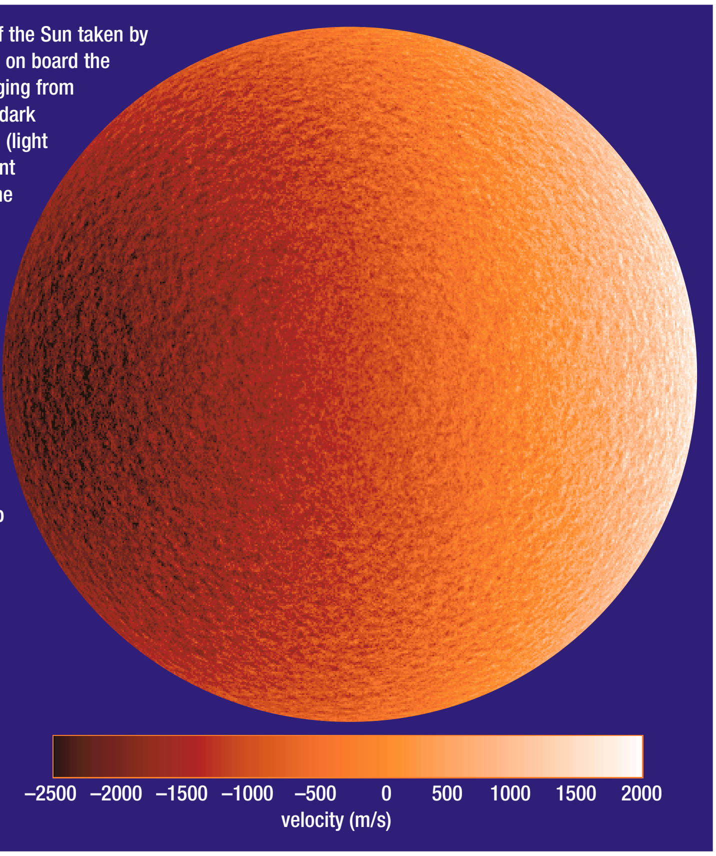
Helioseismology and the Sun's interior

Michael J Thompson gets under the skin of the Sun using waves on its surface.

Abstract

Helioseismology is the study of the solar interior using observations of waves on the Sun's surface. It has done much to improve our understanding of the interior of the Sun, testing the physical inputs used to model stellar interiors and providing a detailed map of the Sun's structure and internal rotation. This in turn has greatly influenced theories of the solar magnetic dynamo. These interior studies thus make a valuable bridge between solar physics and studies of the structure and evolution of other stars. Recent developments include new local techniques for unprecedented studies of subsurface structures and flows in emerging active regions, under sunspots, and even of active regions on the far side of the Sun. These developments hold the possibility of a real understanding of how the interior links to solar magnetic activity in the corona and heliosphere. Finally, studies such as those of the deep solar interior are on the verge of becoming possible for other stars exhibiting similar multimode oscillations.



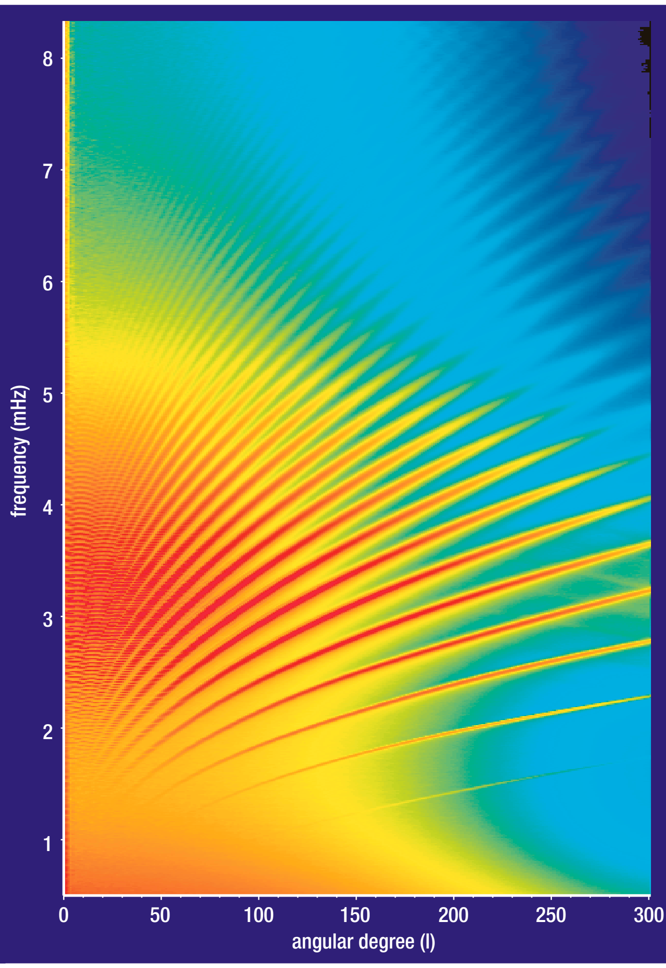
1: Doppler image of the Sun taken by the MDI instrument on board the SOHO satellite, ranging from roughly -2 km s^{-1} (dark tones) to $+2$ km s^{-1} (light tones). The dominant grading is due to the Sun's rotation; but the residual when this and other large-scale motions are corrected for reveals the Sun's resonant-mode oscillations. (Courtesy SOHO/MDI research group at Stanford University.)

