HELIOSEISMOLOGY

Observation and analysis of the vibrations of the Sun allow us to probe its interior structure and dynamics to test and expand our understanding of physics and astrophysics.

John Harvey

What powers the Sun? Why does it have spots? How long will it sustain life on Earth? Efforts to answer these questions about the astrophysical object that is of greatest importance to humanity have produced many advances in physics and helped lay the main foundations of astrophysics. The three questions, however, remain to be answered. For example, the best models of the Sun's nuclear power predict a significantly higher neutrino flux than is observed. (See PHYSICS TODAY April, page 19.) We do not know what causes sunspots and other solar activity or even why the Sun emits x rays. Modeling how stars evolve leads to age estimates for some stars that are greater than recent estimates of the age of the universe.

Until recently, it seemed impossible to resolve these problems by studying the 99.85 percent of the Solar System's mass that is contained within the Sun. The material inside the Sun is so opaque to electromagnetic radiation that it takes 170 000 years for a photon emitted at the core to diffuse outward to where it can escape to space. However, the Sun is nearly transparent to neutrinos and to wave motions. Its transparency to neutrinos is the basis of a celebrated experiment started a quarter-century ago, and new experiments have allowed us to observe a few thousand solar neutrinos and to probe the source of the Sun's power.[1] The Sun's transparency to wave motions is the basis of helioseismology—a powerful new tool for studying the solar interior and addressing fundamental questions about the Sun, stars and the properties of matter.[2] The two techniques have proved so far to be complementary: Solar neutrino experiments have provided unique information about the energy-generating core while helioseismology has provided information about the rest of the Sun. Both techniques have produced many surprises and puzzles.

Simple periodic oscillations of stars have been observed since 1784. That the Sun might be oscillating in a more complicated way was not appreciated until 1960, when physicist Robert Leighton discovered that the solar surface oscillated radially with a period of about five minutes, with a small spatial scale and an amplitude of several hundred meters per second. (See figure 1.) This discovery was initially explained as a local response of the atmosphere to convection immediately below the visible surface. In 1968 Edward Frazier demonstrated that a spatial–temporal spectral analysis of the oscillations was not consistent with the prevailing explanation and that the oscillations most likely originated beneath the surface. This clue led University of California at Los Angeles astronomer Roger Ulrich and, independently, John Leibacher and Robert Stein, to consider acoustic waves trapped in a subsurface resonant cavity as the cause of the oscillations. Ulrich predicted that a specific pattern of wavenumber and frequency ought to be observed. In 1975 Franz Deubner succeeded in clearly observing the predicted pattern. Discrepancies with predictions quickly showed that the contemporary models of the Sun were not correct. These first results marked the birth of helioseismology, which has since thrived. The third decade of helioseismology is starting with a new generation of instruments and projects that will yield more advances in our knowledge of how the Sun works.

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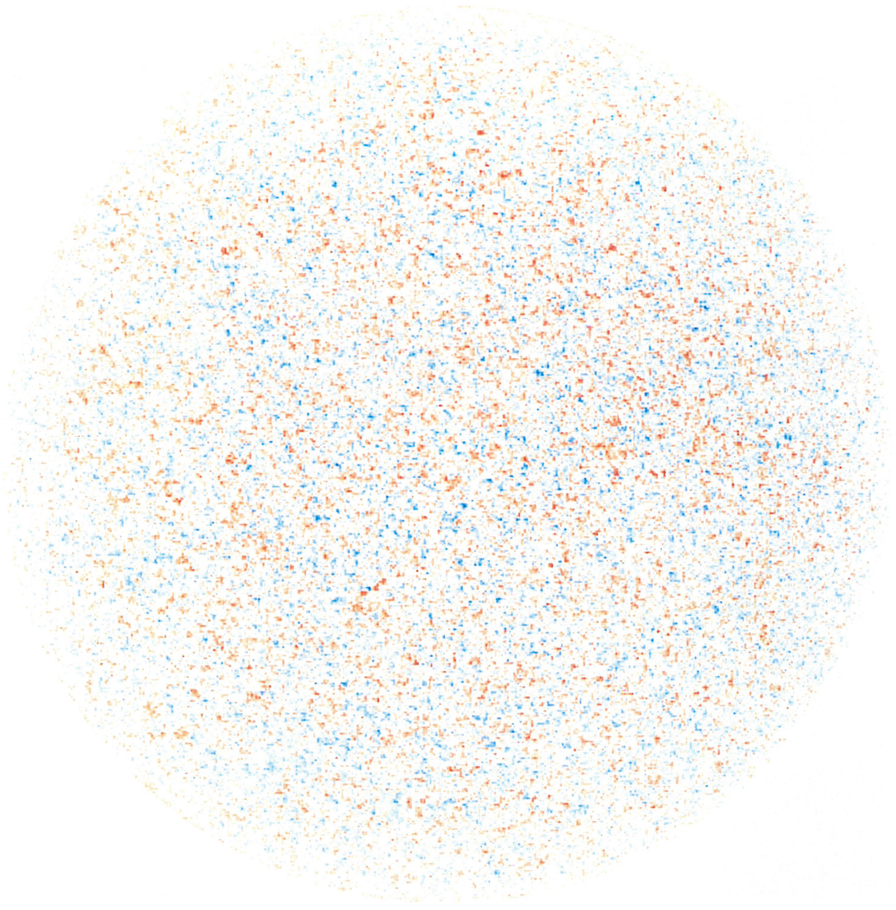
Basics of solar structure

