# Perspectives in Helioseismology

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Helioseismology is probing the interior structure and dynamics of the sun with ever-increasing precision, providing a well-calibrated laboratory in which physical processes can be studied under conditions that are unattainable on Earth. Nearly 10 million resonant modes of oscillation are observable in the solar atmosphere, and their frequencies need to be known with great accuracy in order to gauge the sun's interior. The advent of nearly continuous imaged observations from the complementary ground-based Global Oscillation Network Group (GONG) observatories and the space-based Solar and Heliospheric Observatory instruments augurs a new era of discovery. The flow of early results from GONG resolves some issues and raises a number of theoretical questions whose answers are required for understanding how a seemingly ordinary star actually operates.

Helioseismology has caused an explosion of interest and opportunity in solar and stellar physics. Almost 20 years ago, at the General Assembly of the International Astronomical Union in Grenoble, France, there was widespread incredulity that even the crudest of information about the internal structure of the sun would ever be obtained through seismology. Yet now the sound speed is known throughout much of the solar interior to a precision of about 0.1%, and the density and pressure are known to about 1% (*1*).

Why should one wish to measure the internal structure of a star? Aside from sheer curiosity, there is the intellectual challenge of overcoming a hurdle that the rest of the scientific community has considered to be insuperable. But there is little scientific reason for determining, for example, the density at the center of the sun to extremely high precision. There is, however, good reason for determining the manner in which that density varies through the sun and how it is related to other quantities, for then one might ask why those quantities are so related and thereby raise questions of importance to physics and astronomy.

A case in point was the discovery, with the use of seismology, that the variation of sound speed, and probably temperature, immediately beneath the convection zone was incompatible with the equations that govern the transport of energy (*2*). It appeared that the values of opacity commonly in use for stellar modeling were up to 20% too low at temperatures between about $2 \times 10^6$ and $4 \times 10^6$ K. Because the conditions under which the discrepancy occurred had been so narrowly specified, it was possible to check the calculations, and an error in their formulation was found (*3*). Thus, the sun had been used as a laboratory to measure a physical quantity under conditions that cannot be achieved in a controlled state on Earth. Moreover, there were important ramifications elsewhere in astrophysics, which improved aspects of theories about various kinds of pulsating stars, such as reconciliation of the structure of double-mode Cepheids with stellar evolution and explanation of the excitation of β Cephei pulsations and the slowly pulsating B stars (*4*).

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## Properties of Seismic Waves

Although the sun is opaque to radiation, it is transparent to mechanical seismic waves. These waves are stochastically excited in the turbulent subsurface convective boundary layer. They propagate through the solar interior, and in so doing they are shaped by the properties of the material through which they travel. Thus, when their signatures are determined by measurement of the motion of the atmosphere, which is a reaction to the impulses received as the waves are reflected near the solar surface, information is gathered that relates to the entire region through which the waves have traveled. Different waves sample different regions of the solar interior and therefore provide different information. Unraveling that information in order to present it in a digestible form is a major step in the process of inference.

For example, consider the paths of two acoustic waves (Fig. 1A) that are believed to be generated by the turbulence in the outermost layers of the convection zone. To a first approximation, the paths lie in a plane through the center of the sun. They differ principally by the angle at which they are reflected at the surface. Waves inclined relatively far from the vertical are rapidly refracted by the rising sound speed with depth and soon return to the surface. Those that are more nearly vertical penetrate more deeply. However, only waves that travel exactly in the vertical direction succeed in reaching the center. Because there are only a few such waves, information about the center of the sun, where the interesting nuclear reactions take place, is difficult to obtain.

There is another reason why it is difficult to obtain information about the sun's central core from acoustic waves. The amount by which the properties of a wave are influenced by a given region is proportional to the time the wave spends in that region. In the hot central regions, the sound speed is relatively high, so the influence on the wave is small. Therefore, in order to infer properties of the core, extremely precise measurements of the wave properties must be made. This entails long continuous observations. The situation is rather different from that on Earth, because the speed of seismic waves in the Earth does not increase dramatically with depth.

