillations is their tiny amplitudes. Three methods have been tried:

**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 \( \mu \)A at 5000 \( \AA \). 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.

**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 M67 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

\(^1\)In a star with no rotation or magnetic field, frequencies do not depend on \( m \).
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 (and even less for $\alpha$ Cen A).

3. Recent results

There have been many unsuccessful attempts over the past decade to measure oscillations in other solar-like stars. This continuing commitment reflects both the extreme difficulty of the observations and the tremendous importance that is attached to a successful result (e.g., Brown & Gilliland 1994). Indeed, it is fair to say that theorists have been waiting eagerly – and with some frustration – for the first oscillation data to appear. 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.

$\eta$ Boo  This star is the brightest G-type subgiant. We observed $\eta$ Boo over six nights with the 2.5-m Nordic Optical Telescope (Kjeldsen et al. 1995; Bedding & Kjeldsen 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, Bedding & Kjeldsen 1995, Guenther & Demarque 1996). Since then, the improved luminosity estimate from Hipparcos measurements has given even better agreement (Bedding et al. 1998).

However, a search for velocity oscillations in $\eta$ Boo by Brown et al. (1997) has failed to detect a signal, setting limits at a level below the value expected on the basis of the Kjeldsen et al. result. Brown et al. (private communication) have a more recent and larger set of observations which they are currently processing.

The Sun  Some support for the equivalent-width method was given by Keller et al. (1997), who detected the 5-minute oscillations in the Sun from spatially resolved measurements of H$\beta$ equivalent widths.

$\alpha$ Cen A  This is the brightest G-type main-sequence star. We obtained H$\alpha$ spectra over six nights in April 1995 using the 3.9-m AAT (UCLES) and the 3.6-m ESO (CASPEC). The observations were done in collaboration with S. R. Frandsen and T. H. Dall (Aarhus Univ.). 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). Oscillations were not detected, with an upper limit only slightly higher than the expected signal (Kjeldsen et al., in preparation).
**Procyon**  This star is the brightest F-type subgiant in the sky. 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. More recently, Brown et al. (poster paper at this conference) have obtained new measurements which appear to confirm the excess of power found previously (Brown et al. 1991).

We observed Procyon for several hours per night during the April 1995 run mentioned above. Preliminary analysis of Balmer line equivalent widths appeared to show excess power at the expected amplitude and frequency, but we no longer trust this result. More recently, we obtained Hα spectra over four weeks in February 1997 using the 74 inch telescope at Mt. Stromlo. Those observations were done in collaboration with I. K. Baldry and M. M. Taylor (Univ. Sydney) and analysis is continuing.

During an overlapping period in 1997, Pilachowski et al. (1997) also obtained observations of Procyon. The two projects were coordinated under the SONG program (Stellar Oscillations Network Group) and we intend to merge the data sets.

**Arcturus** and similar red giants are variable in both velocity (e.g., Hatzes & Cochran 1996 and references within; Merline 1995) and intensity (e.g., Edmonds & Gilliland 1996), but the presence of solar-like oscillations has not yet been established.

### 4. Details of the data processing

Here we describe most of the steps involved in processing a typical data set. Step 2 is specific to the equivalent-width method. The other steps could apply, at least in part, to other types of observations (Doppler shift or photometry).

1. **Preliminary reduction:**
   - (a) Correction for CCD bias by subtracting an average bias frame.
   - (b) Correction for CCD non-linearity. 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.
   - (c) Correction for pixel-to-pixel variations in CCD sensitivity by dividing by an average flat-field exposure.
   - (d) Subtract sky background, which can be quite substantial during twilight. The background is estimated from the regions at each end of the spectrograph slit, above and below the stellar spectrum.

[http://www.noao.edu/noao/song/](http://www.noao.edu/noao/song/)
(e) Extraction of one-dimensional spectra. During this step, the seeing in each frame (i.e., the FWHM along the spectrograph slit) and the position of the star (i.e., light centroid along the slit) should be recorded for possible use in decorrelation (see below).

