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Asteroseismic constraints on stellar interiors

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Abstract. Observations of stellar oscillations result in very precise determinations of the frequencies of normal modes of the stars, thus providing stringent constraints on the properties of stellar interiors. Additional constraints result from the presence of given types of oscillations, or from the observed amplitudes and lifetimes of the modes. Analysis of such data provides the basis for asteroseismology which is taking the observational study of stellar interiors to a new level of detail and accuracy. The very extensive data available for the Sun have allowed detailed inferences to be made of solar internal structure and rotation, clearly indicating that much remains to be done before we understand even this comparatively simple star. Substantial data for distant stars are already being obtained from ground-based studies, and a dramatic improvement in the available data is expected from ongoing and upcoming space projects, as well as from dedicated and optimized ground-based facilities.

Key words. Stars: structure – Stars: pulsations – Stars: evolution – Stars: internal physics

1. Introduction

Our understanding of stellar evolution obviously depends on comparing our theoretical models with relevant observations. These observations (with the exception of neutrinos) refer to the outer, optically thin layers of the star and hence additional modelling is required to relate the observations to the physical nature of stellar interiors. Even so, it is evident that, for example, the Hertzsprung-Russell diagram provides an excellent overview of the dependence of stellar properties on mass and age. According to Marcella Marconi, Vittorio Castellani noted that stellar pulsations provide an additional dimension to the HR diagram. Indeed, for single-mode large-amplitude pulsating stars, which can often be assumed to pulsate in the fundamental radial mode, the oscillation frequency provides a measure of the mean density of the star. However, over the last few decades stars, including the Sun, have been found which exhibit large numbers of modes and hence provide a multi-dimensional extension of the HR diagram. This forms the basis of asteroseismology, yielding an entirely new level of detail in the study of stellar properties.

The goal of asteroseismology is to obtain information about stellar properties in the most general way. Even relatively limited observations can constrain the global properties of a star. A classical example is the use of periods of double-mode Cepheids to determine the stellar mass (Petersen 1973), which led to serious discrepancies with the masses determined from evolution calculations (e.g., Cox 1980). Following a plea by Simon (1982) for recomputation of opacities and further analyses by Andreasen & Petersen (1988) it was found that the previously used opacities were in fact seriously underestimated in a critical temperature region (Rogers & Iglesias 1992; Seaton et al. 1994). Improving the opacity calculation largely removed the discrepancy between the evolutionary masses and those obtained from the period ratios (Moskalik et al. 1992; Kanbur & Simon 1994).

However, our ambitions go far beyond that, with the goal to study details of the physics of stellar interiors. This goal has certainly been achieved in the case of the Sun (Christensen-Dalsgaard 2002). For distant stars the field is as yet in its infancy; interesting results have been obtained and new observing projects offer a great deal of promise.

The most obvious diagnostic from stellar oscillations are the oscillation frequencies, which can be determined with extreme accuracy, in some cases rivalling the accuracy of the best man-made clocks. In the frequent cases where many modes are observed this provides an extremely rich source of information. Rotation splits the multiplet frequencies, providing a potential for investigating the internal stellar rotation. I do not discuss this further here but note that in the solar case we have obtained detailed inferences of the internal rotation of the Sun (see, for example, Thompson et al. 2003, for a review). However, also the mere presence of oscillations in a given star, and the amplitudes of the modes, provide information about the internal properties of the star. Examples of this are presented in the following. Finally, the phase and amplitude relations between different types of observations of a given mode may provide information about the properties of the stellar atmosphere (e.g., Deubner et al. 1996; Oliviero et al. 1999).

It is evident that justice cannot be done here to the detailed aspects of stellar oscillations and asteroseismic inferences. For this, reference may be made to a number of reviews (e.g., Gough 1993; Christensen-Dalsgaard 2002; Cunha et al. 2007; Aerts et al. 2008).

2. Properties of oscillations

Oscillations of approximately spherically symmetric stars can be described by spherical harmonics, each mode being characterized by a spherical harmonic degree l and azimuthal order m; the latter only affects the frequencies as a result of departures from spherical symmetry, such as rotation, and is not further considered here. The degree provides a measure of the total number of nodal lines on the stellar surface; $l = 0$ corresponds to spherically symmetric, or *radial*, oscillations. For each (l, m) the star has a set of modes characterized by their radial order n which approximately measures the number of nodes in the radial direction.[1] The physical nature of the modes depends strongly on their frequency. High-frequency modes are typically approximately standing acoustic waves, with pressure being the restoring force, and are known as p modes. Low-frequency modes have the nature of internal gravity waves and are known as g modes.

