The Art of Modelling Stars in the 21st Century
Proceedings IAU Symposium No. 252, 2008
L. Deng & K.L. Chan, eds

doi:10.1017/S1743921308022679

Helio- and asteroseismology

Jørgen Christensen-Dalsgaard[1]

[1]Danish AsteroSeismology Centre, and Department of Physics and Astronomy,
University of Aarhus, DK-8000 Aarhus C, Denmark
email: jcd@phys.au.dk

Abstract. Observations of solar and stellar oscillations are providing detailed information about stellar interiors. In the case of the Sun the set of observed frequencies is sufficiently detailed and accurate that the properties of the solar interior, such as sound speed, density and internal rotation, can be inferred with substantial precision and resolution. This allows detailed tests of solar modelling, with interesting and to some extent controversial results. Observations of solar-like oscillations in distant stars have started only recently, owing their very small amplitudes. However, developments in ground-based equipment and observations from space are revolutionizing this field, promising greatly increased insight into the structure and evolution of the stars.

Keywords. Sun: helioseismology – Sun: abundances – stars: oscillations – stars: evolution

1. Introduction

Most observations of stars provide only indirect information about the properties of stellar interiors. This is an obvious consequence of the fact, as noted by Eddington (1926), that the opaque nature of stellar material constitutes an ‘impenetrable barrier’, such that light from the star comes only from the stellar atmosphere. Thus our knowledge about the internal properties of stars are, to a large extent, based on theoretical modelling. However, the star can be penetrated by sound and gravity waves which therefore, if observed on the surface, carry information about the properties of stellar interiors. This forms the basis for helio- and asteroseismology. To study distant stars, and the more profound internal properties of the Sun, the most relevant observations are of frequencies of global modes; since these maintain phase coherence over several days, and in many cases much longer, the frequencies can be determined with very high accuracy. Also, they bear a relatively simply relationship to the properties of the stellar interior and hence provide rather direct constraints on those properties. In the solar case, in particular, the determination of a large number of accurate frequencies for a wide variety of modes allows inferences to be made of the solar internal structure and rotation with rather high resolution, in most of the Sun.

Here I provide a very brief overview of the properties of solar and stellar oscillations. More extensive presentations can be found, for example, in the book by Unno *et al.* (1989) and the review by Gough (1993). I then discuss some of the recent result on solar structure from helioseismology, including the consequences for solar modelling of the revised solar abundances. In addition, I provide an overview of the present and expected rapid development of asteroseismology, concentrating on the application to solar-like oscillations. Extensive reviews of helio- and asteroseismology were provided by Christensen-Dalsgaard (2002), Basu & Antia (2008), Cunha *et al.* (2007) and Aerts *et al.* (2008), while Christensen-Dalsgaard (2008a) discussed other aspects of asteroseismology.

2. Some properties of stellar oscillations

Stellar oscillations are characterized by the degree l and the azimuthal order m of the spherical harmonics which describe their dependence on position on the stellar surface; here l measures the total number of nodal lines on the surface and m, with $|m| \leqslant l$, the number of nodal lines in longitude. For each (l, m) there is a sequence of modes, characterized by the radial order n which, approximately, determines the number of nodes in the radial direction. Observations of distant stars, in light averaged over the stellar disk, are essentially sensitive only to modes of the lowest degree; for solar-like oscillations we only expect to detect modes of degrees up to 2–3. Solar observations with spatial resolution show oscillations with degrees exceeding 1000.

In the Sun and solar-like stars most observed modes are acoustic modes. An example of such a low-degree mode is illustrated in figure 1, showing that the eigenfunction extends to the core of the star. A simple analysis indicates that such acoustic modes are trapped between the near-surface region and an *inner turning point* at a distance r_{t} from the centre determined by

$$\frac{c(r_{\mathrm{t}})}{r_{\mathrm{t}}} = \frac{\omega}{\sqrt{l(l+1)}} , \tag{2.1}$$

where c is the adiabatic sound speed and ω is the angular frequency of the mode. The properties of this region largely determine the frequency of the mode. For $l = 0$ the modes extend essentially to the centre. Low-degree modes at the frequencies typically excited in solar-like oscillations have turning points in or near the core of the star and hence carry information about the structure of the core. With increasing degree r_{t} increases, and the high-degree modes observed in the Sun are trapped in the outer fraction of a per cent of the solar radius. This variation of penetration, and hence sensitivity, with degree allows the resolution of the solar internal properties through inverse analyses, given that acoustic modes over a broad range of degrees have been observed.

Low-degree acoustic modes satisfy an asymptotic relation that is very important for the interpretation of solar-like oscillations. This is normally written

$$\nu_{nl} \simeq \Delta\nu(n + l/2 + \alpha) , \tag{2.2}$$

where $\nu_{nl} = \omega_{nl}/(2\pi)$ is the cyclic frequency of a mode with radial order n and degree l, α is a quantity determined by the near-surface region of the star and

$$\Delta\nu = \left(2 \int_0^R \frac{\mathrm{d}r}{c} \right)^{-1} \tag{2.3}$$

is the inverse sound travel time across a stellar diameter. The resulting almost equally spaced pattern of frequencies is an important signature of solar-like oscillations (see figure 2 below), characterized by the *large frequency separation* $\Delta\nu_{nl} = \nu_{n-1\,l} - \nu_{nl}$. According to (2.2) the frequencies satisfy $\nu_{nl} \simeq \nu_{n-1\,l+2}$. Taking the asymptotic expansion to higher order lifts this degeneracy, yielding the *small frequency separation*

$$\delta\nu_{nl} = \nu_{nl} - \nu_{n-1\,l+2} \simeq -(4l+6)\frac{\Delta\nu}{4\pi^2\nu_{nl}} \int_0^R \frac{\mathrm{d}c}{\mathrm{d}r}\frac{\mathrm{d}r}{r} . \tag{2.4}$$

This is predominantly sensitive to the properties of the sound speed in the core of the star, reflecting the different depth of the lower turning point in the two nearly degenerate modes.