There are many reasons to study the Sun. It is the only star that can be observed in great detail, so it provides an important input to our understanding of stellar structure and evolution. The Sun greatly influences the Earth and near-Earth environment, particularly through its outputs of radiation and particles, so studying it is important for understanding solar–terrestrial relations. And the Sun also provides a unique laboratory for studying some fundamental physical processes in conditions that cannot be realized on Earth. It was discovered in the 1960s (Leighton *et al.* 1962) that patches of the Sun's surface were oscillating with a period of about five minutes. Initially these were thought to be a manifestation of local convective motions, but by the 1970s it was understood from theoretical work (Ulrich 1970, Leibacher and Stein 1971) and from further observational work (Deubner 1975, Claverie *et al.* 1979) that the observed motions are the superposition of many global resonant modes of oscillation of the Sun. The Sun can support various wave motions, notably acoustic waves and gravity waves: these set up global resonant modes. The modes in which the Sun is observed to oscillate are predominantly acoustic modes, though the acoustic wave propagation is modified by gravity and the Sun's internal stratification, and by bulk motions and magnetic fields. The frequencies and other observed properties of the oscillations can be used to make inferences about the physical state of the solar interior. The excitation mechanism is generally believed to be turbulent convective motions in the subsurface layers of the Sun, which generate acoustic noise. This is a broadband source, but only those waves that satisfy the appropriate resonance conditions constructively interfere to give rise to resonant modes.

One of the first deductions from helioseismology (Gough 1977, Ulrich and Rhodes 1977) was that the Sun's convection zone was substantially deeper than in the contemporaneous solar models. From then up to the present day, much progress has been made in helioseismology through analysis of the Sun's global modes of oscillation. Some results on the Sun's internal structure and its rotation are reviewed here. In the past decade global-mode studies of the Sun have been complemented by so-called local helioseismic techniques such as tomography, which have been used to study flows in the near-surface layers and flows and structures under sunspots and active regions of sunspot complexes.

Solar oscillations

The Sun's oscillations are observed in line-of-sight Doppler velocity measurements over the visible solar disk, and also in measurements of variations of its continuum intensity of radiation caused by compression of the radiating gas by the waves. Wave motions with the largest horizontal scales are detectable in observations of the Sun as a star, in which light from the whole visible disk is collected and analysed as a single time series. Motions on smaller horizontal scales require spatially resolved measurements obtained by separately observing different portions of the disk. To measure the frequencies very precisely, long, uninterrupted series of observations are desirable. Hence observations are made from networks of dedicated small solar telescopes distributed in longitude around the Earth (these include the Global Oscillation Network Group GONG making 1024×1024-pixel resolved observations and the Birmingham Solar Oscillation Network, BiSON, making Sun-as-a-star observations) or from space (for instance, the Solar and Heliospheric Orbiter SOHO satellite has three helioseismology instruments on board; in decreasing order of resolution: MDI, VIRGO and GOLF). In Doppler velocity the amplitudes of individual modes are of order 10 cm s^{-1} or smaller, their superposition giving a total oscillatory signal of the order of 1 km s^{-1}. The largest-amplitude modes have frequencies of around 3 mHz. A snapshot of the Doppler velocity as measured by MDI is shown in figure 1. The large-scale gradient across the image due to the Sun's rotation, and slowly varying signals due to convection, can be removed by subtracting a running average of such Doppler images, to leave the signal of the Sun's global oscillations.



