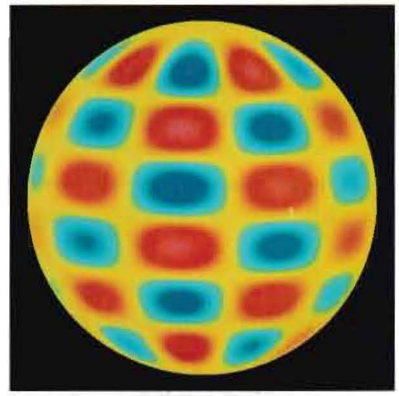
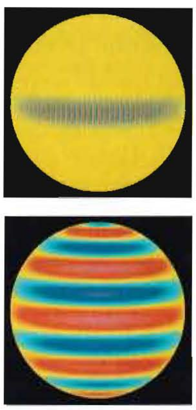
Sounds of the Sun



The sun rings like a well-hit gong, revealing its inner workings to solar astronomers

By Marcia Bartusiak



Computer-generated images show a few ways in which the sun can oscillate. The blue areas are moving toward earth, the red areas are moving away, and the yellow areas represent nodes (stationary planes that belong to each oscillation). As the degree of the acoustic mode increases, smaller regions of the sun oscillate separately. (Courtesy of Douglas Gough, Cambridge University.)

The sun may be the star closest to the earth, yet at the same time it is very remote. To early celestial observers it appeared perfect, an unblemished orb of fire. Today, with modern instruments, we see a solar surface that is turbulent and varied. High-speed streams of solar particles emanate from dark coronal "holes"; solar prominences, immense arches of glowing gas, soar for hundreds of thousands of kilometers; and solar flares, lightning-like cataclysmic explosions, can flash across a region of the sun in a matter of minutes.

Nearly all these effects reflect complicated and tumultous activities inside the sun itself. But an exact description of what lies beneath the sun's fiery surface has been based more on conjecture than explicit measurement. Its center lies some 700,000 kilometers from its surface, and all that material in between acts as an effective shield, keeping solar astronomers from directly viewing the sun's interior.

Theoretical modeling and computer simulations have established that the sun is powered at its core, the inner 20 percent, by the thermonuclear conversion of hydrogen into helium. The resulting energy slowly makes its way out of the core, first by radiative diffusion, and then, starting about seven-tenths of the way out, by convection as the heated gases physically flow upward.The gases subsequently release their energy at the surface, bursting through like bubbles in a pot of boiling fudge, only to recirculate downward to be heated once again. In this way a regular pattern of convection cells—columns of hot gas rising, cooling off, and then descending—is created within the sun.

Many elements in this description, however, are far from secure. Certainty can arrive only if the sun is probed directly. Given the very nature of the sun—its 1.5-million-kilometer width and scorching temperatures—such an endeavor always seemed like an impossible dream. But no longer. In recent decades, solar astronomers have noticed that the sun quivers and shakes. It continually rings, in fact, like a well-hit gong. These reverberations, which carry information about the sun's deep interior, are allowing solar observers to examine the sun's hidden layers, much the way seismic tremors permit geophysicists to scan the earth's interior. Appropriately enough, the name of this new field is helioseismology.

"Two decades ago few people would have believed that it would have become possible to make measurements of conditions inside stars," says Cambridge University's Douglas Gough, a pioneering theorist in this up-and-coming field. "Yet the advent and the rapid development of helioseismology [have] provided accurate probes that have made seeing inside at least one star a reality."