For spherically symmetric stars the frequencies are independent of m. This degeneracy is lifted by rotation (or other departures from spherical symmetry). For acoustic modes

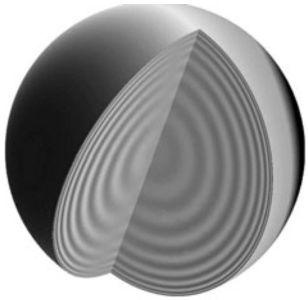

Figure 1. Properties of an eigenfunction in a solar model, for a mode of degree $l = 1$ and frequency $2700\,\mu$Hz. In the cut-out the greyscale indicates schematically the energy density of the mode.

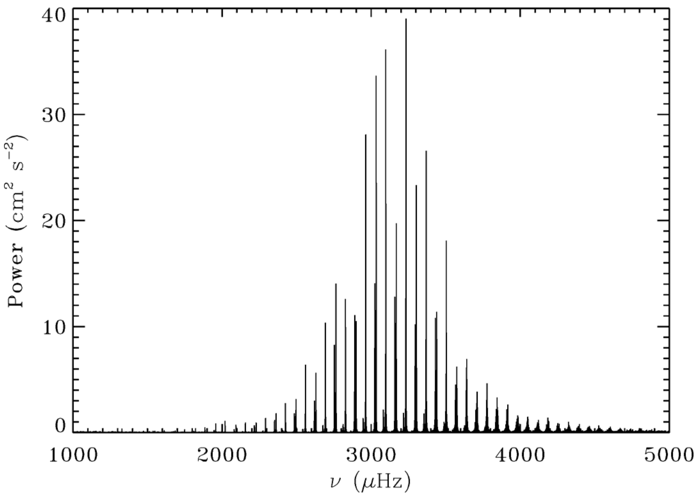

Figure 2. Power spectrum of integrated-disk velocity observations with the GOLF instrument on the SOHO spacecraft. The observations covered 805 days, starting 11 April 1996.

in a slowly rotating star the resulting frequencies are approximately given by

$$\omega_{nlm} \simeq \omega_{nl0} + m\langle\Omega\rangle \ , \tag{2.5}$$

where $\langle\Omega\rangle$ is a suitable average of the angular velocity Ω, approximately weighted by the energy density of the mode. In the solar case observations of a very large number of such rotational splittings have allowed detailed inferences of the internal rotation as a function of position (see Thompson *et al.* 2003, for a review).

Unlike the oscillations seen, for example, in Cepheids solar-like oscillations are characterized by being intrinsically damped and excited by the near-surface convection where motion at near-sonic speed provides an efficient source of acoustic noise. The resulting amplitudes are very small, typically well below $1\,\mathrm{m\,s^{-1}}$ in velocity and a few parts per million in intensity. Thus it is only through the development of very stable measurement techniques that the observation of these oscillations have become possible; in the case of stellar observations the push towards stable spectrographs to detect extra-solar planetary systems has been a major contribution to the recent successes in studying solar-like oscillations.

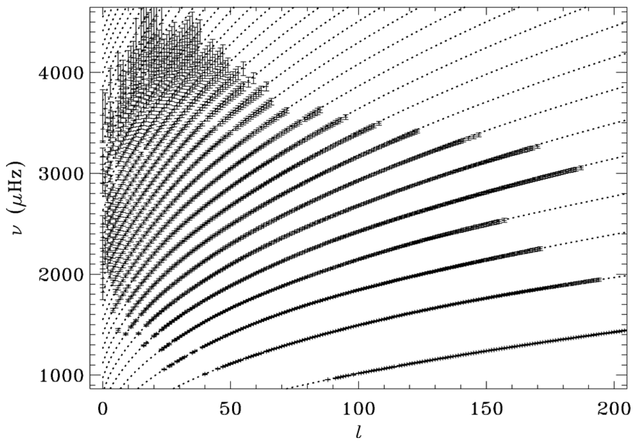

Figure 3. Inferred frequencies, as functions of degree, from 144 days of observations with the MDI instrument on the SOHO spacecraft; 1000σ error bars are indicated. The dotted curves show corresponding computed frequencies for Model S of Christensen-Dalsgaard *et al.* (1996).

3. Helioseismic results on solar structure

Very extensive data on solar oscillations have been obtained through several major projects, on the ground and on the SOHO spacecraft. Data on low-degree modes have been obtained by observing the Sun as a star, in particular in radial velocity with observations spanning more than three decades from the BiSON network (Chaplin *et al.* 2007a) and data from the GOLF instrument on SOHO (Gabriel *et al.* 1997). Spatially resolved velocity data have been obtained from the GONG network (Harvey *et al.* 1996) and the MDI instrument on SOHO (Scherrer *et al.* 1995). Figure 2 shows a power spectrum of observations from GOLF. This clearly reflects the asymptotic structure discussed in (2.2)–(2.4), with a dominant nearly uniform separation of the peaks and closely spaced pairs reflecting the small separation. Also, it is evident that the peaks are quite narrow, particularly at low frequency where the mode lifetime is at least several weeks.

The quality of the frequencies is illustrated in figure 3 which shows results from the MDI observations. Even though 1000σ error bars are shown, they are barely visible in large parts of the diagram, illustrating the extremely high accuracy of the frequencies. For a substantial fraction of the modes the relative frequency error is less than 5×10^{-6}.