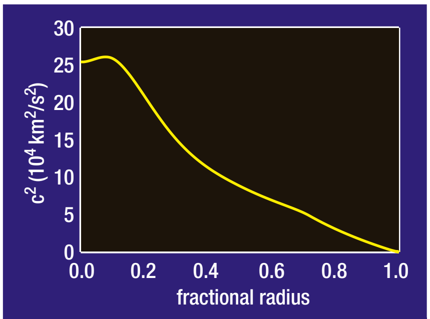
2: The power in the Sun's acoustic p-mode oscillations, as observed by the MDI instrument on board the SOHO satellite, as a function of frequency and angular degree *l*. The power lies on ridges that correspond to branches of the dispersion relation for p-modes, each branch corresponding to a different value of the order *n*. (Courtesy SOHO/MDI research group at Stanford University.)

The outer 30% of the Sun comprises the convectively unstable convection zone. Solar oscillations are stochastically excited by turbulent convection in the upper part of the convection zone: the modes are both excited and damped by their interactions with the convection. Although large excitation events such as solar flares may occasionally contribute, the dominant excitation is probably much smaller scale and probably takes place in downwards plumes where material previously brought to the surface by convection has cooled and flows back into the solar interior. These form a very frequent and widespread set of small-scale excitation sources.

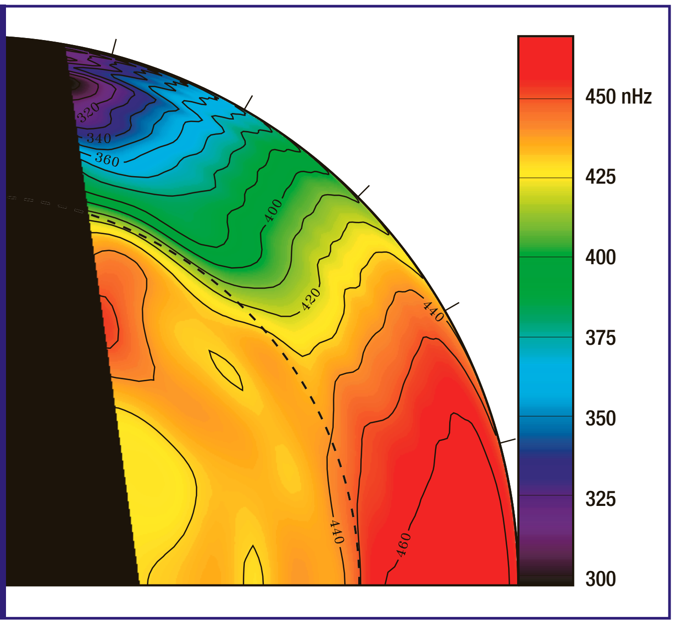
On the timescales of the observed solar oscillations, the bulk of the solar interior can be considered to be in thermal equilibrium and to provide a mean static large-scale equilibrium background state in which the waves propagate. Moreover, the timescales are sufficiently short that the perturbations of pressure (p) and density (ρ) in the interior are related by an adiabatic relation. At high frequencies, pressure forces provide the dominant restoring force for the small perturbative motions about equilibrium, giving rise to acoustic waves. A key quantity for the propagation of such acoustic waves is the adiabatic sound speed c, which varies with position inside the Sun: $c^2 = \Gamma_1 p/\rho$, where Γ_1 is the first adiabatic exponent. To an excellent approximation, $p \propto \rho T/\mu$, where T is temperature and μ is the mean molecular weight of the gas, so $c \propto T^{1/2}$ inside the Sun. Except for waves propagating exactly vertically, inwards-propagating waves get refracted back to the surface at some depth, because the temperature and hence sound speed increase with depth. Near the surface, outwards-propagating waves also get deflected, by the sharply changing stratification in the near-surface layers. Hence the acoustic waves are trapped in a resonant cavity and form modes, with discrete frequencies ω. The horizontal structure of the eigenfunctions of the modes is given by spherical harmonics Y_l^m, where integers l ($l \geq 0$) and m ($-l \leq m \leq l$) are respectively called the "degree" and "azimuthal order" of the mode. The structure of the eigenfunction in the radial direction into the Sun is described by a third quantum number n, called the "order" of the mode: the absolute value of n is essentially the number of nodes between the centre and the surface of the Sun in, for example, the pressure perturbation eigenfunction. Hence each resonant frequency can be labelled with three quantum numbers thus: ω_{nlm}. The labelling is such that at fixed l and m, the frequency ω_{nlm} is a monotonic increasing function of n. A power spectrum of the Sun's oscillations as observed by the MDI instrument is shown in figure 2.