The Sun is larger and brighter than an average star but otherwise appears to be normal. Our understanding of its interior is based on physical models that use specified initial and boundary conditions and equations describing force and energy balance and the behavior of matter at various temperatures and pressures. Many approximations are made, but if they are widely agreed upon, a model is called a "standard" model.[3] The theory of stellar structure and evolution is a principal foundation of astrophysics and of much of our current understanding of the universe.

According to standard solar models, the Sun is a sphere of radius $R_\odot$ initially composed by mass of about 70% hydrogen, 28% helium and 2% heavier elements. It is in equilibrium between gravitational contraction and expansion from the heat produced by nuclear reactions in its core. About half of the mass and 98% of the energy generation reside in a core with a radius of about 0.25 $R_\odot$. The central temperature is about 15.8 million kelvin and the central density is about 1.56×10^5 kilograms per cubic meter. Overlying the core is a stable, "radiative zone" where energy diffuses outward and stratification is governed by the opacity of matter to the passage of radiation. By a radius of 0.713 $R_\odot$, the temperature has dropped to about 2 MK and highly ionized atoms begin to capture electrons with a resulting strong increase of opacity. The increased opacity initiates a "convection zone" reaching nearly to the surface. Within this zone thermal convection is the dominant energy transport mechanism. Stratification in the convection zone is nearly adiabatic, until a rapid drop of density and temperature just beneath the visible surface produces a thin superadiabatic layer. The atmosphere and extended heliosphere above the surface



SOLAR OSCILLATIONS visualized by subtracting two images of the Sun taken two minutes apart. Red and blue patches have heated and cooled, respectively, in response to acoustic vibrations of the interior. The images were obtained at the South Pole on 2 January 1991 as part of an NSF-supported helioseismological observing campaign by astronomers from the Bartol Research Institute, the National Solar Observatory and NASA. FIGURE 1

are the sites of many amazing and poorly understood phenomena, including the greatest explosions in the Solar System. Although important to Earth, the atmosphere and heliosphere constitute a trivial amount of the solar mass and have an almost negligible effect on solar interior models.

Standard models ignore the effects of the Sun's 27-day rotation and its intricate patterns of magnetic fields. The models use many other approximations in an effort to capture the essential characteristics with a minimum of complication. Despite their shortcomings, models of the Sun and stars are extremely successful triumphs of 20th-century physics and astrophysics. But are the models really correct? A major goal of helioseismology is to answer this question.