A first step in the analysis of the observed frequencies is to compare with frequencies of solar models. As a typical, if slightly outdated, example I consider the so-called Model S of Christensen-Dalsgaard *et al.* (1996) which has seen widespread use in helioseismic analyses; further details of the computation were provided by Christensen-Dalsgaard (2008b). This uses detailed equation of state and opacity tables, and includes diffusion and settling of helium and heavy elements. The present surface ratio $Z_{\rm s}/X_{\rm s}$ between the abundances by mass of heavy elements and hydrogen was taken to be 0.0245 (Grevesse & Noels 1993). As is common in computations of solar models the model was adjusted to the correct surface radius, luminosity and composition by adjusting the initial composition and the mixing-length parameter describing the properties of near-surface convection. In figure 3 the dotted curves show the computed frequencies for this model. It is clear that the model reproduces the observed frequency structure and on this scale the differences between observations and model are barely discernible. In fact, close inspection shows a tendency for the computed frequencies to be slightly higher than the observations, particularly at high frequency. As discussed, for example, by Christensen-Dalsgaard *et al.* (1996) a detailed investigation of these frequency differences shows that they arise predominantly

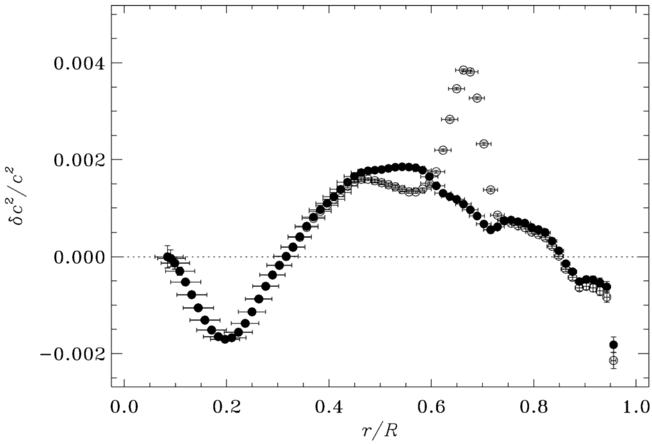

Figure 4. The open symbols show inferred relative differences in squared sound speed between the Sun and Model S, in the sense (Sun) – (model), based on inversion of the 'Best set' of observed frequencies described by Basu *et al.* (1997). One-sigma error bars are indicated but are barely visible. The horizontal bars provide an indication of the resolution of the inversion. The filled symbols show results for a corresponding model including weak turbulent diffusion beneath the convection zone. (From Christensen-Dalsgaard & Di Mauro 2007).

in the superficial layers of the Sun where the modelling of the energy transport and dynamical effects of convection, as well as of the excitation and damping of the oscillations, is inadequate. This must be kept in mind in the analysis of solar oscillations as well as solar-like oscillations in other stars. In the solar case, however, the properties of the effects can be used to suppress them in analyses to infer the structure of the solar interior (e.g., Dziembowski *et al.* 1990; Rabello-Soares *et al.* 1999).

Given the richness of the solar data much more detailed analyses than the simple comparison are possible, using procedures originally developed in geoseismology (see, for example Gough & Thompson 1991, for a review). Specific techniques for inferring solar structure were discussed in some detail by Rabello-Soares *et al.* (1999), while results of helioseismic inversion were discussed by Gough *et al.* (1996). As an example, in figure 4 the open symbols show the result of an analysis of Model S. It is evident that the differences, while highly significant, are comparatively small. A characteristic feature of the differences is the bump at $r \simeq 0.7R$, where the model sound speed is too low. This is in the region just beneath the convective envelope where a strong composition gradient is established by helium settling. An improved match to the observations can be obtained through partial mixing of this region, softening the composition gradient and hence increasing the hydrogen abundance and thus the sound speed (e.g., Brun *et al.* 1999; Elliott & Gough 1999). In figure 4 this is illustrated by the model shown by the filled symbols where mixing was introduced through the inclusion of a suitably parametrized turbulent diffusion (Christensen-Dalsgaard & Di Mauro 2007).

It is important to emphasize that these sound-speed differences, and the corresponding models, provide a well-defined estimate of the sound speed in the solar interior which depends little on the details of the model used as a reference (e.g., Basu *et al.* 2000). Thus in this sense the helioseismic determination is robust.

As discussed by Asplund (these proceedings) a careful analysis, including three-dimensional modelling of the solar atmosphere and effects of departures from local thermodynamic equilibrium, has resulted in a dramatic revision of the determination of the solar surface abundances of oxygen, nitrogen and carbon (for a review, see also Asplund 2005).

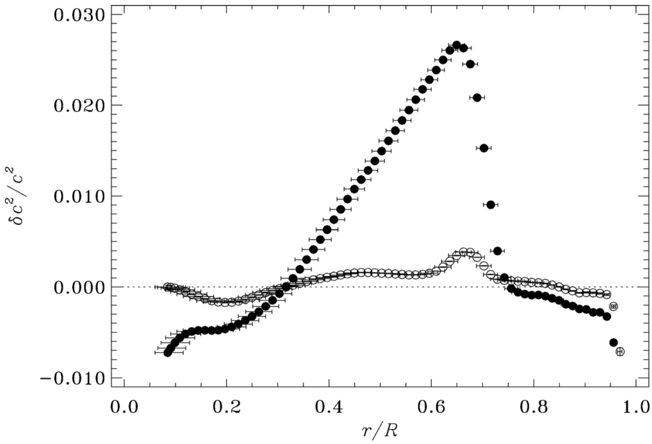

Figure 5. Inferred differences in squared sound speed between the Sun and two models, in the sense (Sun) – (model). The open symbols show results for Model S while the filled symbols show results for a corresponding model, but computed with the Asplund (2005) composition. For details, see the caption to figure 4. (From Christensen-Dalsgaard & Di Mauro 2007).