In a wholly spherically symmetrical situation the frequencies would be independent of m. However, the Sun's rotation breaks this degeneracy and introduces a dependence on m in the eigenfrequencies. Other large-scale motions and any asphericities also contribute to breaking the symmetry of the system. The modes of different m but with the same values of n and l are called a multiplet: it is convenient also to introduce the mean multiplet frequency ω_{nl}.

High-frequency modes, with positive values of the order n, are essentially acoustic modes (p-modes): for them the dominant restoring force is pressure. Low-frequency modes, with negative values of n, are essentially gravity modes (g-modes) set up by gravity waves that can propagate where there is a stable stratification. There is an intermediate mode with $n = 0$: this is the fundamental or f-mode. For large values of l, the f-mode has the physical character of a surface gravity mode. The observed global modes of the Sun are p-modes and f-modes. Modes of low degree (mostly $l = 0,1,2,3$) are detectable in observations of the Sun as a star: low-degree p-modes are sensitive to conditions throughout the Sun, including the energy-generating core. Spatially resolved observations have detected p- and f- modes up to degrees of several thousand: at very high degree the modes are no longer global in character, but nonetheless measuring their properties conveys information about the Sun's outer subsurface layers. Internal g-modes have not unambiguously been observed to date: they are expected to have small amplitudes at the surface because their region of propagation is the stably stratified radiative interior and they are evanescent through the intervening convection zone.



3: Square of the adiabatic sound speed c inside a model of the present Sun, as a function of fractional radius r. The base of the convection zone is located at approximately $r = 0.7R_\odot$, the photosphere is at $r = R_\odot$.



4: The rotation rate inside the Sun inferred from MDI data. The rotation axis is up the y-axis, the solar equator is along the x-axis. Contour spacings are 10 nHz; contours at 450 nHz, 400 nHz and 350 nHz are thicker. The obscured region indicates where a localized solution has not been possible with these data.

The Sun's internal stratification

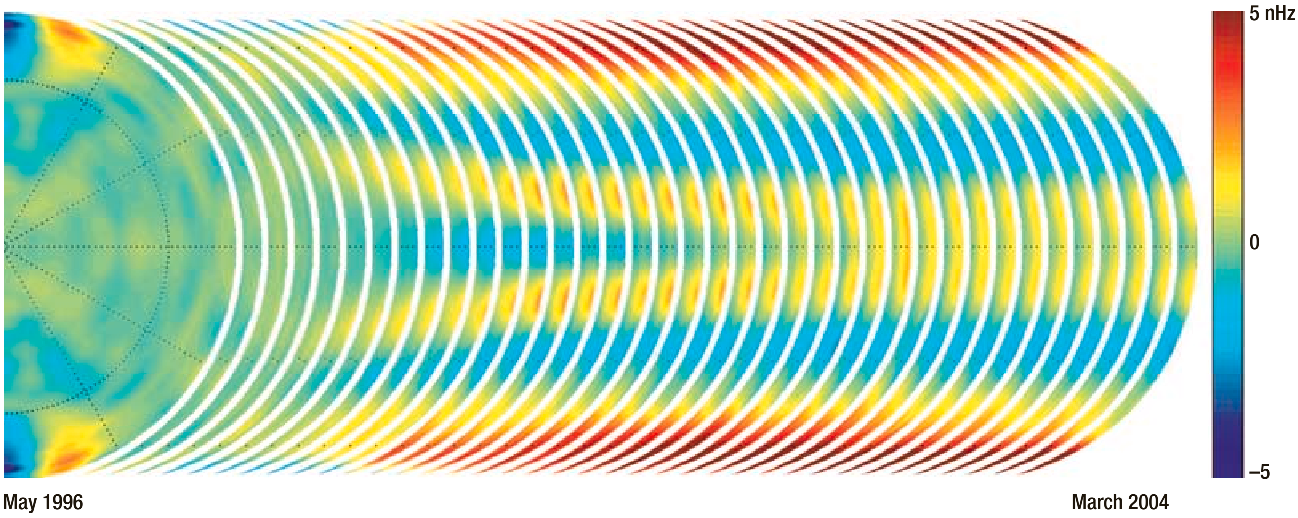
The frequencies of the Sun's global modes are estimated by making suitable spatial projections and temporal Fourier transformations of the observed Doppler or intensity fluctuations. From these, using a variety of fitting or inversion techniques (e.g. Gough 1985, 1996), properties of the solar interior can be deduced. One of the principal deductions from helioseismology has been the sound speed as a function of position in the Sun. The value of this deduction lies not in the precise value of the sound speed but in the inferences that follow concerning the physics that determines the sound speed. A good discussion of the helioseismic results may be found in the review by Christensen-Dalsgaard 2002. The sound speed in a solar model that is closely in agreement with the helioseismic data is illustrated in figure 3.

