Helio- and asteroseismology

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Modelling of stellar structure and evolution is one of the 'classical' branches of astrophysics, upon which many other areas are based. Important examples are determinations of stellar ages, and studies of element synthesis and galactic enrichment. Yet the physical properties of stellar interiors are highly uncertain. The most important example is probably potential instabilities and the resulting motion that might mix the composition gradients established through the nuclear reactions and hence substantially affect stellar evolution; such effects are usually ignored in modelling of stars. However, even the so-called microphysics, characterizing the thermodynamic properties of stellar matter and its interaction with radiation, as well as the nuclear reactions in stellar interiors, are subject to substantial uncertainties. Thus, although models of stellar evolution generally appear rather successful in reproducing the observed properties of stars, one must worry that the apparent success is in fact coincidental and hides fundamental problems. Indeed, traditional observations of stars are relatively insensitive to the properties of their interiors and hence might not reflect such problems. However, during the last decade observations of stellar oscillations have changed this situation drastically.

Stellar oscillations

Stars have been known to vary in luminosity in a more or less cyclical fashion for several centuries. In most cases, the causes of the variations have been identified as intrinsic pulsations. The periods of such oscillations can be determined with very high accuracy, particularly when compared with the other, rather poorly known, observable quantities that might be used to determine the properties of a star. A measure of the pulsation periods of a star is provided by the characteristic dynamical timescale, $t_{\mathrm{dyn}} \simeq 30\,\mathrm{min}(R/R_\odot)^{3/2}(M/M_\odot)^{-1/2}$ where M and R are the mass and radius of the star and $M_\odot$ and $R_\odot$ are mass and radius of the Sun. Thus the range of observed periods in stars, from minutes to years, immediately corresponds to the extreme range in stellar properties, from very compact objects to extremely extended red giants.

However, the diagnostic potential of stellar oscillation periods is vastly increased when many periods are observed in a given star. Each period provides a unique measure of the stellar interior, and by combining them detailed information about the star can be obtained. This has led to new fields of stellar astrophysics, appropriately known as helio- and asteroseismology.

Seismic investigations of the solar interior

Solar oscillations have been observed with a variety of techniques, although the most detailed data are obtained with Doppler-shift measurements of the surface radial velocity. Very extensive observations have been obtained from the GONG[1] network, funded by the National Science Foundation of the US, as well as the joint ESA-NASA SOHO spacecraft. The Sun shows oscillations with periods between around 3 and 15 mins and mode amplitudes below 15 cms^{-1}. The smallest amplitudes detected so far are of order 0:1 cms^{-1}, and it is likely that longer-period oscillations, of even smaller amplitude, will be detected as the sensitivity is improved. Unlike other stars, the solar surface can be resolved with high resolution; this has allowed observation of oscillations over a broad range of spatial scales, from spherically symmetric modes to waves with a wavelength of a few thousand kilometres. In terms of the degree l of the spherical harmonics characterizing the spatial structure of the modes, the observed modes range from the degree $l = 0$ to degrees of more than 2000.

The modes observed in the Sun are predominantly acoustic modes, excited by convection near the solar surface. They are essentially trapped between the surface and a lower turning point, at a distance r_t from the centre. Low-degree modes penetrate to the solar centre, whereas modes of increasing degree are trapped increasingly close to the surface. Observation of modes over the whole range of l, and hence r_t, therefore effectively scans the solar interior in the radial direction, allowing radial resolution of solar internal properties through the use of suitable inversion techniques. Similarly, the variation of latitudinal extent of the spherical harmonics provides resolution in latitude. As a result it has been possible to determine, for example, the dependence of solar internal rotation on both distance r to the centre and latitude.

Owing to their acoustic nature, the solar oscillation frequencies are predominantly determined by the dependence of adiabatic sound speed c on r; inversion has led to precise inferences of $c(r)$ which may be compared with predictions of solar models. An example is illustrated in Fig. 1. The model is a so-called 'standard solar model'. It is based on up-to-date microphysics, including also effects of element settling and diffusion, and was obtained by following the evolution of the composition profile in the Sun from an assumed initially homogeneous state to the present age. It should be emphasized that, although parameters of the calculation have been adjusted to match the present radius, luminosity and surface composition of the Sun, no direct attempt has been made to fit the oscillation data. In this respect the model can be regarded as a prediction of solar structure, based on current knowledge of the physics of the solar interior. The relatively small discrepancy shown in Fig. 1 is thus a striking example of the power of physics to predict the properties of even a complex object such as a star; it must be admitted, though, that amongst stars the Sun is a rather simple example. It is also evident that the remaining differences far exceed the estimated errors; the physical causes for these differences are as yet uncertain, although it is likely that mixing processes, ignored in the model computation, are at least partly responsible.