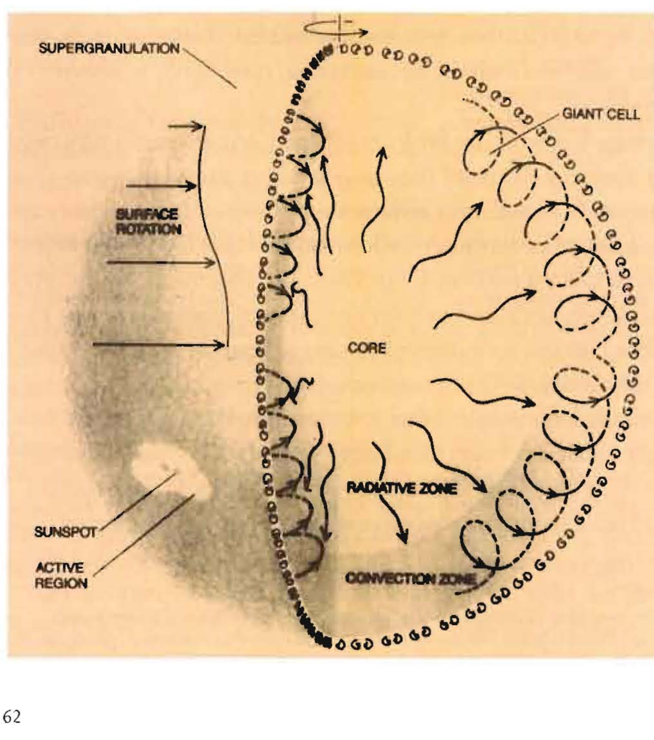
Excerpted from chapter one, "Shake, Rattle, and Shine: New Methods of Probing the Sun's Interior," in A Positron Named Priscilla: Scientific Discovery at the Frontier, *a collection of writings on current research to be published by the National Academy Press in February 1994.*

Although still in its infancy, helioseismology has already challenged and revised several long-held conceptions of the solar interior, such as the depth of the convection zone and the way in which the inner sun rotates. Astronomers expect additional revisions as an international helioseismological network attempts to measure the solar quivers more accurately than ever before. The information that is gleaned may affect far more than solar models. Knowledge of the sun's inner composition affects calculations of the age of the universe, as well as the amount of helium forged in the Big Bang. Moreover, knowing exactly how the sun spins internally is important in testing Einstein's theory of general relativity, which is the anchor for most of modern cosmology. The domain of helioseismology is broad and far-reaching. Yet like so many other significant findings in astronomy, discovery of the quivering sun was totally unexpected.

In 1960, using the 60-foot tower solar telescope atop Mount Wilson in southern California, Robert Leighton of the California Institute of Technology, together with Robert Noyes (now at the Harvard-Smithsonian Center for Astrophysics) and George Simon (now at the National Solar Observatory in Tucson), set out to measure changes in certain absorption lines in the solar spectrum. The lines were observed to Doppler shift, to move to higher or lower frequencies, as gases at the surface of the sun moved either toward or away from the observers. By measuring this shift the observing team hoped to discern the bobbing motions of individual solar granules, the cells of upwelling and sinking gases that cover the solar surface.

A spectral-line feature would move toward the blue end of the spectrum whenever a cell heaved upward; the line would shift toward the red end as the cell dove back down. To the surprise of the Caltech astronomers, these velocity patterns were not chaotic, but instead were fairly oscillatory. Like a churning sea, the entire surface of the sun was found to be awash with periodic waves, not discernable to the naked eye, each rising and falling with a period of about 5 minutes. Moving at a speed of nearly 2,000 kilometers per hour, any one patch can rise and then fall more than 70 kilometers over the five-minute cycle.

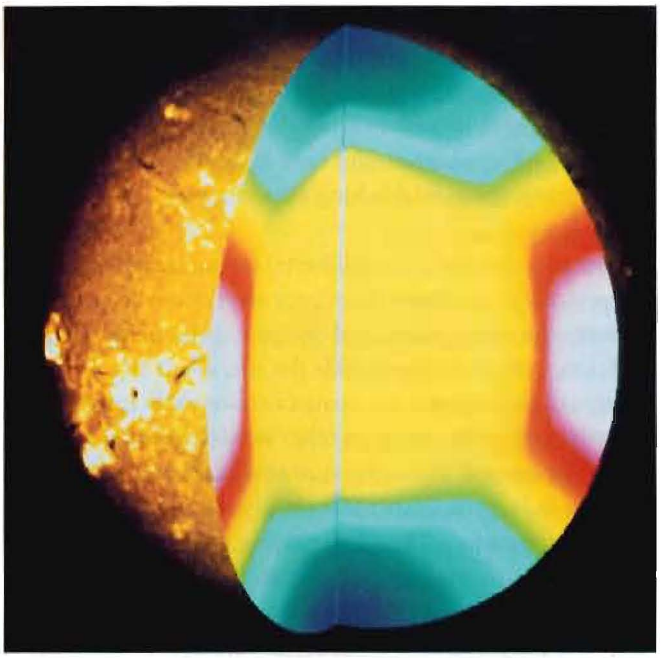
For a while these pulsations, which continually grow and die away at any given site, were thought to be merely a local phenomenon, possibly eruptions from the roiling convection zone just beneath. However, that assumption began to change in 1970 when Roger Ulrich at the University of California in Los Angeles, and, independently, John Leibacher and Robert Stein, who is now with Michigan State University, provided a more global interpretation.