As discussed above, the adiabatic sound speed c is related to temperature T, mean molecular weight μ and adiabatic exponent Γ_1 by $c^2 \propto \Gamma_1 T/\mu$ where the constant of proportionality is the gas constant. The general increase in sound speed with depth reflects the increase in temperature from the surface to the centre of the Sun. The gradient of the temperature, and hence of the sound speed, is related to the physics by which heat is transported from the centre to the surface. In the bulk of the Sun, that transport is by radiation; but in the outer envelope the transport is by convection. A break in the second derivative of the sound speed near a radius of 0.7 $R_\odot$ (where $R_\odot$ is the Sun's photospheric radius) indicates the transition between the radiative interior and convective envelope, and has enabled helioseismology to determine the location of the base of the convection zone (Christensen-Dalsgaard *et al.* 1991): this is important because it delineates the region in which chemical elements observed at the surface are mixed and homogenized by convective motions. Beneath the convection zone, the gradients of temperature and sound speed are influenced by the opacity of the material to radiation: it has thus been possible to use the seismically determined sound speed to find errors in the theoretical estimates of the opacity, which is one of the main microphysical inputs for modelling the interiors of stars. There is some evidence from remaining discrepancies between the sound speed in the Sun and in solar models of partial mixing of material beneath the convection zone and in the outer part of the energy-generating core at a radius of about 0.2 $R_\odot$. The dip in the sound speed at the centre of the Sun is the signature (principally through the mean molecular weight μ) of the fusion of hydrogen to helium that has taken place over the Sun's lifetime: therefore it is an indicator of the history of nuclear reactions in the core. In addition to inversions, a sensitive measure of the sound speed in the core is provided by the difference $\nu_{nl}-\nu_{n-1,l+2}$ between frequencies of p-modes of low degree ($l = 0,1,2,3$) differing by two in their degree. Helioseismology has thus been able to constrain tightly any proposed astrophysical solution of the solar neutrino problem. The recent results from the Sudbury Neutrino Observatory and Super-Kamiokande experiments have provided evidence for neutrino oscillations and give a neutrino production rate in the Sun that is consistent with standard models and with helioseismology (Ahmad *et al.* 2001).

Not readily apparent on the scale of figure 3 is the spatial variation of Γ_1 and hence of sound speed in the regions of partial ionization of helium and hydrogen in the outer 2% of the Sun. This variation depends on the equation of state of the material and on the abundances of the elements: it has been used to determine that the fractional helium abundance by mass in the convection zone, which is poorly determined from surface spectroscopic observations, is 0.23–0.25 (e.g. Kosovichev *et al.* 1992). This is significantly lower than the value of 0.28 believed from stellar evolutionary models to have been the initial helium abundance of the Sun when it was formed. The deficiency of helium in the present Sun's convection zone is understood to arise from gravitational settling of helium and heavier elements out of the convection zone and into the radiative interior over the 4.7 billion years that the Sun has existed as a star. This inference is confirmed by an associated modification to the sound speed profile beneath the convection zone (Christensen-Dalsgaard *et al.* 1993). The sensitivity of sound speed to Γ_1 has also been used to constrain the equation of state of the solar plasma (Elliott and Kosovichev 1998, Basu *et al.* 1999).

Internal rotation

A major deduction of global-mode helioseismology has been the rotation as a function of position through much of the solar interior (e.g. Schou *et al.* 1998, Thompson *et al.* 2003). The rotation inferred from one such inversion is illustrated in figure 4. In the convection zone the rotation varies principally with latitude and rather little with depth: at low solar latitudes the rotation is fastest, with a rotation period of about 25 days; while at high latitudes the rotation periods in the convection zone are in excess of 30 days. These rates are consistent with deductions of the surface rotation from spectroscopic observations and from measurements of motions of magnetic features such as sunspots. The finding is at variance with early hydrodynamical models that indicated the rotation in the convection zone would vary principally with distance from the rotation axis. At low- and mid-latitudes there is a near-surface layer of rotational shear: this may account for the different rotational speeds at which small and large surface magnetic features move. Near the base of the convection zone the latitudinally differential rotation makes a transition to latitudinally independent rotation. This gives rise to a layer of rotational shear at low and high



5: The temporal evolution of the zonal flows inferred from inversions of data from MDI, after subtraction of an average rotation rate. The plot is symmetric around the equator, because global rotational inversion only senses the symmetrical component of the rotation rate. (Courtesy S V Vorontsov.)