Whether or not a mode is observed in a star obviously depends on whether it is excited. Two very different overall excitation mechanisms are possible: intrinsic instability, or overstability, of a mode, and stochastic excitation of an intrinsically stable mode.

In the case of overstable modes, there is a net conversion of thermal energy into mechanical energy, the star as a whole operating as a heat engine. This requires that heat is added in the compression phase of the oscillation and removed at the expansion phase. The phase relation between compression and heating typically varies through the star and in most cases is such as to result in damping of the mode. However, in regions of rapid opacity variation, resulting from partial ionization of a dominant element or other favourable circumstances, heat can be held back at compression and released at expansion, contributing to the excitation of the mode; this mechanism was first proposed by Eddington (1926) and is therefore known as *Eddington's valve*. To result in overall instability the critical region has to be placed at the appropriate depth

[1] This statement hides a considerable amount of complexity; see Takata (2006) for an overview and a recent major advance in the characterization of the radial order.

below the stellar surface, roughly determined such that the thermal energy in the overlying part of the star matches the energy radiated by the star in a pulsation period (Cox 1974).[2] This condition, applied to different opacity features, determines the location of the thermally excited, or *heat-engine*, pulsating stars in the Hertzsprung-Russell diagram, schematically illustrated in Fig. 1. The most important opacity features are associated with the second helium ionization zone, responsible for the stars in the Cepheid instability strip, and a feature resulting from iron-group elements, causing the pulsations of hotter stars such as β Ceph stars and slowly pulsating B stars. It should be noted that for heat-engine pulsators theory predicts instability and hence exponential growth of the mode amplitudes. The limiting amplitude must be determined by non-linear mechanisms, so far poorly understood (e.g., Nowakowski 2005).

Intrinsically stable modes can be excited by external forcing. This appears to be the case for solar oscillations, the forcing being supplied by the near-surface convection approaching sonic speed and hence efficiently emitting acoustic waves (Lighthill 1952; Stein 1967). Similar oscillations are therefore expected to be present in all stars with reasonably vigorous surface convection zones (see Fig. 1); as discussed in Sect. 4 below that does indeed seem to be the case. For stochastically excited modes the width of the peaks in the power spectra reflects the damping rates of the modes and hence provides information about the processes dominating the damping (Christensen-Dalsgaard et al. 1989). Also, the amplitude results from balance between the forcing and the damping, potentially providing a diagnostics of the convection. So far, however, predictions of damping rates and amplitudes of stochastically excited modes (Christensen-Dalsgaard & Frandsen 1983; Houdek et al. 1999) are somewhat discordant with the observed amplitudes (e.g., Houdek 2006).

[2] Thus a given opacity feature, which typically occurs at a well-defined temperature, excites shorter-period modes with increasing effective temperature and hence decreasing depth of the feature beneath the surface.

3. The Sun

Helioseismology has provided stringent constraints on stellar modelling and has emphasized processes that have previously tended to be neglected. An early success was the demonstration that models proposed to reduce the solar neutrino flux were inconsistent with the low-degree helioseismic data (Elsworth et al. 1990; Christensen-Dalsgaard 1991), strongly indicating that the origin of the discrepancy between the observed and predicted solar neutrino flux must be sought in the properties of the neutrino. This was confirmed by later results of helioseismic inversion (e.g., Bahcall et al. 1997; Turck-Chièze et al. 2001). With the direct detection of neutrino flavour conversion (Ahmed et al. 2004) the total observed neutrino flux was in fact found to be consistent with the model predictions.

Early helioseismic inversions (Christensen-Dalsgaard et al. 1985) supported the need for an opacity increase, also inferred from observations of double-mode Cepheids (Simon 1982). Comparisons between observed and computed frequencies also demonstrated the importance of a detailed treatment of the equation of state (Christensen-Dalsgaard et al. 1988). Furthermore, it was found that the inclusion of diffusion and gravitational settling, often ignored in earlier solar modelling, substantially improved the agreement between the model and the inferred solar structure (Christensen-Dalsgaard et al. 1993). As a curiosity, a striking illustration of the sensitivity of helioseismic inferences was provided by the demonstration that early extensive computations of equation-of-state tables had erroneously left out the relativistic effects on electrons, leading to a significant difference between the computed and helioseismically inferred value of the adiabatic compressibility (Elliott & Kosovichev 1998). The advances in solar modelling inspired by helioseismology led to models that were remarkably close to the helioseismic inferences, with no explicit adjustment of parameters to achieve this match (Christensen-Dalsgaard et al. 1996;