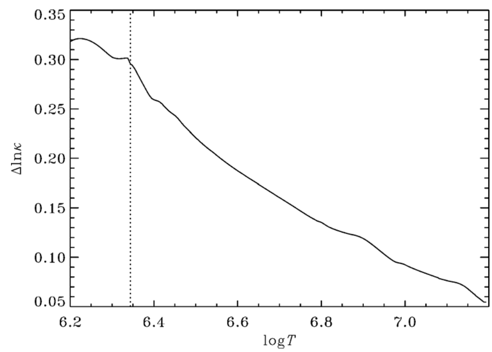

Figure 6. Intrinsic change in $\ln \kappa$, ln being natural logarithm, required to bring a model computed with the revised composition into agreement with Model S; $\Delta \ln \kappa$ has been assumed to depend only on temperature T. The vertical dotted line marks the base of the convective envelope.

As a result, $Z_{\rm s}/X_{\rm s}$ has been reduced from the value of 0.0245 assumed in Model S to 0.0165. This has dramatic consequences on the structure of the resulting models: the reduction in the heavy-element abundances leads to a comparable change in the opacity and hence a substantial change in the structure of the radiative interior. The result is a model deviating much more strongly from the helioseismic results. In figure 5 the open symbols again show results for Model S while the filled symbols are for a corresponding model but with the new composition. It is obvious that the revised abundances lead to a model in far worse agreement with the solar sound speed than Model S. Similar results were obtained, for example, by Turck-Chièze *et al.* (2004) and Bahcall *et al.* (2005). Also, Chaplin *et al.* (2007b) found that the small frequency separation (cf. (2.4)) in the model with the revised composition deviated strongly from the observed value, unlike Model S. An extensive review of such comparisons was given by Basu & Antia (2008).

There have been extensive efforts to modify the models in such a way as to accommodate the revised composition. As reviewed by Guzik (2006) these have met with little success. A simple, if possibly physically unrealistic, solution is to acknowledge that the dominant effect on the models of the change in composition arises from the opacity

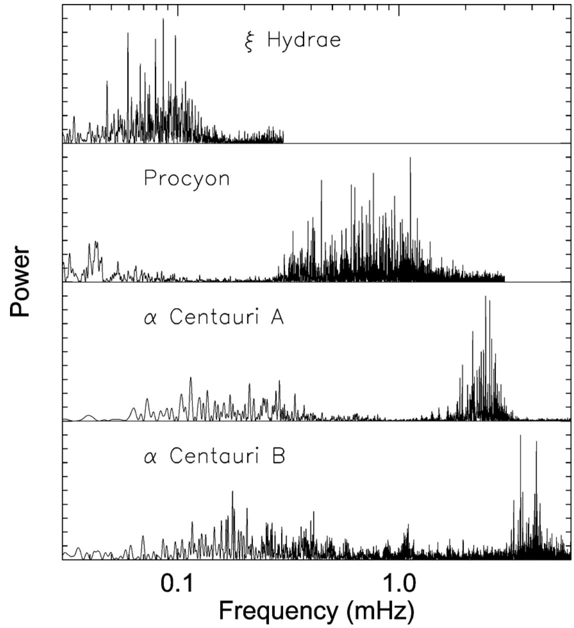

Figure 7. Power spectra as functions of cyclic frequency for four examples of solar-like oscillators. The maximum power corresponds to the following amplitudes: ξ Hydrae: $190\,\mathrm{cm\,s^{-1}}$; Procyon: $42\,\mathrm{cm\,s^{-1}}$; α Centauri A: $38\,\mathrm{cm\,s^{-1}}$; α Centauri B: $12\,\mathrm{cm\,s^{-1}}$.

change, and to compensate for this through a corresponding *intrinsic* change in the opacity (e.g., Montalbán *et al.* 2004; Bahcall *et al.* 2005). Christensen-Dalsgaard *et al.* (submitted) made a simple estimate of the correction to opacity κ, regarded as a function of temperature T, which would be needed to obtain a model structure similar to Model S, but using the new composition. The resulting change in $\ln\kappa$, ln being the natural logarithm, is shown in figure 6. This results in a model with only very small deviations from Model S, and hence providing a similarly good fit to the helioseismically inferred sound speed. However, it remains to be seen whether the required opacity change, of around 30% at the base of the convection zone and with this temperature dependence, is physically realistic.

It is evident that independent confirmation of the revision of the composition would be highly desirable. Thus it is very encouraging that Caffau & Ludwig (these proceedings) present an analysis in many way parallelling the one by Asplund and his collaborators, but on an independent basis (see also Caffau *et al.* 2008). Interestingly, the resulting oxygen abundance is intermediate between the old and new values. It seems likely that the solution to this serious problem for solar modelling may involve a number of factors, both in the composition determination and possibly in the calculation of interior opacities.

