Seismological challenges for stellar structure

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Helioseismology has provided very detailed information about the solar interior, and extensive data on a large number of stars, although at less detail, are promised by the ongoing and upcoming asteroseismic projects. In the solar case there remain serious challenges in understanding the inferred solar structure, particularly in the light of the revised determinations of the solar surface composition. Also, a secure understanding of the origins of solar rotation as inferred from helioseismology, both in the radiative interior and in the convection zone, is still missing. In the stellar case challenges are certain to appear as the data allow more detailed inferences of the properties of stellar cores. Large remaining uncertainties in modelling concerns the properties of convective cores and other processes that may cause mixing. As a result of developing asteroseismic signatures addressing these and other issues, we can look forward to a highly challenging, and hence exciting, era of stellar astrophysics.

1 Introduction

The present is a period of dramatic evolution of the study of stellar structure and evolution, in large part owing to the possibilities offered by the rapidly expanding data on stellar oscillations. The resulting frequencies are expected to provide stringent constraints on stellar properties, including the structure of stellar interiors, and hence challenge our understanding of stellar internal physics and stellar evolution. An obvious requirement for this is that observations are made of a sufficiently broad sample of stars, with sufficient sensitivity and of sufficient duration to secure the required frequency precision. Such observations are now resulting from the CoRoT and Kepler space missions (e.g., Baglin et al. 2006; Borucki et al. 2010), and further improvements are promised by dedicated ground-based facilities for radial-velocity observations (e.g., Grundahl et al. 2009). However, this is not all: we must also be able to analyse the basic observations to extract reliable frequencies, as well as to identify the observed modes. Also, stellar modelling must be sufficiently reliable and accurate that the assumptions about stellar internal physics are faithfully reflected in the frequencies computed from the resulting models. Although substantial progress is being made both in the data analysis and the modelling, it is probably fair to say that further efforts are required in these directions.

In this brief review I discuss some of the issues of observations and modelling, including those where seismic challenges are expected. The emphasis will largely, but not exclusively, be on stars showing solar-like oscillations. Further discussion of some of these issues was presented, for example, by Christensen-Dalsgaard & Houdek (2010), while an extensive overview of asteroseismology was provided by Aerts et al. (2010).

2 The observational situation

The past decade has seen extensive efforts on ground-based observations of solar-like oscillations (for a review, see Kjeldsen & Bedding 2004), culminating in a large coordinated set of observations of Procyon (Arentoft et al. 2008; Bedding et al. 2010). Large campaigns, with important asteroseismic potential, have also been carried out for other types of pulsating stars (e.g., Breger et al. 1995; Kawaler et al. 1995; Kurtz et al. 2002; Aerts et al. 2004; Handler et al. 2004).

A major breakthrough has been the development of space-based asteroseismology, starting with the serendipitous use of the WIRE satellite (e.g., Buzasi et al. 2005). The Canadian micro-satellite MOST (e.g., Walker et al. 2003) probably cannot quite reach the low level of noise required for the observation of solar-like oscillations in main-sequence stars (Matthews et al. 2004; Bedding et al. 2005), but has yielded high-quality data for a substantial number of other types of pulsating stars (e.g., Saio et al. 2006; Matthews 2007). The French-led CoRoT satellite, on the other hand, has resulted in a break-through in the study of solar-like oscillations (e.g., Michel et al. 2003; De Ridder et al. 2009), as well as for more classical pulsating stars (e.g., Degroote et al. 2009; Poretti et al. 2009). A major strength is the availability of nearly continuous observations extending over five months. Even more extensive observations are promised by the NASA Kepler mission, launched in March 2009 (Koch et al. 2010; Kjeldsen et al.)
Even the early analysis of the first month of Kepler data has demonstrated the outstanding quality of these data (Gilliland et al. 2010), and it is expected that, following a year-long survey phase, a substantial number of stars will be observed for the full, or a large fraction of, the remaining duration of at least 2 1/2 years of the mission.

Very extensive asteroseismic data of high quality, as an integral part of the study of extra-solar planetary systems, will be obtained by the ESA PLATO mission, to be launched around 2018 if it is finally selected for implementation (Catala 2009; Zima et al. 2010).

Since the intrinsic stellar ‘noise’ from granulation, activity, etc., is substantially higher relative to the oscillations in intensity than in velocity (Harvey 1988), the ultimate precision of asteroseismic investigations requires radial-velocity observations. These can be carried out from the ground, but the necessary sensitivity, continuity and duration require dedicated facilities, either in a network of telescopes at low or intermediate latitudes or from Antarctica. A network of telescopes is the goal of the SONG project (Grundahl et al. 2009, 2010a, b), while the SIAMOIS project (Mosser et al. 2008) seeks to establish a facility for radial-velocity asteroseismology at the Concordia station on Dome C in Antarctica.

