Bull. Astr Soc. India (1995) **23**, 337–339

Helioseismology – impact and implications

S.S. Hasan

Indian Institute of Astrophysics, Bangalore 560 034, India

Helioseismology is the study of the Sun's internal structure through an analysis of its free oscillations, similar to terrestrial seismology which attempts to probe the Earth's interior through a study of earthquakes. The field took roots in 1960 with the discovery, in the photosphere, of oscillations with typical periods of 5 min. These free oscillations are due to the superposition of a large number ($\sim 10^7$) modes, each having a characteristic frequency and confined to a cavity of varying thickness below the surface. The velocity amplitude of an individual mode is very small (around a few metres per sec) but collectively they yield a fluctuation of around 1 km s^{-1}.

The oscillation spectrum of the detected modes consists of periods ranging from a few minutes to several hours. These oscillations carry a wealth of information regarding the solar interior, mainly because various modes sample different regions inside the Sun and hence allow us to probe the internal structure very accurately. Helioseismology can therefore contribute in a quantitative way to finding out many important parameters inside the Sun.

Solar oscillations are basically produced as a consequence of the response of a stratified atmosphere to pressure and gravity forces. At high frequencies (more accurately above the acoustic cutoff frequency), the oscillations are mainly driven by pressure forces and have the character of acoustic or *p*-modes. Gravity or *g*-modes are driven by buoyancy which leads to low frequency oscillations. Observationally *p*- modes with periods in the 5 min band have received the most attention because they have the largest amplitude and are ubiquitous on the solar surface.

Probing the solar core

Observations of low degree *p*-mode frequencies, provide an effective way to determine physical conditions in the solar core. With the availability of improved opacity tables and better input physics, it has been possible to narrow down the discrepancy between the theoretical and observed frequencies to smaller than 5 μHz. This uncertainty translates into the external layers of the Sun which are still not fully understood. This is a considerable improvement in comparison with previous estimates, but is still a factor of about 5 greater than the experimental error. Because of the accuracy of the solar modelling, the uncertainty of the calculation is still of the order of 1-1.5 μHz.

Inversion of data

The starting point is the determination of the sound speed based upon an inversion procedure which uses the observed frequencies of a large number of p-modes. The calculated sound speed using this method is accurate to about 0.5%.

From an accurate seismic determination of the sound speed, it is possible to estimate the depth of the convection zone and the helium abundance. Recent calculations yield a convection zone depth of $0.287 \pm 0.003R$ (R being the solar radius) beneath the photosphere. The helium abundance has been estimated by two different groups as 0.268 and 0.234 (with an uncertainty of about 0.01).

Rotation

Our current understanding of the solar interior rotation profile consistent with model calculations, is that the angular velocity in the convection zone is roughly independent of radius. The rotational frequency of the radiative interior is in the range 425 to 435 nHz, at least for $r > 0.4$ R and there is a relatively sharp transition in the rotation profiles just below the base of the convection zone. Below 0.4R, our knowledge of the solar rotation rate is poor, due primarily to the inaccuracy of the current p-mode splitting data at very low l.

Furthermore, it is possible to compute the centrifugal distortion of the Sun and hence deduce the quadrupole moment J_2. The result is $J_2 \approx 1.5 \times 10^{-7}$. With this value we may safely conclude that the centrifugal distortion for the Sun is relatively small on the orbit of Mercury.

Solar neutrino problem

The discrepancy of the solar neutrino flux inferred from the chlorine, water and gallium experiments and the predicted flux on the basis of the standard models has still not been satisfactorily resolved. Neutrinos and oscillations provide an independent test of the standard model. The standard model is mainly determined by the microphysics of the solar interior, viz. equation of state, opacity, chemical composition, nuclear reaction rates. Helioseismology has demonstrated that there is very little room for manoeuvre in the first three of the above. Within the standard model there are still some uncertainties in the nuclear reaction rates, but it appears unlikely that this will lead to a significant reduction in the neutrino flux. It appears that a resolution of the problem may lie in a modification of the standard electroweak theory, possibly through the MSW mechanism.

Observational aspects

In order to determine the solar oscillation frequencies very precisely, it is necessary to have long uninterrupted spells of observations. Typically, we require uninterrupted observations for a month to obtain a frequency resolution of about 0.5 μHz. The most important effect that needs to be eliminated is the diurnal cycle which introduces peaks at multiples of 11.57 μHz (1 day). Currently, the strategy for overcoming the above limitation is to use ground-based networks. The most well known of these is GONG (Global Oscillation Network Group) which has been set up to obtain a continuous coverage using 6 stations appropriately placed in longitude, such that 2 of the sites can simultaneously observe the Sun. All the stations are equipped with identical Doppler imaging instruments called Fourier tachometers (basically Michelson interferometers).

In addition to ground-based networks, observations from space are being planned. These will complement the ground networks by allowing the study of high degree (l up to about 4000) modes. Seeing distortions limit the resolution of ground-based instruments to l about 400. These observations will be accomplished by the Solar Oscillations Investigation (SOI) employing a similar instrument as GONG on the SOHO spacecraft to be flown in July 1995. SOHO will also carry a spatially unresolved atomic resonance scattering instrument to study Global Oscillations at Low Frequencies (GOLF) and Variability of solar Irradiance and Gravity Oscillations (VIRGO). Other projects for seismology are PRISMA (Probing Rotation and Interior of Stars), STARS and EVRIS.

References

Brown T.M., Mihalas B.W., Rhodes E.W., 1986, in Physics of the Sun, Vol. I: The Solar Interior, eds P.A. Sturrock, T.E. Holzer, D.M. Mihalas & R.K. Ulrich, D. Reidel, Dordrecht, p.177.

Christensen-Dalsgaard J., Gough D.O., Toomre J., 1985, Science, 229, 923.

Christensen-Dalsgaard J., Berthomieu G., 1992, in Solar Interior & Atmospheres, eds A.N. Cox, W.C. Livingston & M. Mathews, University of Arizona press, p.401.

Christensen-Dalsgaard J., Gough D.O., Thompson M.J., 1991, ApJ 378, 413.

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

Hill F., Deubner F., Isaak G, 1992, in Solar Interior & Atmospheres, eds. A.N. Cox, W.C. Livingston & M. Mathews, University of Arizona press, p.329.

Leibacher J.W., Noyes R.W., Toomre J., Ulrich R.K., 1985, Sci. Am., 253, 48.

Libbrecht K.G., Morrow C.A., 1992, in Solar Interior & Atmospheres, eds A.N. Cox, W.C. Livingston & M. Mathews, University of Arizona press, p.479.

Stein R.F. Leibacher J.W., 1974, ARA&A 12, 407.

Unno W., Osaki Y., Ando H., Saio H., Shibahashi H., 1989, Nonradial Oscillations of Stars, 2nd edn, University of Tokyo press.