2. Measuring equivalent widths:
Achieving high precision requires more than simply fitting a profile. The method described here was developed by HK after trying several different approaches. By analogy with Strømgren Hβ photometry, we calculate the flux in three artificial filters, one centred on the line (L) and the others on the continuum both redward (R) and blueward (B) of the line. For each spectrum, the following steps are followed:

(a) With the three filters placed at their nominal positions, calculate the three fluxes.
(b) Adjust the slope of the spectrum so that R and B are equal. This is done by multiplying the spectrum by a linear ramp.
(c) Re-calculate the filter fluxes and calculate the equivalent width: \( W = \frac{R - L}{R} \).
(d) Move the three filters to a different position and repeat the previous steps. Iterate to find the filter position which maximizes the value of \( W \). The other outputs are: position of line; height of continuum (from R); and slope of continuum.
(e) Repeat the previous steps for four different filter widths.

3. Initial time series processing:
We now have four times series \( (W_1, W_2, W_3, W_4) \), one for each filter width. Note that the quality of the data, as measured by the local scatter, usually varies considerably from hour to hour and night to night. The following procedure is generally applied to each night of data separately.

(a) Clip each of the four time series to remove outlying points (4-σ clipping, where \( σ \) is the local rms scatter).
(b) Calculate weights for each time series. This involves assigning a weight to each data point which is inversely proportional to the local rms scatter.
(c) Calculate \( σ_w \), the weighted rms scatter of each time series, using the weights just calculated. Use this to select the best filter width, i.e., the one which minimizes \( σ_w \). By using a weighted rms scatter, we do not give too much importance to the bad segments of the data. In practice, we do not choose one filter width, but rather a weighted combination. That is, we choose the powers \( a, b, c, d \) to minimize the weighted scatter on the time series \( W_1^a W_2^b W_3^c W_4^d \), where \( a + b + c + d = 1 \).

3The flux in a filter is simply the total counts in the stellar spectrum after it has been multiplied by the filter function.
This step and the subsequent ones rely on the fact that any oscillation signal will be much smaller than the rms scatter in the time series. Most of the scatter is due to noise and any method of reducing the scatter should be a good thing, although care must be taken not to destroy the signal or to introduce a spurious signal.

4. Decorrelation of time series:

As well as measuring the parameter which is expected to contain the oscillation signal ($W$), we also monitor extra parameters. The aim is to correct for instrumental and other non-stellar effects. For example, if we notice that $W$ is correlated with the seeing, we suspect some flaw in our reduction procedure, since hopefully the stellar oscillation will not know what is happening in the Earth’s atmosphere. By correlating measured equivalent widths 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. This process of decorrelation, which can be repeated for other parameters (total light level, position on detector, slope of continuum, etc.), is very powerful but can also be quite dangerous if not done with care (see Gilliland et al. 1991 for a fuller discussion).

Again, the process is done on data from one night at a time. Performing decorrelation over shorter intervals runs the risk of moving power around and creating or destroying signal – simulations are usual to check these effects.

5. Calculation of the power spectrum

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 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 spectrum, with each data point being allocated a statistical weight according to its quality. In practice, the power spectrum is calculated as a weighted least-squares fit of sinusoids (e.g., Frandsen et al. 1995). Note that an ordinary Fourier transform is equivalent to an unweighted least-squares fit.

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.
Space would be a wonderful place to do photometry. Although the COROT mission has been selected[^1] and others are being proposed, for now we will have to continue using ground-based facilities. It is important to remember that we are very close to producing noise levels equal to the solar oscillation signal, and that some stars are expected to oscillate with higher amplitudes than our own Sun.

Acknowledgments. This work was supported by the Australian Research Council, and by the Danish National Research Foundation through its establishment of the Theoretical Astrophysics Center.

DISCUSSION

GIBOR BASRI: When using Balmer lines one should be cognizant of the fact that the line is formed in both the photosphere (wing) and chromosphere (core) and is a NLTE photoionization-dominated line, and so is not sensitive to local temperature variations. Perhaps you are measuring continuum oscillations?