Asteroseismic use of the observed frequencies requires that the observed oscillations be identified with modes of stellar models. In the case of solar-like oscillations, the determination of the spherical-harmonic degree of the modes can in many cases be accomplished through identification of the acoustic-mode asymptotic structure (see Eq. 1 below); however, the example of Procyon shows that this does not always provide definite results (Bedding et al. 2010; Dofani et al. 2010). In stars showing low-order oscillations excited through a heat-engine mechanism no similarly simple frequency structure is typically observed; here it is crucial to determine the degree (and possibly the azimuthal order) of the modes observationally, e.g., by supplementing space observations by ground-based campaigns (Uytterhoeven et al. 2010).

3 Asteroseismic diagnostics

The oscillation spectra of relatively unevolved stars, including the Sun, are essentially separated into high-frequency acoustic (or p) modes and low-frequency buoyancy-driven internal gravity (or g) modes. For solar-like oscillations the observations are of high-order p modes, approximately satisfying an asymptotic relation of the form

\[ \nu_{nl} = \Delta \nu (n + l/2 + \epsilon_0) - l(l + 1)D_0, \]

where \( n \) is the radial order, and \( l \) the spherical-harmonic degree, of the mode. This is characterized by a large frequency separation \( \Delta \nu = (2 \int_0^R \frac{dr}{c})^{-1} \) determined by the integral of the inverse sound speed \( c \) over the stellar radius; \( \Delta \nu \) essentially scales as \( \rho^{1/2} \), where \( \rho \propto M/R^3 \) is the mean density of the star, \( M \) and \( R \) being its mass and radius.

The term in \( D_0 \) gives rise to a small frequency separation \( \delta \nu_{nl} = \nu_{nl} - \nu_{n-1,l+2} \) that is sensitive to the variation of the sound speed in the core of the star, which, for main-sequence stars, in turn changes with the core composition and hence the age of the star. High-order g modes are also observed in several cases, such as \( \gamma \) Dor and slowly pulsating B stars, as well as in white dwarfs. For these the periods \( \Pi_{nl} \) are approximately uniformly spaced, satisfying

\[ \Pi_{nl} = \frac{\Pi_0}{l(l + 1)} (n + \epsilon_g), \]

where the basic period spacing \( \Pi_0 \) depends on the buoyancy frequency in the stellar interior.

For evolved stars the buoyancy frequency, and hence the g-mode frequencies, reach very high values in the stellar core, leading to an overlap between the p- and g-mode spectra. This causes avoided crossings between the frequencies of the two classes as the star evolves, of potentially very high diagnostic value (Deheuvels & Michel 2010). In red giants the extremely dense spectrum of g modes very substantially complicates the frequency computation and to some extent the interpretation of observed frequencies (e.g., Dziembowski et al. 2001; Christensen-Dalsgaard 2004; Dupret et al. 2009).

For spherically symmetric (and hence non-rotating) stars the frequencies are independent of the azimuthal order \( m \) of the modes. Rotation lifts this degeneracy; for slow rotation the resulting frequencies are of the form

\[ \nu_{nlm} \approx \nu_{n0l} + 2\pi m \beta_{nl}(\Omega), \]

where \( \beta_{nl} \) is a constant that in most cases is close to one, and \( \langle \Omega \rangle \) is an average, depending on the mode, of the stellar angular velocity \( \Omega \).

The initial analysis of observed frequencies of solar-like oscillations is typically based on the parameters characterizing the asymptotic behaviour (Eq. 1), in terms of the large and small frequency separations. These provide a measure of the mass and evolutionary state of the star (e.g., Christensen-Dalsgaard 1984, 1988; Ulrich 1986), although subject to other uncertainties in the parameters characterizing the star (Gough 1987). A full use of the observations evidently requires analysis of the individual frequencies, typically through a \( \chi^2 \) fit involving the frequencies and possibly other observed properties of the star, such as effective temperature, luminosity, etc. (e.g., Miglio & Montalbán 2005). An important issue is to ensure that the inferred solution provides the optimum fit to the observations, amongst the parameters characterizing the model, rather than a local minumum in \( \chi^2 \). This can either be achieved through the use of extensive multidimensional precomputed model grids (e.g., Guenther & Brown 2004) or through efficient fitting procedures involving recomputation of models, such as the genetic algorithm (Metcalfe et al. 2003). Once an approximation to the best solution has been found, it can be further refined through a local fit around this approximation; this can efficiently be carried out through singular-value decomposition of the relation between corrections to the model