latitudes, which is called the tachocline (Spiegel and Zahn 1992). It is widely believed that the tachocline is where the Sun's large-scale magnetic field is generated by dynamo action, leading to the 11-year solar cycle of sunspots and the large-scale dipole field (see discussion by Bushby and Mason, pages 4.7–4.13 this issue). Crucial to the tachocline's possible role in the dynamo are its location and depth. Following initial estimates of these by Kosovichev (1996b), various investigators have made detailed studies. Charbonneau *et al.* (1999) estimated the location of the centre of the shear layer at lowest latitudes to be $0.693\pm0.002\ R_\odot$, i.e. beneath the convection zone base, and with a width (suitably defined) of $0.04\ R_\odot$. They also found some indication that the tachocline may be prolate.

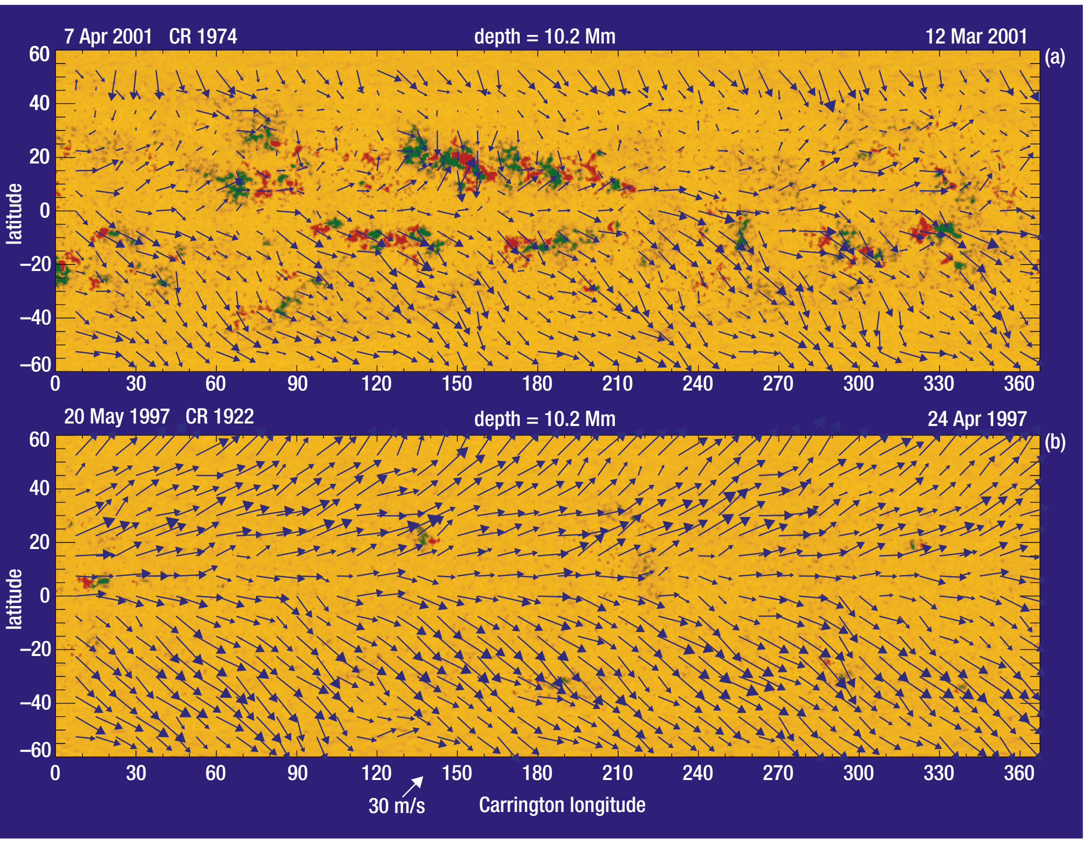
Deeper still the rotation appears to be consistent with solid-body rotation. In the core there is some hint of a slower rotation (Chaplin *et al.* 1999), but the uncertainties on the deductions are quite large: nonetheless, some earlier theoretical predictions that the core would rotate much faster than the surface, a relic of the Sun's faster rotation as a young star, are strongly ruled out by the seismic observations.