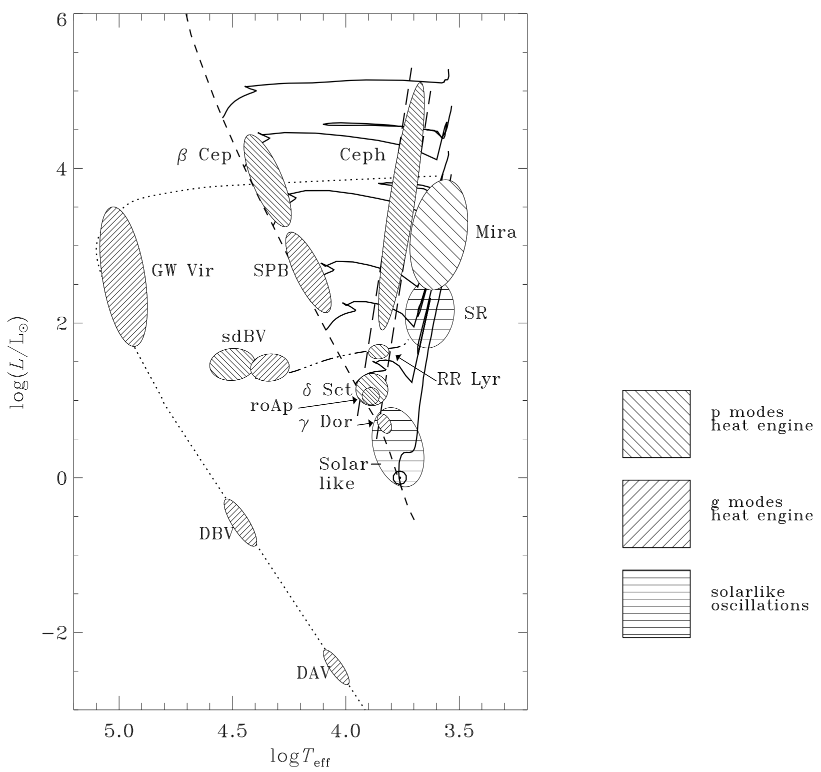

Fig. 1. Schematic illustration of the location of pulsating stars in the HR diagram, showing also the zero-age main sequence (dashed curve) selected evolution tracks (solid curves) and the white-dwarf cooling track (dotted curve). The δ Scuti (δ Sct) stars, the RR Lyr(ae) stars and the Ceph(eids) occupy the Cepheid instability strip, where pulsations are caused by the heat-engine mechanism operating in the second helium ionization zone. Stars on the cool side of this have substantial outer convection zones which cause stochastic excitation of solar-like oscillations. The β Cep(hei) and Slowly Pulsating B (SPB) stars are excited by the heat-engine mechanism operating through iron-group opacities. As indicated to the right of the panel, the hatching marks the type of modes and excitation mechanism. See Cunha et al. (2007) for further details.

Gough et al. 1996). The maximum relative difference between the inferred and computed sound speed was as low as 0.2 %, although still much larger than the estimated errors, typically less than 0.01 %, in the differences.

This satisfactory situation has been severely affected by a recent redetermination of the solar surface abundances, substantially decreasing the inferred abundances of, in particular, oxygen (for a review, see Asplund 2005). The resulting decrease in the opacity in the radiative interior caused a marked increase in the discrepancy between the models and the helioseismically inferred structure, with sound-speed differences as high as 1 % (Turck-Chièze et al. 2004; Bahcall et al. 2005). Although still small by astrophysical standards these discrepancies clearly indicate that some aspects of the model calculations have to be modified, if the revised abundance determinations are accepted. However, despite intensive efforts, no satisfactory solution has been found (Guzik 2006). I note, however, that agreement between the Sun and the model could be restored by an intrinsic opacity increase matching the decrease caused by the change in the abundances, of a magnitude of more than 25 % at temperatures corresponding to the region just below the convection zone. Such a change, which is regarded as unlikely by the groups computing the opacities, would clearly need a physical justification.