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parameters and the misfit to the observations, which furthermore provides useful information about the properties of the solution (Brown et al. 1994; Creevey et al. 2007). Such fits evidently lead to the determination of the parameters characterizing a given set of model calculations but do not in themselves provide a challenge to stellar structure. A challenge may show up, however, as an inconsistency between the resulting models and other, independent, observations of the star; this underlines the importance of including other types of stellar observations in the analysis of asteroseismic data (Molenda-Zakowicz et al. 2010). A formal expression of the level of challenge to the model calculations is obtained if, as is often the case, the model frequencies and other properties differ significantly from the corresponding observed values (assuming, of course, that a reliable measure of the uncertainties in the latter is available). In this case more sophisticated types of analysis are required to determine the origin of the differences, very likely leading to true challenges to the theory of stellar evolution. Such analyses may concentrate on specific features in the star, such as the borders of convective regions (see Section 6 below). Alternatively, it may be possible in a limited way to carry out inverse analyses to infer the differences between the model and stellar structure (e.g., Basu et al. 2002; Roxburgh 2004).

4 Microphysical challenges

An important aspect of asteroseismology is the potential to use stars as ‘laboratories’ for the study of the properties of matter under extreme conditions. In the solar case, striking tests have been made of the treatment of the thermodynamical state of matter, certainly challenging existing formulations (e.g., Elliott & Kosovichev 1998; Basu et al. 1999). Interesting evidence has been found for crystallization in pulsating white dwarfs (e.g., Metcalfe et al. 2004) which may help elucidating these processes, of great importance to the cooling timescale of white dwarfs. On the other hand, thermodynamic effects on solar-like oscillations are probably too subtle to be detectable with present observations. Historically, asteroseismology has played an important role in the development of modern computations of stellar opacity, following Simon’s plea (Simon 1982). The current discrepancies between the helioseismically inferred solar structure and the structure of solar models (for a review, see Basu & Antia 2008), following the revised determinations of solar abundances (Asplund et al. 2009), certainly represent a serious challenge to stellar modelling; as noted by, for example, Bahcall et al. (2005) and Christensen-Dalsgaard et al. (2009) this may be an indication that further opacity revisions are required. Interestingly, discrepancies between the frequency range of modes observed in hot stars, and the range of unstable modes in models of these stars, may also indicate a need for opacity revisions (e.g., Jeffery & Saio 2007; Miglio et al. 2007; Dziembowski & Pamyatnykh 2008). A closely related issue concerns the apparent need for radiative levitation of iron-group elements to explain the excitation of oscillations in subdwarf B stars (Fontaine et al. 2003, 2006).

5 Near-surface problems

A major challenge to the modelling of cool stars and their oscillations is the treatment of near-surface convection. In addition to the resulting temperature structure, usually obtained by means of a simplified parameterized treatment such as the mixing-length formulation, the structure of the star is undoubtedly affected by ‘turbulent pressure’, i.e., the momentum transport resulting from convection; this is generally ignored in computations of stellar models. Also, the perturbations to the convective flux and turbulent pressure are at best included in a simplified, and rather uncertain, manner in the computation of the oscillation properties (see Houdek 2010, for further details).

It is striking that most of the difference between observed and computed frequencies of the Sun does indeed arise in the superficial layers of the model (Christensen-Dalsgaard et al. 1996), very likely caused by such errors in the treatment of convection and possibly in failures to model properly the solar atmosphere. These effects increase rapidly with increasing frequency and hence are less important in stars such as δ Scuti stars where generally modes of relatively low order are observed. However, they obviously affect the interpretation of observed solar-like oscillations. It should be noted that owing to their strong frequency dependence also the large frequency separation is substantially changed by the near-surface effects, and even the small frequency separation is significantly affected. It was noted, however, by Roxburgh & Vorontsov (2003) that appropriate ratios between the small and large separations are virtually insensitive to the outer layers of the star and hence provide good diagnostics of the properties of stellar cores (see also Oti Floranes et al. 2005).

It is obviously highly desirable to use the full information in the observed frequencies and hence to carry out analysis of the individual frequencies, rather than the separation ratios. This requires understanding of, or correction for, the near-surface effect. For stars that are not too different from the Sun it may be a reasonable ansatz to assume that the functional form of the effects, e.g. measuring the frequencies in units of the acoustical cut-off frequency, is similar to the effect in the Sun which can be determined through analysis of the frequencies of modes over a broad range of degree, as available in the solar case. Kjeldsen et al. (2008) assumed a power-law behaviour of the frequency correction, obtaining the exponent from the solar data, and demonstrated that the resulting correction yielded reasonable results for a few solar-like stars. Application to stars observed by Kepler, and to Procyon, has met with mixed success (e.g., Dogan et al. 2010). However, it is likely that observations with Kepler of a broad range of solar-like stars, in what has been termed ‘ensemble asteroseismology’, will yield impor-
tant insight into these effects and their dependence on stellar properties.