Basics of helioseismology

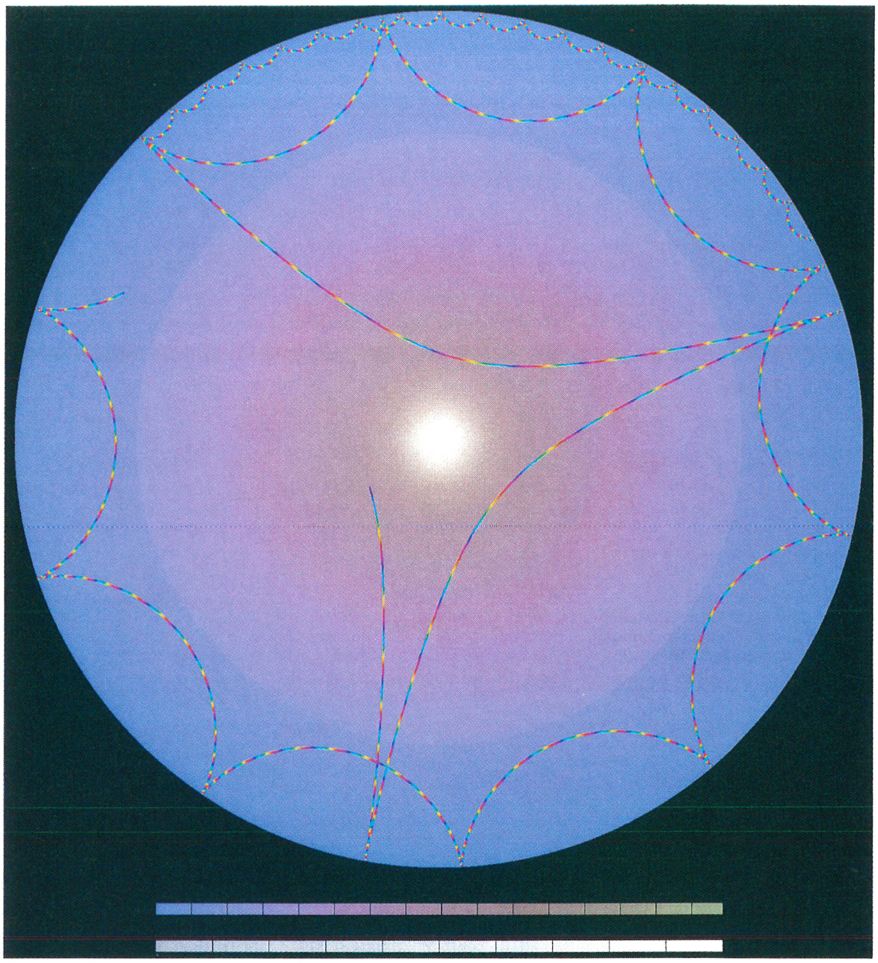
Helioseismology is possible because wave motions are excited and can propagate in the Sun, and because the motions can be observed at the surface. Three types of waves are sought: acoustic waves for which pressure is the restoring force, internal gravity waves restored by buoyancy, and surface gravity waves. Resonant cavities within the Sun constructively organize acoustic, internal gravity and surface gravity waves into standing wave patterns named p, g and f modes, respectively. An astounding number of solar modes are possible—about 10^7 p and f modes alone. Both standing wave patterns and propagating waves are used for helioseismology.

The propagation of waves within the Sun is described by a relation between the displacement of matter and restoring forces. It is frequently assumed that the wave motions are linear (because of their small amplitudes) and adiabatic, and that the wavelength is small compared to the scale over which solar structure changes. These are reasonable assumptions except close to the Sun's surface.

Equipped with the basic equations and a model of the Sun, there are two main analyses used in helioseismology. The first is a study of the normal modes of the Sun's vibrations. Acoustic waves may be trapped in a region bounded on top by the large drop in density near the surface, and on the bottom by an increase in sound speed that refracts a downward propagating wave back toward the surface. (See figure 2.) The radial dependence of a standing wave is characterized by n, its number of radial nodes. If the wave motions are long-lived enough to travel around the solar circumference, standing wave patterns are also formed in longitude and latitude and are characterized by spherical harmonic degree l, and azimuthal order m.

A standing wave mode thus samples conditions within a spatially well-defined cavity and its frequency is sensitive to average conditions within the cavity. Even if the waves are too short-lived to travel coherently around the solar circumference, they are frequently analyzed in terms of spherical harmonics as if they were global normal modes. Deep cavities have a small value of l/ν, where ν is the cyclic frequency. Internal gravity waves are expected to be principally confined beneath the convection zone, and only a feeble surface effect would be observable. There is no consensus that g modes have been observed. (See PHYSICS TODAY, September, p. 19.) Current helioseismological results come from analyses of p and f modes and propagating acoustic waves.

The second helioseismology technique is ray tracing of acoustic waves. An acoustic wave of a specified frequency propagates inward, is turned around by refraction and reaches the surface at a distance Δ from its origin after a time t. The relation between Δ and t is sensitive to conditions along the ray path. Since the Sun does not have discrete quakes akin to those on Earth, the solar analysis is based on statistical correlations between oscil-



RAY PATHS OF ACOUSTIC WAVES inside a model of the Sun. Paths are shown for waves of 3-mHz frequency, starting downward from near the surface at three different initial angles. The ray paths are bent as the sound speed increases with depth. As they approach the surface, they are reflected back inward by the strong density gradient. Along each ray path the colors repeat once per wavelength. Color assigned to the solar model corresponds to temperature as shown on the scale below, with the color at the far right corresponding to 15.8×10^6 K and that at left to 0 K. The brightness in the core is proportional to the energy-generation rate. The brightness transition at 0.713 $R_\odot$ represents the boundary between the region where energy is transported by radiation and that where it is transported primarily by convection. (Ray-path calculations courtesy of Sydney D'Silva.) FIGURE 2

lations observed at a point and in an annulus at some distance from the point.