4. Solar-like oscillations

Solar-like oscillations are excited stochastically by near-surface convection. Their detection is made difficult by their very small amplitudes: for main-sequence stars the expected amplitude is a few parts per million in intensity and less than $1\,\mathrm{m\,s^{-1}}$ in radial velocity. Thus it is only within the last 10 – 15 years that definite detection and studies of such modes have been possible (for reviews, see Kjeldsen & Bedding 2004; Bedding & Kjeldsen 2007). As indicated in Fig. 1, there are now definite detections for stars along the main sequence, between spectral types F5 and K0, as well as for red giants in the lower part of the red-giant branch and substantial evidence that semi-regular oscillations of more luminous red giants have the same physical cause.

The modes at low degree observed in the Sun are high-order acoustic modes; their cyclic frequencies ν_{nl} approximately satisfy the asymptotic relation (Vandakurov 1967; Tassoul 1980; Gough 1993)

$$\nu_{nl} \simeq \Delta\nu \left(n + \frac{l}{2} + \alpha \right) + \epsilon_{nl} \,, \tag{1}$$

where

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

is the inverse sound travel time across a stellar diameter, r being the distance to the centre of the star, R its surface radius and c the adiabatic sound speed. Also, α is a function of frequency primarily determined by conditions near the surface and ϵ_{nl} is a small correction term. To leading order the frequencies are uniformly spaced, with $\Delta\nu_{nl} \equiv \nu_{nl} - \nu_{n-1\,l} \simeq \Delta\nu$, and $\nu_{nl} \simeq \nu_{n-1\,l+2}$. The term in ϵ_{nl} breaks this degeneracy, introducing *the small frequency separation* $\delta\nu_{nl} = \nu_{nl} - \nu_{n-1\,l+2}$. As are the frequencies, *the large frequency separation* $\Delta\nu$ is approximately proportional to the square root of the mean density of the star, $\Delta\nu \propto M^{1/2}R^{-3/2}$, M being the stellar mass; the small frequency separation depends on the sound-speed gradient in the core of the star, which in turn is sensitive to the composition structure and hence the evolutionary state of the star. Accordingly, observational determination of the large and small separations provides a measure of the mass and evolutionary state of stars on the main sequence (Christensen-Dalsgaard 1984, 1988; Ulrich 1986), assuming that other parameters of the star, such as its initial composition, are known (Gough 1987). More generally, owing to the high accuracy to which oscillation frequencies and frequency separations can be determined, they serve as powerful constraints on overall stellar properties (Brown et al. 1994; Creevey et al. 2007).

The contribution α in Eq. (1) is sensitive to the properties of the superficial layers of the star and their effect on the oscillation frequencies. The modelling of these layers, which includes effects of convection, non-adiabaticity and radiation in the stellar atmosphere, is quite uncertain and introduces a corresponding uncertainty in the computed frequencies and in the inferences obtained from comparing observed frequencies with models, particularly at high frequencies (e.g., Christensen-Dalsgaard & Thompson 1997). It was demonstrated by Roxburgh & Vorontsov (2003) that a measure of the properties of the core unaffected by these uncertainties could be obtained from a suitable ratio between the small and large frequency separation (see also Otí Floranes et al. 2005). However, these near-surface effects remain a significant concern in the analysis of solar-like oscillations.

Although strong evidence was found for the presence of solar-like oscillations in Procyon by Brown et al. (1991), the first tentative detection of the frequencies of such oscillations was made by Kjeldsen et al. (1995) in η Boo, later confirmed by other observations (Kjeldsen et al. 2003; Carrier et al. 2005). In the last few years the availability of very stable spectrographs has enabled observations of solar-like oscillations in a number of stars, including data of high quality for the components of the binary system α Cen (e.g., Bouchy & Carrier 2001, 2002; Bedding et al. 2004; Kjeldsen et al. 2005; Fletcher et al. 2006; Bazot et al. 2007). Combining the oscillation frequencies with determinations of stellar parameters from photometry, spectroscopy, parallaxes and orbital motion has led to stringent constraints on the properties of the system (Eggenberger et al. 2004; Miglio & Montalbán 2005), and possibly beginning evidence for features in the oscillation spectrum of α Cen A which are not consistent with standard modelling.