Current models propose that a chain of fusion reactions within the sun's core release energy that moves outward, first by radiative diffusion, then via a hierarchy of convection cells of progressively smaller size. The many granules that mottle the sun's surface are the topmost parts of these convection cells. (Courtesy of National Optical Astronomy Observatories.)

Leibacher, now the director of the National Solar Observatory, says that his insight was due to a bit of theoretical serendipity, a stroke of good fortune that occurred as he was trying to simulate the 5-minute solar oscillation on a computer. "Hard as I tried, I couldn't get my model to yield the answer that I wanted," he recalls. "Another mode kept overwhelming it. I tried and tried to get rid of what I thought was an error, but nature, or in this case the computer's simulation of nature, would not yield. It gave us the right answer."

Ulrich, Leibacher, and Stein came to realize that the 5-minute oscillation was not a local effect but rather the superposition of millions of acoustic or sound vibrations ringing throughout the sun. Since the sun is a spherical cavity with set dimensions, only particular wavelengths can be trapped inside and resonate, much the way an organ pipe resonates at specific frequencies. At any given spot on the sun, the 5-minute oscillation thus grows and decays as these myriad modes, each with its own period, velocity and strength, move in and out of phase.



A cutaway picture of the sun shows how the rate of solar rotation varies with depth and latitude. The period of rotation ranges from 36 days at the poles (blue) *to 25 days at the equator* (red). *Starting near the base of the convection zone, the sun begins to rotate as a solid body with a period of 27 days* (yellow). *(Courtesy of Ken Libbrecht, Caltech.)*

It is as if the sun were a symphony orchestra, with all the instruments being raucously played at the same time. It sounds like a cacaphony, but when the noise is properly analyzed the separate instrumental tones emerge (although the sounds are far below audible frequencies). All these vibrations combine at times to produce a net oscillation on the solar surface that is thousands of times stronger than any one vibration.

The physics of these solar acoustic waves were already well understood from studies of the earth's atmosphere. Such waves propagate at the speed of sound by means of alternating compression and rarefaction of the solar gas, with pressure as the restoring force. Hence, these waves are also known as p modes. If you squeeze the sun, it rebounds under pressure. The individual p modes have periods ranging from a few minutes to nearly an hour.

Helioseismologists believe that the sun should also exhibit gravity waves, or g modes, just as seen in the earth's atmosphere. In this mode the solar material would be oscillated by the pull of gases of different density upon one another. Here, buoyancy is the principal restoring force. For example, if a mass of gas is displaced downward, entering a denser medium, it is buoyed upward. Once this rising mass becomes heavier than its surrounding medium, though, it falls downward once again, ready to repeat the cycle.

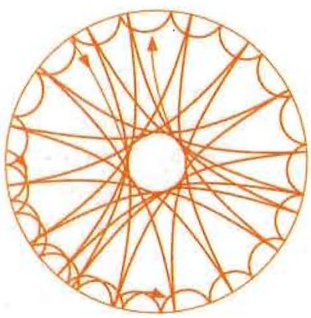
Primarily originating in the sun's central regions, these longer-period waves (40 minutes or longer) do not propagate very well through the convection zone and are therefore expected to have extremely small amplitudes at the surface. The unstable convection zone does not support buoyancy oscillations very well. So far, reported sightings of g modes in the sun have not been confirmed. There are also modes, called f modes, that exist at the surface of the sun and travel about much like waves on the ocean. Such waves are essentially surface gravity waves and are virtually compressionless.