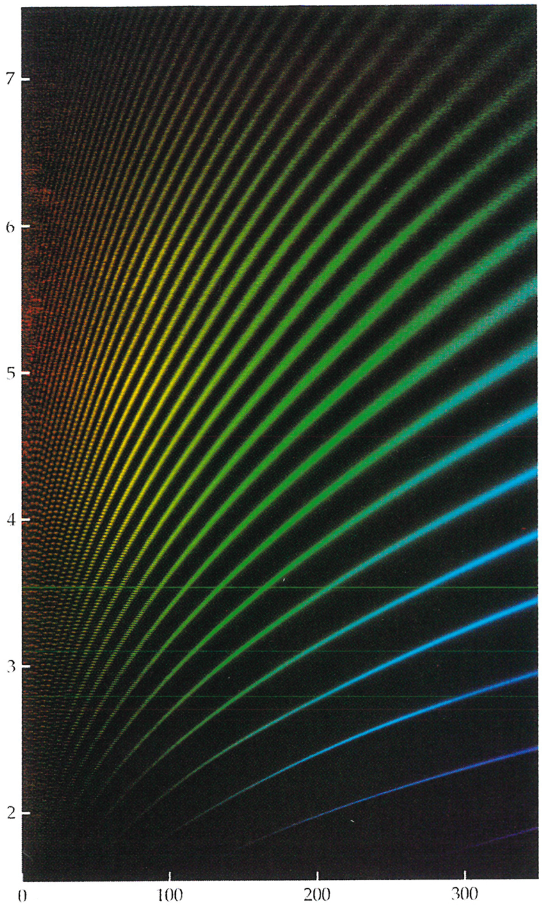
Both forward and inverse analyses are used. In a forward analysis a solar model is specified and used to compute some property of the oscillations, such as frequencies. The model is varied slightly to produce a family of predicted values. The model that best matches the observations is then considered to best define the varied parameter. An inverse analysis starts with an observed property of the oscillations and then determines a function of position that is most consistent with the integrals of the function to which the observed properties are sensitive.

Observational helioseismology

Solar oscillations eluded detection for centuries because the amplitudes of the oscillations are small. They were first seen as Doppler shifts of spectrum lines, and this is still the principal way they are observed. A typical visible solar spectrum line has a wavelength of about 600 nanometers and a width of about 10 picometers. A velocity of 1 meter per second shifts the line about 0.002 pm. Individual oscillation modes have amplitudes of no more than about 0.1 $m\ s^{-1}$, so the observational task is to measure shifts of a spectrum line to an accuracy of parts per million of its width. This requires high signal-to-noise ratios and great stability. At spherical harmonic degrees above four, differential methods can be used because the oscillation patterns have considerable spatial structure that averages out across the solar disk and, to first order, instrumental drifts cancel out. This cancellation cannot be used to observe low-degree modes, and stability is crucial in this case.

An early and powerful way to observe Doppler shifts uses an atomic vapor as a spectrometer.[4] Polarized sunlight is sent into a heated potassium or sodium vapor in a strong magnetic field. The Zeeman effect on the ground state resonance lines of sodium or potassium acts so that, with appropriate vapor optical depth and magnetic field strength, light is scattered at two narrow wavelength ranges in the red and blue wings of the corresponding solar spectrum line. The polarization state is changed to switch from one wing to the other. The relative intensity of the light from the two wings is a measure of the Doppler shift of the solar spectrum line with respect to the laboratory. This principle is also used to build magneto-optical filters with which images of the Sun in the two wings of the spectrum line can be produced, recorded and analyzed.[5]

However, few spectrum lines may be used with atomic resonance line filters, and it is difficult to obtain a linear response to Doppler shift. Other filter systems have been developed that trade stability, speed or signal-to-noise ratio for flexibility and linearity. A popular current technique combines a narrow-band interference filter with birefringent polarizing filter elements to isolate a single solar spectrum line within a fixed transmission band that is a few line widths wide. Following that are one or two tunable Michelson interferometer elements. These inter-



POWER SPECTRUM OF SOLAR OSCILLATIONS computed from three weeks of nearly continuous observations made at the South Pole. The bright curves are power enhancements produced by standing acoustic wave patterns with 0 (lower right) to 40 (upper left) radial nodes in the vertical component of the velocity beneath the surface. When the modes are globally coherent, the curves break up into individually resolved spectral features (lower left). Warm and cool colors represent deep- and shallow-penetrating modes, respectively. The power levels in the original spectrum cover four decades. This range has been reduced in the figure by a combination of local background subtraction and peak normalization. FIGURE 3

ferometers are tuned to generate a time sequence of images from which the Doppler shift of the spectrum line can be calculated at each element of the image.[6]