Internal gravity waves depend on negative buoyancy to provide the restoring force, and therefore, unlike acoustic waves, they cannot propagate through the convection zone. Consequently, only a slight vestige of a gravity wave reaches the surface, making it difficult to detect. Indeed, no internal gravity wave has yet been unambiguously seen. Gravity waves are potentially valuable diagnostic tools, however, because (as is evident from Fig. 1B) they penetrate to the center of the sun. Moreover, in contrast to acoustic waves, their properties are most strongly influenced by the central regions. It is therefore of the utmost importance to try to detect and measure these waves.

The response of the photosphere to the superposition of all the seismic waves resembles motions at the surface of the ocean. One of the ways of analyzing the motion is to decompose the wave field into normal

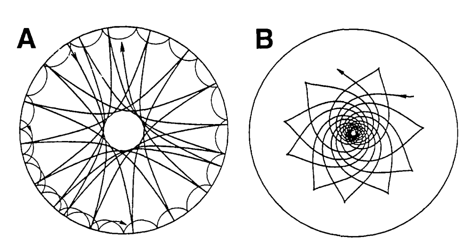


**Fig. 1.** (**A**) Ray paths within the sun for two acoustic waves, with the shallower wave of degree $\ell = 100$ and order $n = 8$ and the more deeply penetrating wave with $\ell = 2$ and $n = 8$. The path of an internal gravity wave, which is confined to the deeper interior, is shown in (**B**) for $\ell = 5$ and $n = 10$.

modes by projection onto theoretical eigenfunctions, the spatial variation of each of which is approximately proportional to a spherical harmonic (Fig. 2). Spherical harmonics are identified by their degree, $\ell$, which is an integer characterizing the total horizontal wave number; and by the azimuthal order, $m$, which is also an integer and is a measure of the component of $\ell$ in the direction of varying longitude. The temporal variation of the projection coefficients is then Fourier-analyzed to reveal a discrete set of frequencies, each corresponding to an overtone labeled with an integer $n$, called the order of the mode, associated with different radial variation of the eigenfunction of oscillation such that frequency $\nu$ increases with $n$.

Because the projection does not cover the entire solar surface, the spherical harmonics are not orthogonal, and consequently there is contamination of the signal from neighboring spherical harmonics. Those contaminating modes have different temporal frequencies, and therefore, in principle, their influence might be removed in the temporal domain. Such removal requires that continuous data be gathered over a long period of time to provide accurate, sharp power spectra with essentially no temporal sidelobes. It was to satisfy this requirement that the Global Oscillation Network Group (GONG) observatories were set up.

## Observation of Seismic Waves

Observation of solar oscillations is a challenging task. The velocity amplitude of a typical acoustic ($p$) mode is on the order of 1 cm $s^{-1}$, with an associated relative brightness variation of about $10^{-7}$; and the theoretically predicted amplitudes of gravity ($g$) modes are at least 10 times smaller. The oscillations are recorded by measurement either of the Doppler shift of a spectrum line or of the intensity of the optical radiation. The measurements must be made over a long period of time in order to determine oscillation frequencies to the high precision that is necessary for making useful inferences about the solar interior; and they also must be uninterrupted, because gaps in the data produce confusing spurious peaks in the oscillation power spectrum, which hinder subsequent analysis. The first attempts to obtain such observations were made at the South Pole during the austral summer (5); later, data from several midlatitude sites were combined. But those observations were spatially unresolved, combining light from the entire visible surface of the sun as though it were a distant star, which limited detectability to only those few modes of oscillation whose wavelengths are comparable with the diameter of the sun.

GONG consists of six identical Doppler imaging instruments, distributed around the Earth. It has been established with the support of the National Science Foundation in order to make almost continuous observations of a wide variety of modes of the sun. In addition, the European Space Agency (ESA) and NASA have recently launched the Solar and Heliospheric Observatory (SOHO) spacecraft, which carries (among other instruments) three different helioseismological experiments (6) to observe the sun continuously from a halo orbit near the sun-Earth Lagrangian point $L_1$ (7).