Present data are limited by the availability of telescope time at the required ground-based telescopes, typically heavily oversubscribed, with stable spectrographs. Also, to minimize gaps in the data observations from two or more suitably distributed telescopes must be combined, further adding to the complexity of the observations; a recent major effort was the coordinated observations of Procyon with 10 telescopes (Hekker et al. 2007). The observational situation is going to improve dramatically over the next few years with data from the CoRoT satellite (Baglin et al. 2006; Michel et al. 2007), launched in December 2006, and the Kepler mission (Christensen-Dalsgaard et al. 2007) with expected launch in early 2009. These missions will provide nearly continuous observations over very extended periods of time, hence greatly increasing the frequency precision. Further improvements in data on a limited number of selected stars would result from planned dedicated facilities for ground-based Doppler-velocity observations. The SIAMOIS project (Mosser et al. 2007) aims at setting up a telescope on Dome C in Antarctica, permitting observations with high duty cycle though the 3 months of the full polar night at that location, while the goal of the SONG project (Grundahl et al. 2007) is to establish a network of 8 modest-size telescopes optimized for Doppler-velocity observations, and with a suitable geographical distribution to attain a high combined duty cycle.

The data expected from these projects will allow detailed investigations of stellar interiors. An interesting example is the study of 'acoustical glitches', features in the star varying on a scale short compared with the local wavelength of the modes. Such features induce an oscillatory signature in the frequencies which contains information about the depth and other properties of the feature. Examples are the relatively rapid variation in the adiabatic compressibility Γ_1, and hence in the sound speed, associated with the second helium ionization zone and the rapid change in the sound-speed gradient at the base of the convective envelope. Analysis of these signals may provided estimates of the helium content and depth of the convective envelope (see Houdek & Gough 2007, for a detailed analysis), provided that sufficiently precise frequencies are available (Ballot et al. 2004; Verner et al. 2006). Similarly, the sharp variations of sound speed associated with convective cores cause departures from the simple asymptotic behaviour which provide information about the properties of the core (e.g., Roxburgh & Vorontsov 2001; Cunha & Metcalfe 2007).

5. Diagnostic potential of heat-engine excitation

As discussed in Sect. 2, self-excitation of stellar pulsations often requires that an appropriate opacity feature is at an appropriate depth beneath the stellar surface. Thus even the presence of oscillations, and their distribution in frequency, provides information about the internal structure of the star. This in part motivated the plea of Simon (1982) to reconsider opacity calculations: the proposed opacity increase would also offer a way to explain the pulsations in the β Cepheid stars which up to that point had been a mystery. The revised opacities have in fact been extremely successful in accounting for the presence of pulsations in the β Cepheids and in Slowly Pulsating B stars (e.g., Cox et al. 1992; Moskalik & Dziembowski 1992); an extensive overview of pulsation excitation in these stars was provided by Pamyatnykh (1999). Interestingly, recent analyses have shown that even finer details in the opacity computations and stellar composition can be probed by the the distribution of stars in this region of the HR diagram observed to pulsate, and the dependence on metallicity (Jeffery & Saio 2006; Miglio et al. 2007).

The opacities obviously depend on the distribution of stellar abundances and hence on processes that might modify this distribution. Here I briefly discuss two recent examples of analyses based on such effects: the subdwarf B pulsators and the GW Virginis stars which are hot white-dwarf precursors.

5.1. Sub-dwarf B pulsating stars

The sub-dwarf B (sdB) stars are extremely hot horizontal-branch stars. Thus they are in the core helium-burning phase and have lost most of their hydrogen-rich envelopes and represent essentially the final stage before the stars become white dwarfs. As such, they potentially provide crucial information of the previous evolutionary phases, including the evolution on the asymptotic giant branch. The mechanisms behind the extreme mass loss are still uncertain, although they likely involve binary evolution, at least in some cases (Han et al. 2003; Hu et al. 2007).

Observational evidence for oscillations in sdB stars (Kilkenny et al. 1997) was found in parallel with, and independently of, the prediction that the stars should pulsate (Charpinet et al. 1996). The initial observations showed rich spectra of acoustic modes. Later, long-period oscillations, corresponding to g modes, have also been detected (Green et al. 2003; Reed et al. 2004). In accordance with the description of heat-engine pulsations in Sect. 2 these are found in slightly cooler stars.