Another way to measure solar oscillations makes use of changes in the surface brightness that accompany the up-and-down motion of the solar matter. Individual oscillation modes have brightness change amplitudes of less than a few parts per million. As a result it is difficult to observe low-degree modes from inside Earth's atmosphere, but such measurements have been made from space. At higher degrees the differential nature of the measurement allows ground-based equipment to work well.[7]

The frequency with which observations must be made for helioseismology should be twice the highest frequency of the oscillations. Solar models show that waves with frequencies above about 5.5 millihertz are not trapped and so should not be seen—requiring an observing frequency of at least 11 mHz. In light of these considerations, the observation of modelike oscillations with frequencies as high as 10 mHz was surprising. They appear to be caused by interference between outward propagating waves and waves that pass once through the Sun's interior.[8] High-frequency oscillations are weak, so the requirement of an observing frequency of 20 mHz is often relaxed to the convenient value of 16 2/3 mHz (period = 1 minute).

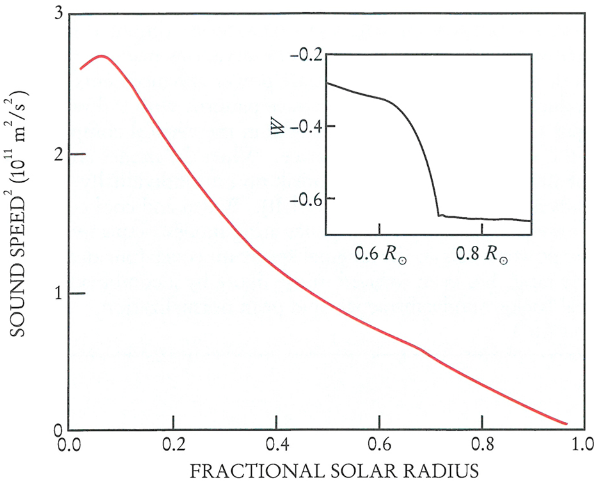
A major goal of observational helioseismology is the accurate measurement of the frequencies, amplitudes and line shapes of oscillation modes. Because the oscillation spectrum is rich and crowded, and the coherence time of the modes ranges from hours to months, great effort has been devoted to improving the duration and duty cycle of observations to make possible better measurements. Increasing duration improves frequency resolution and, for resolved spectral features, signal-to-noise ratio, in part by reducing the level of spurious spectral features caused by gaps in the data. A typical single observing site has a duty cycle of about 30% because of nights and weather. Seasonal variations tend to limit the good-quality observations to a few months of the year. One way to improve the duty cycle is to observe from the geographic South Pole during the local summer. Last season, helioseismological observations were made there for 65 days at a duty cycle of about 75%. This performance is about the practical limit for ground-based observations at a single site. To do better, we have to go to space or build networks of ground-based instruments. Both of these strategies are major focuses of current observational helioseismology.

Reducing a series of Doppler-shift or intensity images to a normal-mode spectrum is straightforward but tedious because an enormous quantity of data is involved. Images are first decomposed into spatial spherical harmonics. Time series of these coefficients are then Fourier transformed into frequency spectra. The final result is a power spectrum of three variables: ν, l and m. The frequencies of modes with different values of m but the same values of l and n are nearly degenerate. For many purposes, therefore, the small m-dependent frequency splitting is determined and removed. The frequency-corrected spectra are then averaged over the range of m states to produce an l–ν spectrum of the sort shown in figure 3.

Surprises inside the Sun

A few months after Deubner's first measurements of p-mode frequencies in 1975, Douglas Gough showed that discrepancies with model predictions could be substantially reduced by increasing the depth of the convection zone in standard models by about 50%. This first result from helioseismology started a flood, as observers and theoreticians improved and exploited the new techniques. When measurements of the low-degree p modes that penetrate the solar core became available, models of the Sun having low helium abundance in the core (constructed to solve the solar neutrino problem) were found to be inconsistent with observations. As measurements improved in quality and quantity, it became clear that the standard models could not simply be fudged to fit. The discrepancies between models and observations constitute a solar model problem similar to the solar neutrino problem. The absolute size of discrepancies has been steadily reduced by model improvements, but observations have also improved so that significant relative discrepancies still remain.