4. Asteroseismology of solar-like stars

Oscillations excited by near-surface convection, as observed in the Sun, are expected in all stars with substantial convective envelopes. Thus attempts to detect such oscillations started as soon as the global nature of the solar oscillations had been realized (e.g., Noyes *et al.* 1984; Gelly *et al.* 1986). However, the very low amplitudes clearly present a major challenge to such observations. Perhaps the first detection of the expected power envelope of solar-like oscillations in another star was made by Brown *et al.* (1991), observing

https://doi.org/10.1017/S1743921308022679 Published online by Cambridge University Press

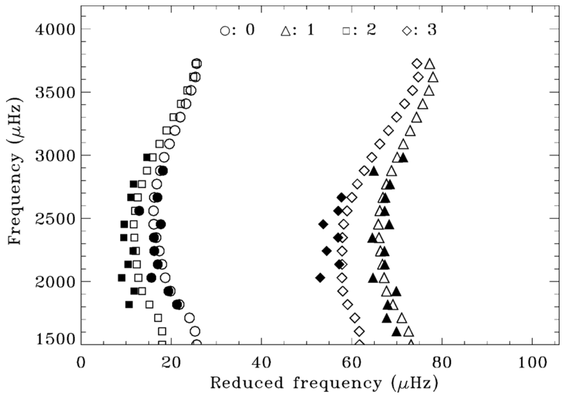

Figure 8. Echelle diagram for α Cen A. The abscissa is reduced frequency, corresponding to reducing $\nu_{nl} - \nu_0$ modulo the large frequency separation, taken to be $\Delta\nu = 106\,\mu\mathrm{Hz}$; here ν_0 is a suitable reference frequency. The ordinate is frequency. The filled symbols are from the observations of Bedding *et al.* (2004), while the open symbols correspond to a model fitted to the data by Teixeira *et al.* (in preparation). The symbol type indicates the degree, as shown.

Procyon, while the first determination of solar-like oscillation frequencies, in the subgiant η Bootis, was made by Kjeldsen *et al.* (1995). In the last decade the development of very stable spectrographs, and extensive observational campaigns, has revolutionized the study of solar-like oscillations, resulting in the detection of such oscillations in a substantial number of stars (see Aerts *et al.* 2008, for a recent brief overview). A few examples of the resulting spectra are shown in figure 7. It should also be noted that evidence for solar-like oscillations has been found in very non-solar-like stars, such as red giants (Frandsen *et al.* 2002; Kiss & Bedding 2003; De Ridder *et al.* 2006) and long-period semiregular variables (Christensen-Dalsgaard *et al.* 2001).

Solar-like oscillations observed in distant stars are typically low-degree high-order acoustic modes and hence satisfy the asymptotic relations (2.2) and (2.4). This frequency pattern is an important diagnostic for the nature of the oscillations and the determination of average values of the large and small frequency separations is a likely early result of the analysis of the observations. The large frequency separation $\Delta\nu$ reflects the global properties of the star and hence, as do the frequencies, essentially scale as the square root of the mean density, $\Delta\nu \propto (M/R^3)^{1/2}$, where M and R are the mass and radius of the star. On the other hand, the small separation $\delta\nu$ (cf. (2.4)) is sensitive to the sound speed, and hence the composition structure, of the stellar core and hence changes as a result of the fusion of hydrogen to helium during stellar evolution, providing a measure of stellar age (e.g., Christensen-Dalsgaard 1984; Ulrich 1986; Gough 1987).

In the analysis of solar-like data the near-surface effects on the frequencies, discussed above, must be taken into account. Given their strong frequency dependence they directly affect $\Delta\nu$ but they also have a significant effect on $\delta\nu$. It was demonstrated by Roxburgh & Vorontsov (2003) that this effect can be suppressed by considering instead frequency-separation ratios, such as

$$r_{02} \equiv \frac{\nu_{n+1\,0} - \nu_{n\,2}}{\nu_{n+1\,1} - \nu_{n\,1}} \tag{4.1}$$

(see also Otí Floranes *et al.* 2005). This similarly provides a measure of stellar age. As discussed by Houdek & Gough (these proceedings) a more careful analysis is required to take into account other features, such as acoustical 'glitches', in the structure of the star which may affect the age determination.

https://doi.org/10.1017/S1743921308022679 Published online by Cambridge University Press

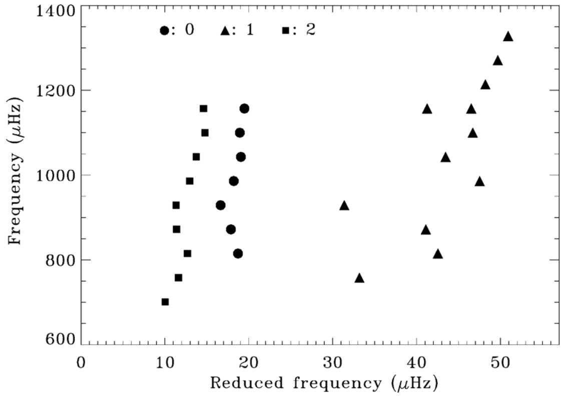

Figure 9. Echelle diagram, with $\Delta\nu = 57\,\mu$Hz, based on observed frequencies for β Hydri obtained by Bedding *et al.* (2007). See caption to figure 8.

An asteroseismically very interesting case is the well-studied binary system α Centauri. The masses of the A and B components have been determined precisely, as $1.105\,\mathrm{M}_\odot$ and $0.934\,\mathrm{M}_\odot$, respectively, where $\mathrm{M}_\odot$ is the mass of the Sun (Pourbaix *et al.* 2002); thus the components nicely span the Sun. Both components show solar-like oscillations whose frequencies and other properties have been determined in substantial detail, from several observations of α Cen A (Bouchy & Carrier 2001, 2002; Bedding *et al.* 2004; Bazot *et al.* 2007) and α Cen B (Carrier & Bourban 2003; Kjeldsen *et al.* 2005). By fitting the frequencies as well as other observations the properties of the system, including its age and initial composition, have been determined with substantial precision (e.g., Eggenberger *et al.* 2004; Miglio & Montalbán 2005). An interesting issue is obviously whether the resulting fitted models are consistent with the observed frequencies or whether the observations indicate further significant problems in the modelling of the star. Indications that the latter may be the case are provided in figure 8. Here the frequencies are illustrated in a so-called *echelle diagram*, essentially corresponding to dividing the spectrum in segments of length $\Delta\nu$ and stacking them. The observed frequencies are compared with frequencies for a model resulting from a fit to the stellar parameters, suitably corrected for the effects of the near-surface errors. Although the agreement is generally good, there is a suggestion of a systematic shift in the position of the modes with $l = 3$. Given the present data, with a substantial scatter reflecting the stochastic nature of the excitation, this difference is barely significant; further observations, ideally extending much longer in time than the 5 days in the data illustrated, are highly desirable.