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The model used in Fig. 1 shares with other solar models predicted neutrino capture rates far exceeding those observed. The helioseismic measurements do not directly constrain the solar internal temperature T, upon which the neutrino fluxes mainly depend. However, since c^2 is approximately proportional to T/μ, where μ is the mean molecular weight, the agreement in Fig. 1 leaves little room for changes to the model reducing significantly the neutrino fluxes. Thus it is very interesting that the recently announced measurements of solar neutrinos at the Sudbury Neutrino Observatory through charge-current reactions indicate that the total flux of high-energy neutrinos from the Sun is consistent with solar models.

In addition to solar structure, the observed frequencies have provided detailed inferences of solar internal rotation, generally in conflict with earlier models of solar rotation. The outer 28% of the solar radius, where energy is transported by convective motions, shows a marked variation of rotation with latitude, the equator rotating substantially faster than the poles. At the base of the convection zone there is a transition over a narrow radial extent, only a few per cent of the solar radius, to essentially uniform rotation of the solar interior; in particular, there is no indication of a rapidly rotating core, left over from a normally presumed earlier phase of more rapid rotation. The origin of this complex pattern of rotation is highly uncertain; it is likely that

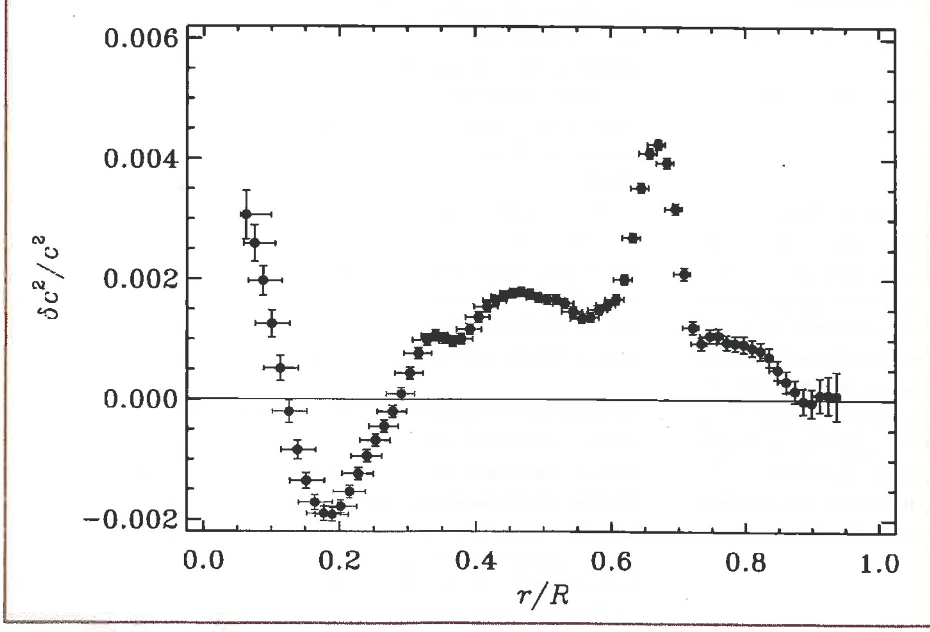

Fig. 1: Difference in squared sound speed c^2 between the Sun and a standard solar model, in the sense (Sun) – (model), inferred from helioseismic inversion of observed solar oscillation frequencies. The abscissa is distance to the solar centre, in units of the surface radius. The vertical error bars are 1-σ errors on the inferred differences, while the horizontal bars provide a measure of the resolution of the inversion. (From Basu *et al.*, 1997; Mon. Not. R. astr. Soc. 291, 243).

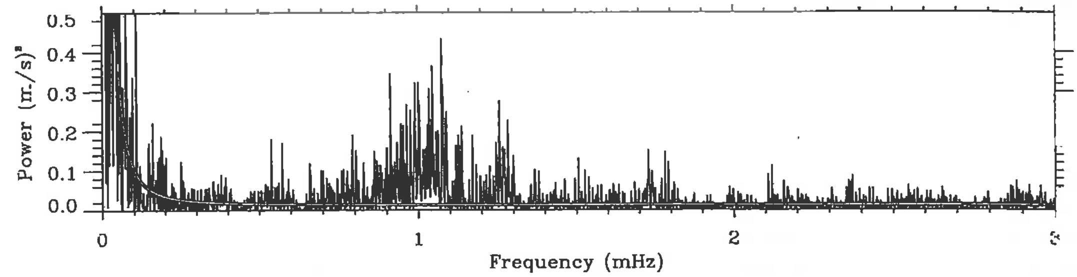

Fig. 2: Power spectrum of oscillations of the star β Hydri, obtained from observations of Doppler velocity at the Anglo-Australian telescope, plotted against cyclic frequency. The power enhancement with a maximum near a frequency of around 1 mHz, corresponding to a period of 17 min, is very similar to that observed for the Sun. (From Bedding *et al.*, 2001; Astrophys. J. 549, L105).