A big clue to the model problem came from the first



SQUARED SOUND SPEED INSIDE THE SUN derived by inverting measurements of oscillation frequencies. Consumption of the Sun's hydrogen fuel causes the dip near the center. The inset shows the weighted derivative of the squared sound speed, *W*, which changes abruptly at the base of the convection zone.[11] FIGURE 4

inversion of *c(r)*, the sound speed as a function of depth.[9] To first order, the frequency of a p mode is inversely proportional to an integral of $c^{-1}(r)$ over the depth of the mode's cavity. The top of the mode's cavity is near the surface of the Sun, and the bottom depends on the local sound speed and the *l* value of the mode. This is a classic Abel's integral equation problem, whose solution produces *c(r)* without reference to a solar model. Early results persistently showed that, between 0.3 $R_\odot$ and 0.5 $R_\odot$, the sound speed was higher in the real Sun than in models. This finding implied that the opacity used in models was too low for a range of intermediate temperatures. Investigations of the basic calculations of opacity of matter led to substantial improvements that not only greatly reduced the solar model problem, but also helped solve several other problems in astrophysics.[10]

The derivative of $c^2(r)$ is not constant, particularly at a radius of about 0.7 $R_\odot$. (See the inset to figure 4.) Important results have come from analysis of this derivative. If the material in the interior behaved like a perfect gas in adiabatic hydrostatic equilibrium, the quantity

$$W = \frac{r^2}{Gm}\frac{dc^2}{dr}$$

where m is the mass interior to r, would equal $-\frac{2}{3}$. Measurement of W allows one to assess departures from these assumptions. One result is that most of the convection zone is indeed adiabatically stratified, as had been expected. The slope change at 0.7 $R_\odot$ signals the bottom of the convection zone, beneath which stratification is no longer adiabatic. The best current estimate of the base location is 0.713 ± 0.003 $R_\odot$, a value that now tightly constrains solar models.[11] Further study suggests that the boundary between the convection and radiative zones (thought to be the seat of the solar activity cycle) is thinner than 0.04 $R_\odot$. W is sensitive to changes in the equation of state resulting from the ionization of elements within the convection zone. This sensitivity can be used to determine the abundance of helium within the convection zone, with the uncertainty due in part to uncertainties in the equation of state. As the accuracy of helioseismological data improves, sensitive tests of different formulations of the equation of state should be possible. Current determinations of the mass abundance of helium in the convection zone are between 0.23 and 0.26. Standard solar models and Big-Bang cosmology require a larger, primordial value of about 0.28. This discrepancy was solved by adding gravitational settling and diffusion of helium and heavier elements to models as the second major improvement to the solar model problem.

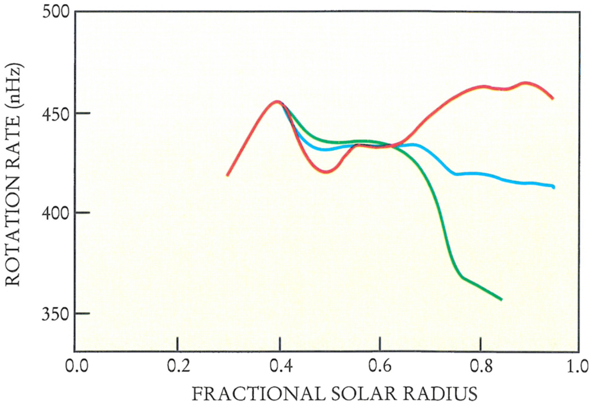
Unfortunately, current data are not accurate enough to do inversions all the way into the energy-generating core. Different data sets and different treatments give conflicting results,[12] leaving unresolved such issues as whether material in the core has mixed—an effect not considered in standard solar models. If mixing occurred or is occurring, the evolution of the Sun would be different than is currently believed. Current data are also inadequate to study the possibility that *c(r)* varies with latitude, longitude or time. The next improvement in the solar model problem may be inclusion of the effects of momentum transfer by convection near the surface. Recent results show that model discrepancies are reduced by including this effect. Including such effects opens the prospect of testing various models of convection—long a weak area of stellar modeling.

Oscillation frequencies are altered by rotation. For the case of p modes, the shift in frequency is proportional to the azimuthal order, m, and a weighted average of the rotation over the depth and latitude of the confining cavity. The surface rotation has long been known to decrease with increasing latitude. (See figure 5.) Models constructed to explain this differential rotation produced internal rotation profiles constant on cylindrical surfaces parallel to the rotation axis. An early result of helioseismology was an indication that the rotation rate in the vicinity of the equator unexpectedly increased with depth.[13] Later observations probed more deeply, at first along the equatorial region and then over a wide range of latitudes. The frequency shifts are tiny, about one-half microhertz per integer of m, so deep regions and high latitudes associated with small values of m are particularly difficult to measure. However, inversions of frequency shift measurements give two robust results. First, rotation throughout the convection zone is similar to that at the surface, contrary to expectations. Second, the outer part of the radiative zone appears to rotate at a constant, intermediate rate.[14] The resulting shear may hold the key to the origin of the 11-year cycle of solar activity, but there is no theoretical explanation for this kind of rotation. This is the solar rotation problem.