Another interesting case is the subgiant β Hydri which approximately represents a later evolutionary state of the Sun. Solar-like oscillations were discovered in this star, as an early example of the clear detection of power resulting from solar-like oscillations, by Bedding *et al.* (2001), and detailed results were obtained from a two-site campaign by Bedding *et al.* (2007). Figure 9 shows an echelle diagram for the frequencies obtained from the latter observations. Unlike the corresponding diagram for α Cen A this shows some irregularity for the modes identified as having $l = 1$. This probably arises as a result of the relatively late evolutionary stage of this star: this causes high values of the buoyancy frequency in the deep interior of the star, giving rise to so-called *mixed modes*, behaving like internal gravity waves, in the frequency range of the observed modes. Such modes do not satisfy the asymptotic relations (2.2) and (2.4) and hence do not follow the expected behaviour in the echelle diagram. A similar behaviour has been found in the case of the subgiant η Boo (Christensen-Dalsgaard *et al.* 1995; Guenther & Demarque 1996).

https://doi.org/10.1017/S1743921308022679 Published online by Cambridge University Press

If this identification can be confirmed the observations potentially provide a sensitive probe of conditions in the stellar core.

5. Concluding remarks

Asteroseismology, of both solar-like and other types of stars, has seen a remarkable development over the past decade, and further major progress is expected in the coming years. Space asteroseismology was started by the WIRE (Buzasi 2004) and MOST (Walker *et al.* 2003) missions which have provided important results on a substantial number of stars, although lacking the sensitivity to provide detailed observations of solar-like oscillations in main-sequence stars. The French/European CoRoT mission (Baglin *et al.* 2006), launched in December 2006, has produced early very promising results on a number of stars, including a detailed study of the solar-like star HD 49933 (Appourchaux *et al.*, submitted); this mission will undoubtedly provide a breakthrough in space-based asteroseismology. Excellent data on a very large number of stars are expected from the NASA Kepler mission with scheduled launch in December 2009 (Borucki *et al.* 2003; Christensen-Dalsgaard *et al.* 2007). An almost overwhelming amount of asteroseismic data can result from the PLATO mission (Catala 2008), now under study for possible selection by ESA, which will observe of order 10^5 relatively bright stars.

These extremely promising photometric space missions do not eliminate the need for ground-based observations. To reach the highest precision in observations of solar-like oscillations, given the inevitable background from other processes in stellar atmospheres, Doppler-velocity observations are required (Harvey 1988). Nearly continuous observations of sufficient duration can only be obtained from dedicated facilities; on the other hand, for bright stars these can be of relatively modest size. A very interesting proposal is the SIAMOIS project to carry out such observations from Dome C in Antarctica (Mosser 2006). Observations from mid-latitudes require a dedicated network, similar to the helioseismic networks discussed above. One such project is the Stellar Observations Network Group (SONG) network (Grundahl *et al.* 2007, see also Grundahl *et al.*, these proceedings) which aims at setting up eight 1-meter class telescopes at suitably distributed sites.

Given these projects, and the further development of techniques for the analysis of the resulting data, the prospects seem excellent for using asteroseismology to address at least some of the many issues involved in modelling stars in the 21st century.

Acknowledgements

I am very grateful to the organizers for the invitation to attend this extremely interesting and enjoyable conference. H. Kjeldsen and P.-O. Quirion are thanked for help with figures.

References

Aerts, C., Christensen-Dalsgaard, J., Cunha, M., & Kurtz, D. W. 2008, *Solar Phys.*, in the press

Asplund, M. 2005, *Annu. Rev. Astron. Astrophys.* 43, 481

Baglin, A., Michel, E., Auvergne, M. and the CoRoT team 2006, in: K. Fletcher (ed.), *Proc. SOHO 18 / GONG 2006 / HELAS I Conf. Beyond the spherical Sun*, ESA SP-624 (Noordwijk, The Netherlands: ESA Publications Division)

Bahcall, J. N., Basu, S., Pinsonneault, M., & Serenelli, A. M. 2005, *Astrophys. J.* 618, 1049

Basu, S. & Antia, H. M. 2008, *Phys. Rep.* 457, 217

Basu, S., Chaplin, W. J., Christensen-Dalsgaard, J., Elsworth, Y., Isaak, G. R., New, R., Schou, J., Thompson, M. J., & Tomczyk, S. 1997, *Mon. Not. R. astr. Soc.* 292, 243

Basu, S., Pinsonneault, M. H., & Bahcall, J. N. 2000, *Astrophys. J.* 529, 1084

Bazot, M., Bouchy, F., Kjeldsen, H., Charpinet, S., Laymand, M., & Vauclair, S. 2007, *Astron. Astrophys.* 470, 295

Bedding, T. R., Butler, R. P., Kjeldsen, H., Baldry, I. K., O'Toole, S. J., Tinney, C. G., Marcey, G. W., Kienzle, F., & Carrier, F., 2001. *Astrophys. J.* 549, L105

Bedding, T. R., Kjeldsen, H., Arentoft, T., *et al.* 2007, *Astrophys. J.* 663, 1315

Bedding, T. R., Kjeldsen, H., Butler, R. P., McCarthy, C., Marcy, G. W., O'Toole, S. J., Tinney, C. G., & Wright, J. T. 2004, *Astrophys. J.* 614, 380

Borucki, W. J., Koch, D. G., Lissauer, J. J., *et al.* 2003, in: J. C. Blades & O. H. W. Siegmund (eds), *Future EUV/UV and Visible Space Astrophysics Missions and Instrumentation*, *Proceedings of the SPIE* Volume 4854, p. 129

Bouchy, F. & Carrier, F. 2001, *Astron. Astrophys.* 374, L5

Bouchy, F. & Carrier, F. 2002, *Astron. Astrophys.* 390, 205

Brown, T. M., Gilliland, R. L., Noyes, R. W., & Ramsey, L. W. 1991, *Astrophys. J.* 368, 599

Brun, A. S., Turck-Chièze, S., & Zahn, J. P. 1999, *Astrophys. J.* 525, 1032 (Erratum: *Astrophys. J.* 536, 1005).