TIM BEDDING: Yes, the oscillations probably are mostly in the continuum. However, in the presence of scintillation it is impossible to measure absolute continuum levels, so there is no way to determine whether it is the line or the continuum that is oscillating. The only thing which can be measured with useful precision is the ratio of line to continuum – in other words, the equivalent width. To first order, this is insensitive to scintillation, which is why we choose to observe it. Note that spatially resolved observations of the Sun by Ronan et al. (1991) and also by Keller et al. (1997) imply that the Balmer lines are stable and the continuum is oscillating.

BERNARD FOING: What increase of sensitivity do you expect by applying the temperature method to cross-dispersed echelle spectra, with a proper weighted combination of equivalent widths of many lines? If a decisive advantage, this would allow to use multi-site spectroscopic networks such as MUSICOS, with a good prospect for solar-type asteroseismology.

TIM BEDDING: Yes, there could be a substantial gain in sensitivity. In fact, for the AAT observations of α Cen A we were able to observe three orders around both Hα and Hβ. In the order next to Hβ there was a strong iron line, which is expected to have a temperature sensitivity opposite to that of the Balmer lines. The ratio of the equivalent widths of iron to Hβ (using suitably weighted powers) proved to have extremely low scatter. Essentially, we used the width of the iron line as a decorrelation parameter and were able to greatly reduce instrumental effects. Whether the addition of more (weaker) lines would give useful improvements is still to be determined.

BOB NOYES: Following up on this, simulations carried out by Noyes et al. (1996) suggest that using the entire AFOE spectral range (~4000 Å to 6600 Å, R ~ 50,000) to estimate temperature change in the photosphere (by comparing changes in line depth at all wavelengths to predictions of Kurucz models) should

[^1]: http://www.astrsp-mrs.fr/www/corotpage.html
allow detection of individual oscillation modes in Procyen in \( \sim 4 \) nights of observation. Three attractive features of this approach are: (a) we can get the data simultaneously with radial velocity data, so it is ‘free’; (b) the temperature and velocity oscillations are (roughly) in quadrature, hence if we can detect both, we can use cross-power spectral analysis to strengthen detection; and (c) if we can detect both temperature and velocity oscillations, we can learn more physics from precise phase relations.

References

Bedding, T. R., Kjeldsen, H., 1995. In: Stobie, R. S., Whitelock, P. A. (eds.), IAU Colloquium 155: Astrophysical Applications of Stellar Pulsation, A.S.P. Conf. Ser., Vol. 83, Utah: Brigham Young, p. 109

Bedding, T. R., Kjeldsen, H., Reetz, J., Barbuy, B., 1996, MNRAS 280, 1155

Bedding, T. R., Kjeldsen, H., Christensen-Dalsgaard, J., 1998. In: Donahue, R. A., Bookbinder, J. A. (eds.), Poster Proc. 10th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun (in press)

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., Gilliland, R. L., Noyes, R. W., Ramsey, L. W., 1991, ApJ 368, 599

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

Gautschy, A., Saio, H., 1996, ARA&A 34, 551

Gilliland, R. L., Brown, T. M., Ducan, D. K., et al., 1991, AJ 101, 541

Gilliland, R. L., Brown, T. M., Kjeldsen, H., et al., 1993, AJ 106, 2441

Gough, D., Toomre, J., 1991, ARA&A 29, 627

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. In: Deubner, F. (ed.), Proc. IAU Symp. 185, New Eyes to See Inside the Sun and Stars, Dordrecht: Kluwer (in press)

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., 1995, PhD thesis, University of Arizona

Noyes, R. W., Korzennik, S. G., Krockenberger, M., et al., 1996, BAAS 188, 5906+

Pilachowski, C. A., Barden, S. C., Hill, F., et al., 1997. In: Deubner, F. (ed.), Proc. IAU Symp. 185, New Eyes to See Inside the Sun and Stars, Dordrecht: Kluwer (in press)

Ronan, R. S., Harvey, J. W., Duvall, Jr., T. L., 1991, ApJ 369, 549