Superimposed on the rotation of the convection zone are weak but coherent migrating bands of faster and slower rotation (of amplitude only a few metres per second, compared with the surface equatorial rotation rate of about $2\ \mathrm{km\,s^{-1}}$), which have been called torsional oscillations (Howard and LaBonte 1980). These are illustrated in figure 5. Helioseismology has shown that these flows extend at least one third of the way through the convection zone and possibly the deep convection zone and high latitudes are also involved (Howe *et al.* 2000a, Vorontsov *et al.* 2002). There are also reported weak variations in the rotation rate, with periodicities around 1.3 years, at low latitudes in the deep convection zone and in the vicinity of the tachocline (Howe *et al.* 2000b): these could be a manifestation of the dynamo field. However, the causal connection between all these time-varying flows and the solar dynamo and activity cycle is as yet uncertain (see Bushby and Mason, this issue pages 4.7–4.13).

Local helioseismology

Analysis of the Sun's global mode frequencies has provided an unprecedented view of the interior of a star, but the approach has limitations. In particular, the frequencies sense only a longitudinal average of the internal structure. To make more localized inferences, various local helioseismic techniques have been devised. One technique is ring analysis. The wave motions are analysed as a function of frequency and the two horizontal components of the wavenumber in localized patches. To obtain good resolution in wavenumber, the patches are usually quite large: square tiles of up to about 2×10^5 km on the side. The method is called ring analysis because the mode power lies on rings in the horizontal wavenumber plane when viewed at fixed frequency. By performing inversions for the depth dependence under each tile, maps with horizontal resolution similar to the size of the tiles can be obtained of structures and flows in the outer few per cent of the solar interior. As well as the zonal flows, the meridional (i.e. north–south) flow components have also been measured. The analyses have revealed complex and changing flow patterns within the shear layer near the top of the convection zone: these flows, which have been termed solar subsurface weather (e.g. Toomre 2003), exhibit temporal variations on timescales of days to years (Haber *et al.* 2002). Two examples of flow maps are shown in figure 6. The large-scale patterns show strikingly different character as magnetic activity intensifies. In particular, active regions appear as zones of convergence and possible subduction. At solar minimum, the meridional flow in both hemispheres in this shear layer is polewards. Starting in 1999, however, in the approach to the maximum of the Sun's 11-year magnetic cycle, a band or cell of equatorwards meridional flow forms in the northern hemisphere at latitudes >40°: in the southern hemisphere the meridional flow remains polewards.

Another local technique is time–distance helioseismology, in which the travel times of waves between different points on the surface of the Sun are used to infer wave speed and flows under the surface. This can result in much finer horizontal resolution than has yet been achieved by ring analysis, down to just a few thousand kilometres. By comparing the measured travel times with those of a solar model, inversion techniques similar to those used in global-mode helioseismology have been used to map conditions in the convection zone using travel-time data. Structures and flows beneath sunspots have been investigated using high-resolution observations from MDI on board SOHO (Kosovichev *et al.* 2000, Zhao *et al.* 2001). The wave propagation speed in the outer few thousand kilometres immediately beneath a spot is reduced relative to similar depths under quiet Sun: at greater depth, however, the wave speed is increased relative to that in the quiet Sun. The horizontal flow in the subsurface layers down to 3×10^6 m converges on the spot, which is the opposite to the well-known Evershed flow detected in surface measurements: there is also strong downflow surrounding the sunspot. At greater depth (6–9×10^6 m) these investigations indicate that the spot is surrounded by a ring of upflow. Other results from time–distance helioseismology include maps of convective structures



6: Synoptic maps of horizontal flows deduced from ring-analysis probing at 10×10^6 m depth below the photosphere from observations taken in (a) 1997 (Carrington rotation 1922) and (b) 2001 (Carrington rotation 1974). (Courtesy J Toomre and D A Haber.)

(Duvall *et al.* 1997) and time-resolved maps of emerging active regions (Kosovichev 1996a).

A rather different application of "local" helioseismology is far-side imaging: here the technique of acoustic holography is being used to map active regions on the far side of the Sun prior to their appearance on the Earth-facing solar disk (Lindsey and Braun 2000).

Recently a new study of seismology of the corona, the Sun's hot, rarefied outer atmosphere, has been initiated with studies of wave motions, particularly of coronal magnetic flux tubes. The corona is dominated by the magnetic field. A major uncertainty is the magnetic field strength in localized structures such as coronal loops. By fitting the observed oscillations with MHD wave theory, the field strength in a coronal loop has been estimated as 13±9 gauss (Nakariakov and Ofman 2001). The waves are rapidly damped, which is itself prompting much study (e.g. De Moortel and Hood 2003). Nakariakov and Verwichte discuss this emerging but promising field in greater detail on pages 4.26–4.27 of this issue.