Since the sun is three-dimensional, each solar acoustic wave is a bit more complicated than a simple wave resonating in an organ pipe. What is known as the "degree" of the wave, a parameter conventionally labeled l by helioseismologists, can loosely be thought of as the total number of horizontal wavelengths that encircle the sun's surface. These wavelengths range from the width of an individual solar granule—a few thousand kilometers, resulting in a high degree number—to the entire solar circumference, a degree number approaching unity.

Each degree, in turn, can have varied frequencies and overtones, which reflect the variety of resonances possible in the other directions as well. Being three-dimensional, the nodes of these standing waves—the regions where nothing moves—are not points but either concentric spheres or planes that slice through the sun parallel and perpendicular to each other. The quantity l, in fact, corresponds to the total number of nodal planes, both parallel and perpendicular to the solar equator, belonging to each oscillation.

Why should solar acoustic waves exist at all? That is not known with certainty, but helioseismologists have their suspicions. "Something is driving these modes," says solar astronomer Ken Libbrecht of Caltech. "We think it is due to the sun's turbulent convection. The turbulence in the surface layers generates acoustic noise, and if you generate noise within a cavity, then you excite the normal modes of that cavity."

What is better understood is the method by which these waves travel around the sun. Imagine a sound wave diving into the depths of the sun. Both temperature and density increase as the wave, traveling at around 200 kilometers per second, penetrates deeper and deeper, and this causes the wave to refract, or bend, as it travels inward. "The surface of the sun is cold, some 5,800 degrees. The center is hot, around 15 million degrees. So, the sound speed actually increases as you go down into the sun, because sound speed increases with temperature," explains Gough. "A wave propagating downward into the sun thus experiences a faster speed deeper in than it does near the surface. As a result, it gets refracted." Eventually, the wave turns completely around and heads back up to the surface, where, because of the sharp drop in density at that boundary, it is reflected downward once again. In this way, the acoustic wave can travel around the sun many times, establishing a standing-wave pattern that lasts for days or weeks.



Acoustic waves refracting within the sun penetrate to different depths depending on their wavelength. Long-wavelength, or low-degree, oscillations penetrate deeply into the sun's interior. Short-wavelength, or high-degree, waves stay near the surface. (Courtesy of Douglas Gough, Cambrige University.)

Acoustic modes above a certain frequency (roughly 5.5 millihertz) cannot be reflected by the sun's photosphere (its visible surface). These higher-frequency waves simply move into the sun's chromosphere (the region above the photosphere) and dissipate their energy. Thus there exists a finite number of p modes that can be trapped inside the sun, about 10 million. Not all are detectable, but a good fraction of these modes are excited to observable amplitudes.

In general, the longer the horizontal length of the wave (in other words, the lower its degree), the deeper its plunge into the solar interior. This is because acoustic waves with longer wavelengths are refracted more gradually and so propagate more steeply into the sun. Shorter wavelengths, on the other hand, stay near the surface. Thus, by studying a wide range of modes, solar physicists can effectively "enter" the sun, peeling away each of the star's layers as if it were an onion. And with a wave's propagation dependent on the temperature, velocity and density of the medium through which it is traveling, each mode offers valuable clues on the makeup and structure of the solar interior.

Over the years, solar observers have refined their techniques for detecting both high- and low-degree modes. For the lowest modes, waves with values from zero to three, whose lengths are comparable to the size of the sun, observers look at the collective Doppler shift of a spectral line averaged over all or much of the solar disk. Since day/night gaps introduce spurious signals that make analysis difficult, investigators at the University of Birmingham in Great Britain and the Observatory of Nice in France established field stations around the globe to obtain an uninterrupted record of the sun's activity. Researchers have also made (and continue to make) long-term observations at the South Pole, where the sun never sets during austral summers.

Modes with degrees in the tens to hundreds, however, do not show up in such globe-spanning Doppler-shift data. The wavelengths of these modes are relatively small compared to the size of the sun and so are averaged out. These higher-degree modes are effectively discerned in spectrograms that register very localized Doppler motions across the face of the sun, much like the first Caltech measurements. Ground-based instruments can observe parcels as small as 1,000 kilometers across, about the width of the state of Texas.