Buzasi, D. L. 2004, in: F. Favata & S. Aigrain (eds), *Proc. 2nd Eddington workshop, "Stellar structure and habitable planet finding"*, ESA SP-538 (Noordwijk, The Netherlands: ESA Publications Division), p. 205

Caffau, E., Ludwig, H.-G., Steffen, M., Ayres, T. R., Bonifacio, P., Cayrel, R., Freytag, B., & Plez, B. 2008, *Astron. Astrophys.*, in the press [arXiv:0805.4398v1]

Carrier, F. & Bourban, G. 2003, *Astron. Astrophys.* 406, L23

Catala, C., and the PLATO consortium 2008, in: L. Gizon & M. Roth (eds), *Proc. HELAS II International Conference: Helioseismology, Asteroseismology and the MHD Connections, Göttingen, August 2007*, *J. Phys.: Conf. Ser.*, in the press

Chaplin, W. J., Elsworth, Y., Miller, B. A., & Verner, G. A. 2007a, *Astrophys. J.* 659, 1749

Chaplin, W. J., Serenelli, A. M., Basu, S., Elsworth, Y., New, R., & Verner, G. A. 2007b, *Astrophys. J.* 670, 872

Christensen-Dalsgaard, J. 1984, in: A. Mangeney, & F. Praderie (eds), *Space Research Prospects in Stellar Activity and Variability* (Paris Observatory Press), p. 11

Christensen-Dalsgaard, J. 2002, *Rev. Mod. Phys.* 74, 1073

Christensen-Dalsgaard, J. 2008a, *Mem. Soc. Astron. Ital.*, in the press.

Christensen-Dalsgaard, J. 2008b, *Astrophys. Space Sci.*, in the press [arXiv:0710.3114v1]

Christensen-Dalsgaard, J. & Di Mauro, M. P. 2007, in: C. W. Straka, Y. Lebreton & M. J. P. F. G. Monteiro (eds), *Stellar Evolution and Seismic Tools for Asteroseismology: Diffusive Processes in Stars and Seismic Analysis*, EAS Publ. Ser. 26 (Les Ulis, France: EDP Sciences), p. 3

Christensen-Dalsgaard, J., Bedding, T. R., & Kjeldsen, H. 1995, *Astrophys. J.* 443, L29

Christensen-Dalsgaard, J., Däppen, W., Ajukov, S. V., *et al.* 1996, *Science* 272, 1286

Christensen-Dalsgaard, J., Kjeldsen, H., & Mattei, J. A. 2001, *Astrophys. J.* 562, L141

Christensen-Dalsgaard, J., Arentoft, T., Brown, T. M., Gilliland, R. L., Kjeldsen, H., Borucki, W. J., & Koch, D. 2007, *Comm. in Asteroseismology* 150, 350

Cunha, M. S., Aerts, C., Christensen-Dalsgaard, J., *et al.* 2007, *Astron. Astrophys. Rev.* 14, 217

De Ridder, J., Barban, C., Carrier, F., Mazumdar, A., Eggenberger, P., Aerts, C., Deruyter, S., & Vanautgaerden, J. 2006, *Astron. Astrophys.* 448, 689

Dziembowski, W. A., Pamyatnykh, A. A., & Sienkiewicz, R. 1990, *Mon. Not. R. astr. Soc.* 244, 542

Eddington, A. S. 1926, *The internal constitution of the stars*, (Cambridge: Cambridge University Press)

Eggenberger, P., Charbonnel, C., Talon, S., Meynet, G., Maeder, A., Carrier, F., & Bourban, G. 2004, *Astron. Astrophys.* 417, 235

Elliott, J. R. & Gough, D. O. 1999, *Astrophys. J.* 516, 475

Frandsen, S., Carrier, F., Aerts, C., *et al.*, 2002, *Astron. Astrophys.* 394, L5