Evolutionary models suggest that much of the angular momentum of the gas cloud that contracted to form the Sun was shed by transfer to the solar wind. However, models also show that the core should have retained most of its original angular momentum. Is this the case? A very rapidly spinning core seems excluded by current helioseismological results. Whether it is spinning faster than the overlying layers is an unsettled issue. The latest results surprisingly indicate that it may even be the most slowly rotating part of the sun.[15] If the core does not harbor much angular momentum, the questions of how and where the angular momentum was shed add to the solar rotation problem.

P-mode frequencies change by about 1 part per thousand during the 11-year cycle of solar activity. This unexpected finding is now attributed to variations of

PROFILES OF INTERNAL SOLAR ROTATION at the equator (red), and averaged over both hemispheres at 45° (blue), and at 90° (green) were derived by inverting frequency splitting measurements from three different instruments. The rotation rate at the surface and in the convection zone vary as a function of latitude in a similar manner. Deeper inside, the rotation becomes nearly uniform. Rotation profiles at high latitudes, below 0.5 $R_\odot$, and just beneath the surface are currently not well determined. FIGURE 5



temperature and magnetic field strength at the surface. Current evidence for deeper-seated changes that might give clues to the origin of solar activity is tantalizing but weak at best.

Analyses of the frequency profiles of mode spectra, and observations of propagating waves, have confirmed theoretical ideas that acoustic oscillations are excited about 200 km beneath the surface. The cause may be acoustic noise generated in the wakes of cool, supersonic, downdrafting plumes created in the violent convection near the solar surface. Oscillations appear to be damped in several ways. Much of the oscillation energy is converted to radiation that escapes from the surface. Some of the energy propagates into the atmosphere and is lost by coupling with other types of wave motion. Another factor is probably scattering of modal oscillations by local inhomogeneities into small-scale propagating waves.

Helioseismology of local inhomogeneities such as sunspots and active regions is in its infancy.[16] The first result is that sunspots efficiently scatter incoming acoustic waves having spatial properties matched to the dimensions of the spots. These studies, and ray-tracing work, suggest that sunspots are acoustically quite shallow phenomena. Maps of oscillation power at the surface show poorly understood frequency-related variations in the magnetic regions around sunspots. The first maps of variations of the travel time between surface reflections of waves that penetrate to different depths have recently been made (see figure 6). Intriguing patterns suggest that large-scale magnetic, temperature and velocity structures may lie beneath active regions.

New projects and prospects

The first two decades of helioseismology have been dominated by observations from single sites using instruments often designed for other purposes and not optimized for helioseismology. Furthermore the observations have often been sporadic campaigns rather than continuous, well-controlled efforts. After more than a decade of preparations, 1995 is a banner year for helioseismological observations. This winter brings the launch of the Solar and Heliospheric Observatory (SOHO), a European Space Agency project with major participation the National Aeronautics and Space Administration. The year has also seen operation of several ground-based networks of helioseismological instruments, particularly the start of the six-site network of the Global Oscillation Network Group (GONG) managed by the National Solar Observatory and supported by the National Science Foundation.