angular-momentum transport by convection causes the variation seen in the convection zone, whereas the rigid rotation of the interior may have been enforced by a weak magnetic field. Observations over the past 5 – 6 years with GONG and SOHO have also shown complex variations with time in the rotation rate within and just beneath the convection zone, likely related to the variations in solar activity reflecting the solar cycle.

Asteroseismology

Given the striking success of helioseismology, it is not surprising that a great deal of effort has gone into extending seismic investigations to other stars. This will allow study of phenomena not observed in the Sun, such as mixing by convective cores, as well as the study of physics under circumstances far more extreme than those attained in the solar case. In fact, a broad range of stars, from red giants to white dwarfs, show oscillations, often with substantial numbers of modes promising detailed information. Major successes have been obtained in the study of white dwarfs, the very compact final stage of evolution for stars of masses below about 10 $M_\odot$. Here the observations have led to precise determinations of the masses and composition profiles of the stars, and hence to important constraints on the late stages of stellar evolution. Measurements of the period changes of the hottest white dwarfs are also providing information about neutrino cooling of these stars, and hence about physical processes under very extreme conditions of temperature and density. Very interesting results have also been obtained in the last few years for hot so-called horizontal-branch stars, in the phase of core helium burning, and extensive data, so far not fully interpreted, are available for several classes of stars on the main sequence.

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However, much interest centres on the study of oscillations similar to those observed in the Sun. The excitation mechanism, through turbulent convection, is sufficiently well understood that the presence of such oscillations can be predicted in all relatively cool stars. Also, although only modes of the lowest degrees will be detectable in observations of distant stars, these are precisely the modes that provide information about the cores of the stars reflecting, for example, the age of the star through the change in composition caused by nuclear reactions. The difficulty is the very small amplitudes expected, of order 1 ms^{-1} or less in radial velocity or a few parts per million in intensity. In ground-based observations such small signals are easily masked by effects of the Earth's atmosphere. Even so, over the past decade indications of solar-like oscillations have been found in several stars. Very recently, the first incontrovertible detection was made with Doppler-velocity observations for the star β Hydri, a $1 M_\odot$ star in a somewhat later stage of evolution than the Sun. The observed power spectrum, illustrated in Fig. 2, shows a strong power enhancement corresponding closely to what is observed in the Sun; however, in agreement with theoretical predictions, the observed power is somewhat higher than for the Sun. An even clearer signal has since been obtained for the star α Centauri A, which is quite similar to the Sun. Thus, asteroseismology of solar-like stars is finally set to take off.

Although such ground-based studies are very encouraging, they are limited to the brightest stars. Also, adequate frequency resolution would require extended observations with fairly large dedicated telescopes, suitably distributed around the Earth to avoid daily gaps in the data. Thus, major advances in the field will result from the launch of several small satellites dedicated to asteroseismology over the coming few years: the Canadian MOST mission, the French COROT mission and the Danish Rømer mission, all three to observe the tiny intensity oscillations outside the disturbances of the Earth's atmosphere. In the slightly longer term a very promising prospect is the Eddington project which has been included in the ESA programme as a reserve mission. In addition to searching for Earth-size planets by observing transits, Eddington will provide very accurate asteroseismic data on a broad variety of stars. This will yield a firm observational basis for the study of stellar interiors and the application of the results to other areas of astrophysics.

About the author

Jørgen Christensen-Dalsgaard is Research Professor in helio- and asteroseismology at the University of Aarhus, Denmark. After graduating from University of Aarhus in 1975 he obtained his PhD from Cambridge University in 1978 and then held postdoctoral positions in Liège, Belgium, Boulder, CO (USA), and at NORDITA, Copenhagen. Professor Christensen-Dalsgaard participates in the Global Oscillations Network Group and is Co-Investigator on instruments on the SOHO spacecraft, as well as Principal Investigator for the Rømer mission and member of the Eddington Science Team.