Global-mode studies are now also beginning to be made in more limited fashion for some other stars, in a field known as asteroseismology. Stars of many different types in terms of mass and evolutionary age exhibit global-mode oscillations. Many, such as γ Dor, δ Scuti and slowly pulsating B stars as well as solar-type stars such as α Cen, are multimode pulsators and thus in principle are accessible to seismological investigations such as have been developed for the Sun (e.g. Thévenin *et al.* 2002). Such studies will likely develop rapidly in the next five years with improving ground-based studies, the small-satellite missions MOST from Canada and COROT from France, and NASA's Kepler mission.

A major new technological step for helioseismology will come with NASA's Solar Dynamics Observatory (SDO) which will carry the HMI instrument, a high-resolution MDI making measurements at 4096×4096-pixel resolution across the whole solar disk. These observations will greatly enhance the capabilities of local helioseismology to probe structures and flows and their variability in the Sun's convection zone. Combining HMI observations with those of SDO's AIA instrument, which will make TRACE-like measurements across the whole disk, SDO will enable solar physicists to make linkages between flows and magnetic structures beneath the photosphere with solar activity in the corona and out into the heliosphere. The forthcoming STEREO mission does not carry helioseismology instrumentation, but in the future stereoscopic and out-of-ecliptic observations from space would improve global-mode coverage of the Sun. They would also allow measurementof travel times of waves propagating deep inside the Sun and hence provide detailed latitudinal and longitudinal probing of *inter alia* the solar tachocline. ●

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References

Ahmad Q R *et al.* 2001 *Phys. Rev. Lett.* **87** 071301.
Basu S *et al.* 1999 *Astrophys. J.* **518** 985.
Chaplin W J *et al.* 1999 *MNRAS* **308** 405.
Charbonneau P *et al.* 1999 *Astrophys. J.* **527** 445.
Christensen-Dalsgaard J 2002 *Rev. Mod. Phys.* **74** 1073.
Christensen-Dalsgaard J *et al.* 1991 *Astrophys. J.* **378** 413.
Christensen-Dalsgaard J *et al.* 1993 *Astrophys. J.* **403** L75.
Claverie A *et al.* 1979 *Nature* **282** 591.
De Moortel I and Hood A W 2003 *Astron. Astrophys.* **408** 755.
Deubner F-L 1975 *Astron. Astrophys.* **44** 371.
Duvall T L Jr *et al.* 1997 *Solar Phys.* **170** 63.
Elliott J R and Kosovichev A G 1998 *Astrophys. J.* **500** L199.
Gough D O 1977 in *Proc. IAU Colloq. No. 36* eds R M Bonnet and P Delache (G de Bussac, Clermont-Ferrand) 3.
Gough D O 1985 *Solar Phys.* **100** 65.
Gough D 1996 Lect. *Notes in Earth Sci.* **63** 1.
Howard R and LaBonte B J 1980 *Astrophys. J.* **239** L33.
Haber D A *et al.* 2002 *Astrophys. J.* **570** 855.
Howe R *et al.* 2000a *Astrophys. J.* **533** L163.
Howe R *et al.* 2000b *Science* **287** 2456.
Kosovichev A G 1996a *Astrophys. J.* **461** L55.
Kosovichev A G 1996b *Astrophys. J.* **469** L61.
Kosovichev A G *et al.* 1992 *MNRAS* **259** 536.
Kosovichev A G *et al.* 2000 *Solar Phys.* **192** 159.
Leibacher J and Stein R F 1971 *Astrophys. Lett.* **7** 191.
Leighton R B *et al.* 1962 *Astrophys. J.* **135** 474.
Lindsey C and Braun D C 2000 *Science* **287** 1799.
Nakariakov V M and Ofman L 2001 *Astron. Astrophys.* **372** L53.
Schou J *et al.* 1998 *Astrophys. J.* **505** 390.
Spiegel E A and Zahn J-P 1992 *Astron. Astrophys.* **265** 106.
Thévenin F *et al.* 2002 *Astron. Astrophys.* **392** L9.
Thompson M J *et al.* 2003 *Ann. Rev. Astron. Astrophys.* **41** 599.
Toomre J 2003 in *Stellar Astrophysical Fluid Dynamics* eds M J Thompson and J Christensen-Dalsgaard (Cambridge Univ. Press) 299.
Ulrich R K 1970 *Astrophys. J.* **162** 993.
Ulrich R K and Rhodes E J 1977 *Astrophys. J.* **218** 521.
Vorontsov S V *et al.* 2002 *Science* **296** 101.
Zhao J *et al.* 2001 *Astrophys. J.* **557** 384.