Gabriel, A. H., Charra, J., Grec, G., *et al.* 1997, *Solar Phys.* 175, 207

Gelly, B., Grec, G., & Fossat, E. 1986, *Astron. Astrophys.* 164, 383
Gough, D. O. 1987, *Nature* 326, 257
Gough, D. O. 1993, in: Zahn, J.-P. & Zinn-Justin, J. (eds), *Astrophysical fluid dynamics, Les Houches Session XLVII* (Amsterdam: Elsevier), p. 399
Gough, D. O. & Thompson, M. J. 1991, in: A. N. Cox, W. C. Livingston & M. Matthews (eds), *Solar interior and atmosphere*, Space Science Series (University of Arizona Press), p. 519
Gough, D. O., Kosovichev, A. G., Toomre, J., *et al.*, 1996, *Science* 272, 1296
Grevesse, N. & Noels, A. 1993, in: N. Prantzos, E. Vangioni-Flam & M. Cassé (eds), *Origin and evolution of the Elements* (Cambridge: Cambridge Univ. Press), p. 15
Grundahl, F., Kjeldsen, H., Christensen-Dalsgaard, J., Arentoft, T., & Frandsen, S. 2007, *Comm. in Asteroseismology* 150, 300
Guenther, D. B. & Demarque, P. 1996, *Astrophys. J.* 456, 798
Guzik, J. A. 2006, in: K. Fletcher (ed.), *Proc. SOHO 18 / GONG 2006 / HELAS I Conf. Beyond the spherical Sun*, ESA SP-624 (Noordwijk, The Netherlands: ESA Publications Division)
Harvey, J. W. 1988, in: J. Christensen-Dalsgaard & S. Frandsen (eds), *Proc. IAU Symposium No 123, Advances in helio- and asteroseismology* (Dordrecht: Reidel), p. 497
Harvey, J. W., Hill, F., Hubbard, R. P., *et al.* 1996, *Science* 272, 1284
Kiss, L. L. & Bedding, T. R. 2003, *Mon. Not. R. astr. Soc.* 343, L79
Kjeldsen, H., Bedding, T. R., Butler, R. P., Christensen-Dalsgaard, J., Kiss, L. L., McCarthy, C., Marcy, G. W., Tinney, C. G., & Wright, J. T. 2005, *Astrophys. J.* 635, 1281
Kjeldsen, H., Bedding, T. R., Viskum, M. & Frandsen, S. 1995, *Astron. J.* 109, 1313
Miglio, A. & Montalbán, J. 2005, *Astron. Astrophys.* 441, 615
Montalbán, J., Miglio, A., Noels, A., Grevesse, N., & Di Mauro, M. P. 2004, in: D. Danesy, D. (ed.), *Proc. SOHO 14 - GONG 2004: "Helio- and Asteroseismology: Towards a golden future"* ESA SP-559 (Noordwijk, The Netherlands: ESA Publication Division), p. 574
Mosser, B. 2006, in: K. Fletcher (ed.), *Proc. SOHO 18 / GONG 2006 / HELAS I Conf. Beyond the spherical Sun*, ESA SP-624 (Noordwijk, The Netherlands: ESA Publications Division)
Noyes, R. W., Baliunas, S. L., Belserene, E., Duncan, D. K., Horne, J., & Widrow, L. 1984, *Astrophys. J.* 285, L23
Otí Floranes, H., Christensen-Dalsgaard, J., & Thompson, M. J. 2005, *Mon. Not. R. astr. Soc.* 356, 671
Pourbaix, D., Nidever, D., McCarthy, C., *et al.* 2002, *Astron. Astrophys.* 386, 280
Rabello-Soares, M. C., Basu, S., & Christensen-Dalsgaard, J. 1999, *Mon. Not. R. astr. Soc.* 309, 35
Roxburgh, I. W. & Vorontsov, S. V. 2003, *Astron. Astrophys.* 411, 215
Scherrer, P. H., Bogart, R. S., Bush, R. I., Hoeksema, J. T., Kosovichev, A. G., Schou, J., Rosenberg, W., Springer, L., Tarbell, T. D., Title, A., Wolfson, C. J., Zayer, I., and the MDI engineering team 1995, *Solar Phys.* 162, 129
Thompson, M. J., Christensen-Dalsgaard, J., Miesch, M. S., & Toomre, J. 2003, *Annu. Rev. Astron. Astrophys.* 41, 599
Turck-Chièze, S., Couvidat, S., Piau, L., Ferguson, J., Lambert, P., Ballot, J., García, R. A., & Nghiem, P. 2004, *Phys. Rev. Lett.* 93, 211102
Ulrich, R. K. 1986, *Astrophys. J.* 306, L37
Unno, W., Osaki, Y., Ando, H., Saio, H., & Shibahashi, H. 1989, *Nonradial Oscillations of Stars, 2nd Edition* (University of Tokyo Press).
Walker, G., Matthews, J., Kuschnig, R., *et al.* 2003, *Publ. Astron. Soc. Pacific* 115, 1023

Discussion

Stepień: Could the problem of lower metal abundance reported for the solar atmosphere be solved by assuming more efficient diffusion of heavy elements, so that the chemical composition below the convection zone is close to adopted earlier?

Christensen-Dalsgaard: That is not likely. Since settling only changes Z by about 10% the change in settling rates required would probably be unphysical, and in fact attempts to solve the problem in this manner have in any case been unsuccessful.

Deng: You mentioned observations of solar like oscillation in Dome A, I have 2 questions: (1) What is your expectation from the current project at Dome A? (2) If a permanent base will be made in Dome A, is it a good replacement of SONG?

Christensen-Dalsgaard: (1) The data obtained so far are likely not sufficiently precise to allow study of solar like oscillations, but they should be great for large-amplitude 'classical' pulsators. They will be very interesting to analyze. (2) Apart from the difficulty of operating delicate equipment on Dome A, that site only covers the southern sky and continuous dark sky is restricted to ~ 4 months. However, it could be a great complement to SONG. I should also mention the French SIAMOIS proposal to put an asteroseismic instrument on Dome C.

Turck-Chieze: (1) In complement to the presentation I mention the existence of the successor of GOLF/SoHO (which discovers the first g modes) – the name is GOLF-NG. A prototype is now ready to observe in Tenerife. The modes at different heights in the atmosphere of the Sun – The objective will be to detect more g-modes first in Dome C. (2) Could you give us more on the whole program of SONG?

Christensen-Dalsgaard: In my talk I concentrated on studying solar-like oscillations with Kepler and SONG, but both projects will certainly be open to other types of pulsating stars. For SONG a careful selection of targets will be required, given the limited number that can be observed. For Kepler procedures for target selection are being established to be discussed at the June KASC meeting.

https://doi.org/10.1017/S1743921308022679 Published online by Cambridge University Press