The instability in these stars is driven by opacity features arising from iron-group elements. However, as noted by Fontaine et al. (2003) instability requires that the abundance of these elements is increased in the critical region of the star, compared with the general heavy-element abundance. This may take place through radiation-driven levitation which occurs selectively, depending on the details of the absorption of the relevant elements in the relevant ionization states. Such processes have been studied in detail in cooler stars where they account for observed surface abundance anomalies (e.g., Michaud 1970; Richer & Michaud 2000). In the case of sdB stars the result is typically an enhanced abundance in a region below the surface, with little observable effect on the surface abundances. For such stars Fontaine et al. (2006) demonstrated that all modes are stable in a model with uniform iron abundance, but that radiative levitation can cause instability of some modes through a build-up of an iron-abundance excess in the critical region, over a period of around 10^5 years, short compared with the sdB evolution time on the horizontal branch. More detailed comparison with the modes actually observed in specific stars may clearly provide important diagnostics on such transport processes. Including also analysis of the typically rich oscillation spectra observed for these stars promises a substantially increased understanding of the late evolution of intermediate-mass stars (e.g., Brassard et al. 2001; Charpinet et al. 2006).

5.2. GW Virginis stars

Moving beyond the pulsating horizontal-branch stars very interesting groups of pulsating stars occupy the white-dwarf cooling sequence. These provide the potential for studies of the last stages of evolution of low- and intermediate-mass stars, reflecting effects of earlier evolutionary stages and the processes that cool the white dwarfs, including neutrino emission and possibly processes involving more exotic particles (e.g., O'Brien & Kawaler 2000; Kim et al. 2005).

The hottest of these groups are at the hot end of the cooling sequence. These pulsating stars have variously been known as Planetary Nebula Nucleus Variables (PNNV), PG 1159 stars or DO variables. Quirion et al. (2007a) argued that these stars form a coherent group of pulsating stars and recommended that they be called GW Virginis pulsators. They are characterized by near-surface layers poor in hydrogen and rich in carbon and oxygen. This is probably a result of evolution through the so-called 'born-again AGB phase', where helium burning is ignited in a late flash after the initial arrival of the star on the white-dwarf sequence (e.g., Werner & Herwig 2006).

The GW Vir stars are excited by the heat-engine mechanism operating through opacity bumps caused by ionization regions of carbon and oxygen. As discussed in detail by Quirion et al. (2007a) the instability therefore depends on the abundances of these elements, leading to a mixture of pulsating and non-pulsating stars in the instability region. A further important aspect is the balance between mass loss, which tends to keep the near-surface layers of the star chemically homogeneous by bringing fresh material towards the surface, and gravitational settling, which tends to remove carbon and oxygen from the critical region in the star which causes instability. As the star cools along the cooling sequence the mass-loss rate decreases, eventually leading to a dominance of settling and hence to a suppression of the instability (Quirion et al. 2007b). Thus the cool edge of the instability region is a sensitive measure of the mass-loss rate, at a level which cannot be probed by traditional measurements of mass loss. On the other hand, instability is limited towards the hottest stars by the critical opacity features being located too close to the surface, as in the case, e.g., of the Cepheid instability strip.

In addition to the asteroseismic constraints obtained from the extent of the region of instability, it is evident that extensive information is available in the detailed frequency spectra of these stars (e.g., Córsico & Althaus 2006).

6. The next steps

Further advances in asteroseismology are to a large extent dependent on improved data. The outlook for such data is extremely promising. Initial data from the CoRoT mission (Baglin et al. 2006) will be released to the co-investigators towards the end of 2007, with a general release of the first data at the end of 2008. Extensive data on a broad range of pulsating stars will result from the Kepler mission (Christensen-Dalsgaard et al. 2007), to be launched in early 2009, and a *Kepler Asteroseismic Science Consortium*[3] has been established to prepare for, and take part in, the analysis of these data. In the somewhat longer term, the successful establishment of the dedicated SIAMOIS facility on Antarctica (Mosser et al. 2007), and of the Stellar Oscillations Network Group (SONG) network (Grundahl et al. 2007), both for Doppler-velocity observations, would provide exquisite data for selected stars, and the selection of the PLATO mission (Catala 2007), now under assessment study in the ESA Cosmic Vision programme, would provide extensive data on oscillations of a huge number of stars. In the more distant future, we may hope to obtain interferometric observations of distant stars which resolve their surfaces, thus allowing study of oscillations of moderate degree, such as proposed in the Stellar Imager concept now being studied by NASA (Schrijver et al. 2007).

These observational advances will undoubtedly uncover significant deficiencies in our, so far, rather simplified modelling of stellar interiors. It is promising that extensive development of stellar modelling is taking place, involving more realistic treatments of hydrodynamic instabilities, rotation, magnetic fields, and aspects of the microphysics. The combination of improved modelling and strong observational constraints on stellar interiors will surely lead to a much improved understanding of stellar evolution.

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[3] see `http://astro.phys.au.dk/KASC`

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