An important goal is clearly to achieve more realistic modelling of these effects. Detailed and relatively realistic radiation hydrodynamical models of the outer parts of the solar convection zone are in fact possible (for a review, see Nordlund et al. 2009); unlike most of the star the dynamical and thermal timescales are comparable in this region and hence these processes can be treated fully. Using average properties of the resulting models to represent the outer layers of full models does yield a substantial improvement in the agreement between computed and observed solar oscillation frequencies (e.g., Rosenthal et al. 1999; Li et al. 2002). This suggests that the effect of turbulent pressure in the equilibrium model may play a significant role. In principle it may become possible also to study the convective effects on stellar pulsations through such hydrodynamical simulations, although longer simulation runs than currently available will likely be required to isolate the oscillations of the simulation box and determine the frequencies and other properties with sufficient accuracy. One may hope from such simulations to obtain insight that can then inform simpler treatments that may realistically be included in extensive computations of stellar oscillations.

### 6 Borders of convective regions

Except in extreme stages of stellar evolution the bulk of stellar convection zones is very nearly adiabatically stratified and fully mixed. This represents no significant problems for stellar modelling. However, the borders of convective regions are seas of great uncertainty. It is evident that convective motion does not stop at the edges of convectively unstable regions, yet the extent and nature of the motion in the adjacent stable region are highly uncertain (e.g., Maeder 1975; Zahn 1991). Also, in regions of varying chemical composition additional uncertainty may arise in semi-convective regions that are formally stable to convection but unstable to growing oscillatory motion (see Kippenhahn & Weigert 1990 for an overview). Related problems occur in models with growing convective cores (Popielski & Dziembowski 2005, Montalbán et al. 2007). The uncertainty associated with these processes has an important effect on possible mixing, particularly outside convective cores, affecting the resulting composition profile and hence the subsequent evolution of the stars.

The rapid variations in the density gradient associated with the transition to convective stability and possibly composition variations at the edges of convective regions give rise to glitches in the acoustic and gravity-wave properties which affect stellar oscillations. Specifically, they introduce an oscillatory behaviour in the frequencies, as a function of frequency, arising from the varying phase of the oscillation at the location of the glitch, and causing departures from the simple asymptotic behaviour in Eqs (1) or (2). For acoustic modes Gough (1990) proposed considering the second difference $\Delta_2 \nu_{nl} = \nu_{n-1,l} - 2 \nu_{nl} + \nu_{n+1,l}$, which obviously vanishes if Eq. (1) is valid. Effects of acoustic glitches are clearly seen in observed solar oscillation frequencies and have been used to constrain conditions at the base of the solar convective envelope (e.g., Basu et al. 1994, Monteiro et al. 1994, Roxburgh & Vorontsov 1994).

A similar analysis is in principle possible based on just the low-degree modes observed in solar-like stars (e.g., Monteiro et al. 2000). It should also be noted that other features in the star may cause acoustic glitches; particularly important is the effect on the sound speed of the ionization of helium which gives rise to a signature that has been used to determine the solar helium abundance. A careful analysis of the effect of such acoustic glitches was reported by Houdek & Gough (2007).

In evolved main-sequence stars, particularly with convective cores, the variation in the core of the hydrogen abundance gives rise to a rapid variation of the sound speed with potentially observable effects on the oscillation frequencies. This is particularly dramatic in stars with growing convective cores, as typically found for masses below around $1.5 \, M_\odot$ where a discontinuity in composition, density and hence sound speed results if diffusion is neglected. This behaviour, including asteroseismic diagnostics, was analysed by Popielski & Dziembowski (2005) and Cunha & Metcalfe (2007); further analyses of the resulting diagnostics are presented by Cunha & Brandão (2010) and Brandão et al. (2011).

For g modes the relevant property are sharp variations in the buoyancy frequency, giving rise to departures from the uniform period spacing in Eq. (2). This has been used extensively to characterize the properties of pulsating white dwarfs (for a review, see Fontaine & Brassard 2008). The variation in the buoyancy frequency outside convective cores also has a substantial effect on g modes in main-sequence stars, particularly visible when, as in the case of slowly pulsating B stars, high-order modes are observed. Miglio et al. (2008) carried out a careful analysis of the resulting signatures in the period spacings. Remarkably, this behaviour was recently observed in CoRoT data on a B star (Degroote et al. 2010a,b), promising very valuable constraints on the mixing outside convective cores in such stars.