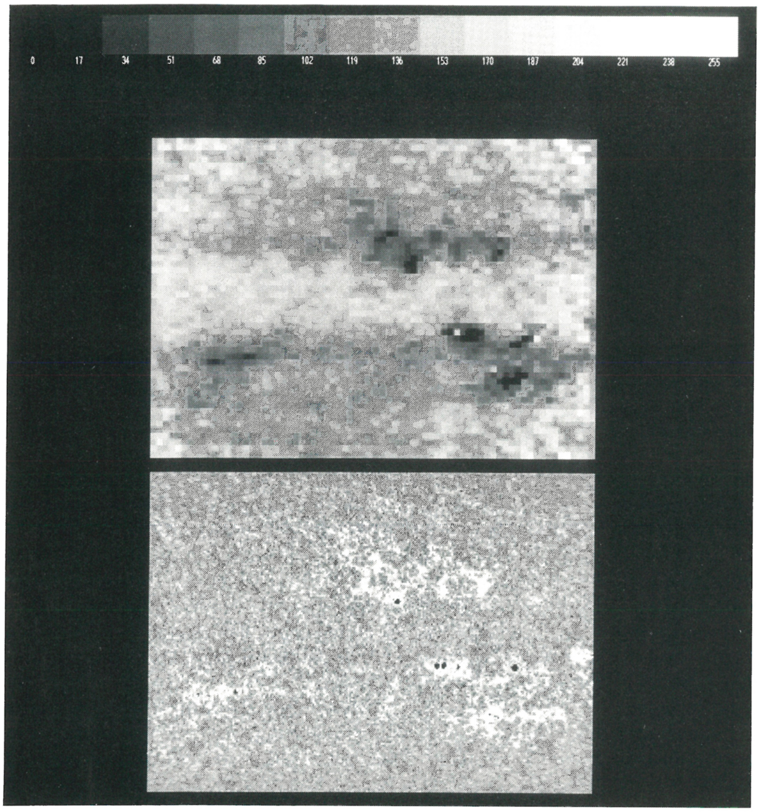
The SOHO spacecraft will be placed into an orbit circling the L_1 Lagrangian point, between the Sun and Earth, for a nominal two-year mission. There are three helioseismological instruments on board: GOLF, an atomic resonance scattering spectrometer designed to observe spatially unresolved low-degree oscillations with great stability; VIRGO, a combination of absolute radiometers, spectral photometers and a low-spatial-resolution photometer designed to measure low-degree oscillations in light intensity, free from the disturbing influences of Earth's atmosphere; and SOI, a Michelson interferometer Doppler imager that will make Doppler velocity images using a million-pixel charge-coupled device camera with sustained and stable high angular resolution that is impossible to obtain on Earth.[17]

Two spatially nonresolving ground-based networks have been operating for several years. The Birmingham Solar Oscillation Network (BISON), a UK project started in 1981, employs resonance scattering spectrometers with the 770-nm potassium line at six sites. The second network is a French-led project, International Research on the Interior of the Sun (IRIS), which reached its full deployment of six instruments in 1994. IRIS uses sodium resonance scattering spectrometers.

Three ground-based networks of imaging helioseismological instruments are in various stages of development. The first to deploy multiple instruments is the Taiwan Oscillation Network (TON), started in 1993. It produces intensity images using million-pixel CCD cameras. Three stations are currently operating, with eventual plans for six. The GONG project is an effort involving the entire helioseismological community and is currently scheduled to run continuously at six sites through the end of 1998. GONG produces Michelson interferometer Doppler images that resolve all the p modes having global extent. If the results continue to be as exciting as the initial results have been, it is hoped to upgrade the resolution of the GONG instruments and continue operations long enough to study the causes and effects of the 11-year cycle of solar activity. The third network is the High-Degree Helioseismology Network (HDHN) led by the University of Southern California. Its plans are to install Doppler-imaging magneto-optical filter instruments in Ukraine and Kazakhstan to complement an instrument already operating in California. Deployment is planned for 1995, with plans to reach million-pixel resolution by the middle of 1996. Operation is scheduled for several months each year.[18]

The major space and ground projects nicely complement each other, particularly since there is enough overlap in observing capabilities to detect systematic errors and fill in time gaps. In addition to the major projects, there are several single-site instruments in operation that fill niches in observational capabilities not addressed by the major projects.

What are the prospects for helioseismology? The advent of projects specifically designed to do helioseismol-



MAP OF SOUND-WAVE TRAVEL TIME VARIATIONS computed by repeated cross correlation of oscillations at a point with oscillations averaged in an annulus a fixed distance away. The lower panel shows corresponding surface features. Dark patches in the upper panel are areas of locally shorter travel times. The horizontal and vertical axes are longitude and sine latitude, respectively, with the equator in the middle. Faint, dark zonal bands at intermediate latitudes in both hemispheres, imaged here for the first time, may be subsurface regions of temperature or magnetic field perturbations. (Courtesy of Tom Duvall Jr) FIGURE 6

ogy puts us on the threshold of a golden age for increased understanding of how stars work. We can expect the global properties of the Sun, such as its structure and rotation, to be much better defined in the next few years. Tight limits will be placed on how these characteristics change with time, particularly as a result of the solar activity cycle. This information will help us to understand what causes the solar activity and variability that is so important to human activities. Combined with results from the new neutrino detectors, it should be possible to finally solve the solar neutrino problem. Local helioseismology will become a powerful tool for studying inhomogeneous properties of the Sun.

There is tantalizing evidence that asteroseismology of other Sun-like stars may be possible. (See PHYSICS TODAY, May 1995, p. 19.) Such an advance would make possible additional tests of the theory of stellar structure and evolution and also check whether the Sun is anomalous. If the long-sought solar g modes can be detected and measured, the solar core could be probed much more accurately than is possible with p modes. The forthcoming results from helioseismology make this an exciting time for solar physics, astrophysics and physics.

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