The ground-based GONG and space-based SOHO programs are complementary. From space, it is possible to observe with high spatial resolution, free from distortion by atmospheric turbulence, which is essential for studying dynamic processes in the solar convection zone. Moreover, global variations in intensity and Doppler velocity can be followed accurately to detect long-period gravity waves in the deep interior. The ground-based programs have the advantage of enabling one to study the oscillation modes from sites where instruments can readily be visited and upgraded, and such programs could last longer than a solar cycle, if so desired. The deployment of the GONG instruments was completed in October 1995; however, a network of three observatories has been operational since June 1995. SOHO was launched in December 1995 and began normal uninterrupted observations in April 1996.

Even as the large international GONG and SOHO projects proceed, there continues to be a need for complementary and correlative observations, some with a longer temporal baseline and some detecting oscillations at different heights in the solar atmosphere. Examples of the former are the Birmingham Solar Oscillation Network (BiSON) and International Research on the Interior of the Sun (IRIS), which view the sun as a star (8). Examples of the latter are the Doppler or intensity imaging being carried out by the Mount Wilson–Crimean–Kazakhstan mini-network, the low- and intermediate-degree experiment (LOWL) operated by the High Altitude Observatory, the high-degree helioseismometer (HDH) operated by the National Solar Observatory (NSO) at Kitt Peak, the Taiwanese Oscillations Network, and the continuing NSO–Bartol–NASA observations being made with HDH from the South Pole (9).

The articles following in this issue summarize the GONG project: how the data are being analyzed and what we know about the sun's internal structure and its angular velocity from the first GONG data. Not all the findings are new, but they are now much more robust, partly because they have been established from almost continuous data sets and partly because in every case several independent analyses have been carried out. An analysis of the state of the convection zone, for example, sheds light on the equation of state of the dense plasma. The inferred stratification of the radiative interior confirms that gravitational settling of helium and heavier elements has a substantial influence on the solar structure; however, the extent of the settling appears to have been overestimated in the theoretical models. This suggests the presence of a weak mixing layer immediately beneath the convection zone, in which motion is predicted to be driven by the rotational shear inferred to be present in the interfacial layer between the convective and radiative regions. Such mixing might explain the anomalously low abundance of lithium observed in the photosphere. There is also an unexplained region of rotational shear in the outer layers of the convection zone.

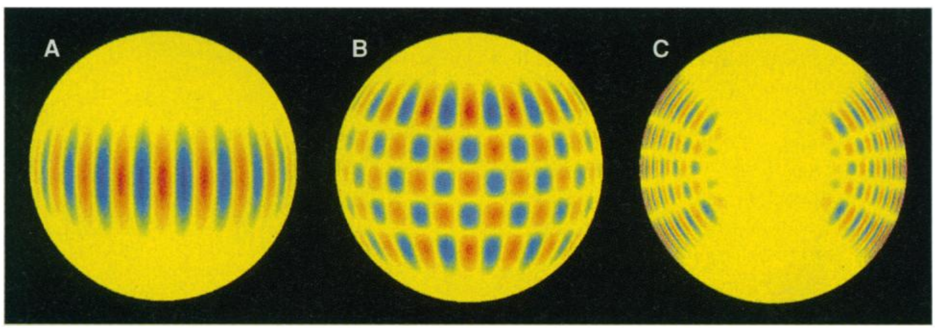

**Fig. 2.** Doppler velocities of solar $p$ modes, with red and blue denoting the line-of-sight component of velocity, which is primarily radial, as shown for modes of degree $\ell = 20$ on the solar disk in (**A**) for a sectoral mode with $m = 20$ and in (**B**) for a tesseral mode with $m = 16$. For the latter mode for order $n = 14$, (**C**) shows, in a cut along a meridional plane, the eigenfunction of the density perturbation, scaled so as to accentuate the amplitude in the deep interior, which would otherwise not be visible.

## Helioseismological Inferences

Early inversions determined the variation of sound speed with radius (2); subsequent, more refined inversions have provided the density and pressure as well. They have permitted an investigation of the pressure-density relation in the convective zone, particularly in and beneath the second ionization zone of helium where entropy is uniform. The original motivation was to determine the helium abundance, with the use of the deviation from the perfect-gas law produced by partial ionization (*10*). However, in the course of that investigation it was revealed that the equations of state for solar modeling were inadequate and that more sophisticated calculations that account for the influence of neighboring particles on atomic and ionic structure produced better models (*11*).