### 7 Effects of rotation

In the solar case the availability of a huge number of modes, spanning a large range in degree and azimuthal order, has allowed detailed inferences of the internal rotation of the Sun (see Thompson et al. 2003; Howe 2009 for reviews). The results represented serious challenges, so far not entirely resolved, to the existing models of the evolution of rotation in stellar interiors. In particular, the transport of angular momentum from an initially rapidly rotating solar interior, as is generally assumed, remains contentious. Inferences of internal rotation of other solar-like stars would be extremely
helpful in resolving this issue. Unfortunately, the rotational splittings (cf. Eq.\(^3\)) for the low-degree acoustic modes observed in most solar-like oscillations are predominantly sensitive to rotation in the outer parts of the star; however, if compared with a measure of the surface rotation, e.g., from variations caused by the rotation of surface features, \(\langle \Omega \rangle\) as inferred from the splitting provides an indication of the variation of rotation in the stellar interior. More detailed information about rotation in the deep interior will be available from observations of mixed modes, with partial g-mode character, in evolved stars (Lochard et al. 2004). Observations of low-order modes are also generally more sensitive to the internal rotation. In particular, Dupret et al. (2004) found that the core rotation of the \(\beta\) Cephei star HD 129929 substantially exceeded the rotation of the outer parts.

Modelling of rotating stars remains somewhat uncertain (for a detailed overview, see Maeder 2009). The dynamical effects of the centrifugal acceleration are relatively straightforward to include, at least if rotation is not too rapid. Far more uncertain is the modelling of the rotationally induced circulation and other mixing processes, and the related evolution of the internal rotation profile. The formulation of Zahn (1992), with further refinements, has seen extensive use in stellar modelling, with some successes, e.g., in reproducing observed surface abundances as the result of mixing processes. However, these models fail to reproduce the helioseismically inferred solar internal rotation. This clearly underlines the importance of further observational information about the evolution of rotation in other stars, as additional constraints for the modelling.

The rotational splitting in Eq.\(^3\) provides a clean diagnostic of the internal stellar rotation, but only for slow rotation. With faster rotation higher-order terms in \(\Omega\) must be included. Also, the rotational splitting becomes comparable with the frequency separation between different multiplets \((n, l)\), greatly complicating the interpretation of the observed spectra. As reviewed by Reese (2010) the perturbative description, in which Eq.\(^3\) is the lowest order, breaks down for sufficiently rapid rotation, leading to more complex types of oscillation; in practice this happens at rotation rates such as to be relevant for many asteroseismically interesting stars. Much work is required on the analysis and asteroseismic interpretation of observed oscillations in such cases.

8 How do we proceed?

It is traditional for a review on asteroseismology to end by asking for more and better data. It is certainly the case that our wishes are being granted; the present situation, with CoRoT and Kepler, has been described as ‘drinking from a firehose’, and the situation will get even more extreme if PLATO is selected for implementation. However, in particular the availability of very long timeseries at the highest possible quality, and for a broad range of stellar types, will be crucial to investigate the physical processes in stellar interiors, moving beyond the overall properties of stars. This is also the strong argument for extended observations in radial velocity from the ground, as will be provided by the SONG network.

Given the huge effort that is going into the observations, major efforts are also called for to optimize the analysis of the resulting data. Even in the case of helioseismology it is far from clear that the data are utilized optimally (Jefferies & Vorontsov 2004). In asteroseismology challenges are the lower signal-to-noise ratio than for the best solar data, as well as the potentially more complex oscillation spectra than for the Sun, in many cases; also, as in the solar case, the stochastic nature of the excitation must be taken into account. For the further interpretation of the data it is important to obtain statistically meaningful estimates of the oscillation properties. Such estimates can in principle be obtained from global fits to the power spectra, constrained by Bayesian priors (e.g., Appourchaux et al. 2008; Benomar et al. 2009; Gruberbauer et al. 2009). To be fully reliable, such analyses depend on a thorough understanding of the statistical properties of the oscillations, stellar background and observing procedure.

In conclusion, how serious are the current seismological challenges to stellar structure? There are certainly examples of observations that are not yet understood; however, with the exception of helioseismology these are perhaps not quite yet at a level where our fundamental understanding of stellar structure and evolution has been challenged. To reach this level must be a serious challenge for the whole asteroseismic community, from observations, through data analysis and interpretation, to a reliable confrontation of the results with the stellar models. We shall surely meet this challenge!

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