The outcome was even more improvement in the modeling. It came about because the helium abundance found in the convection zone was substantially lower than what was required in the radiative interior for reproduction of the observed luminosity, which drew attention to the importance of gravitational settling of helium and heavier elements (*12*). It is encouraging that explicit improvements in the physics yield solar models that, on the whole, agree more closely with the data. Yet the agreement is not perfect, and, as the following articles describe, the form of the residual discrepancies suggests the presence of interesting dynamic phenomena such as meridional circulation, shear-induced turbulent mixing, and mass loss in the course of solar evolution.

The sun's rotation is another issue to which helioseismologists have been able to devote attention. For decades, astrophysicists had argued over the extent to which the solar wind torque, which continually slows down the rotation of the convection zone, is transmitted to the core. How much higher is the angular velocity at the sun's center than at its surface? Helioseismology has shown that most of the radiative interior rotates quite slowly, more slowly even than the photosphere near the equatorial plane (*13*). The implied quadrupole moment $J_2$ of the sun's gravitational potential, coupled with planetary radar ranging measurements, is consistent with general relativity. Subsequent, more sophisticated helioseismological analyses have led to debates about the extent to which the differential rotation of the convection zone is consistent with ideas in dynamo theory, and whether it varies with time. A severe difficulty in the analysis has arisen from the interference between rotational splitting and diurnal influences on the observations; GONG and SOHO are essentially free from such disturbing confusion.

## Future Developments

As data continue to accrue, frequencies will be determined more accurately and low-amplitude modes with low frequency will emerge from the noise. Our views of the solar interior will become more refined, and we will be able to assess the extent to which the sun can be described by a standard theoretical model. We will learn more about the solar core and whether or not it is spherically symmetrical, which will have important implications for the solar neutrino problem (*14*). Solar neutrinos are produced by nuclear reactions in the central energy-generating core and can be detected on Earth. However, all detectors built so far have found fewer neutrinos than had been predicted. Helioseismology has provided strong evidence that the neutrino deficit cannot be explained by adjusting the structure of a standard model of the sun. Perhaps the deficit is a result of transitions from one type of neutrino to another (*15*). Neutrino transitions are of great interest to particle physicists, particularly in relation to the development of Grand Unified Theories. The establishment of neutrino transitions would mean that neutrinos have mass and might therefore constitute a substantial part of the dark matter in the universe.

Helioseismology will also contribute to ascertaining what causes the 22-year cycle of magnetic activity. This phenomenon results from the complicated interaction between rotation, turbulent convection, and the magnetic field. Most of our knowledge about the physics of the solar cycle will come from accurate measurements of the internal differential rotation and global asphericity and their temporal and spatial variations. The high-resolution data from SOHO offer the opportunity to study the internal structure and dynamics of active regions and individual sunspots. By using techniques to analyze the wave field locally, we will measure important properties of the convection zone, such as the large-scale velocity and temperature fluctuations and the structure of at least the near-surface magnetic field, and how they all vary with time. We thus hope to learn how the sun's magnetic field is maintained and modified and what causes the sun's radiation to change with the solar cycle. For such studies, data that cover a substantial fraction of the 11-year sunspot cycle will be required. The results will have practical implications for the National Space Weather Program. In addition, accurate inferences about how pressure and density are related in the convection zone will make possible further investigations of the equation of state. And by studying the variation of amplitude and phase of the oscillations, we will learn more about how the oscillations are excited and scattered and how they dissipate.

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7. The Lagrangian point $L_1$ is located about $1.5 \times 10^6$ km sunward from the Earth. It is the point at which the combined gravitational pull of the Earth and the sun cancels the centrifugal force and affords uninterrupted observation of the sun with hardly any relative motion. The NASA Deep Space Network will be required for communication and active orbital control, the latter to stabilize the spacecraft in the looping orbit as it is perturbed principally by the moon and Jupiter.
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18 March 1996; accepted 9 May 1996