When processed, pictures of these parcels, known as velocity images, look like salt and pepper strewn over the solar disk. The dark areas depict the regions on the solar surface that are sinking; the bright spots, conversely, are rising or moving toward the earth. It is these oscillations that are differentiated into the high-degree components. This method has enabled observers to differentiate modes with degrees up to a few thousand, although atmospheric distortion does play havoc with degrees that measure above 400. "The surface of the sun is seething with movement. There's a background noise of about a kilometer per second," points out Libbrecht. "But, on top of that, there are oscillations as little as a millimeter per second, which we can see. It's quite remarkable."

Analysis of the helioseismological data can be handled in one of two ways. Traditionally, researchers have constructed a set of solar models and then adjusted certain parameters, such as the temperature and density of various solar elements, until they best fit the p modes observed ringing through the sun. More recently, however, theorists have been developing mathematical techniques known collectively as inversion, which extract the solar parameters directly from the modes themselves. Inversion, in essence, converts the solar "tones" into a map of its essential features. This second approach is far more challenging than the first. Supercomputers are often used to deal with tens of thousands of modes at one time.

Interpretation of the p modes began soon after they were discovered. Franz-Ludwig Deubner of West Germany reported that the modal frequencies he had uncovered were actually lower than theoretical predictions. These observations led Gough in 1975 to deduce that the sun's convection zone must be deeper than previously estimated. Additional observations prompted Edward Rhodes (now at the University of Southern California), Roger Ulrich and George Simon to draw the same conclusion.

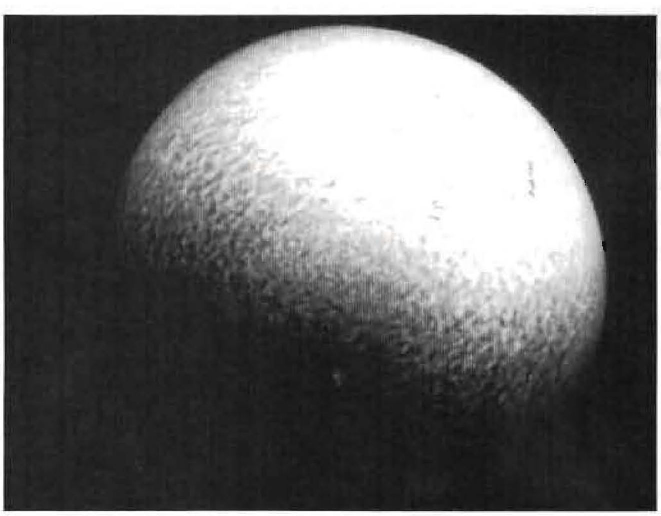
It had long been assumed that the convection zone's depth was 20 to 25 percent of the solar radius. Calculations by Rhodes and his group determined that it was more like 30 percent. It was the first major solar parameter to be adjusted based on helioseismological data. The convection zone's greater depth means that convection can transport heat from the bowels of the sun more efficiently than once thought.

A view of the sun that has changed most dramatically since the birth of helioseismology is the overall profile of the sun's internal rotation. It has long been known, from observations of sunspot movements, that the sun's rate of rotation steadily declines from the solar equator to the poles. The poles complete a circuit in about 36 days, the equator in just 25. (Being a ball of gas, the sun is not constrained to rotate like a rigid body.) "This is poorly understood," notes Libbrecht, "but possibly linked to both convection processes and Coriolis forces."

Numerical simulations of this process had led to a model of the sun's differential rotation that was commonly referred to as "constancy on cylinders." The sun in this picture, at least through the convection zone, was supposedly composed of a set of nested cylinders that extended from pole to pole, aligned with the sun's axis of rotation. The inner cylinders, which surfaced at the higher latitudes, rotated more slowly than the outer ones, which met the surface at the more rapidly rotating lower latitudes. This also meant that the angular velocity at a particular latitude should have gradually decreased with depth.

But this picture failed to fit the observations of a number of helioseismologists, including Timothy Brown at the National Center for Atmospheric Research in Colorado and Cherilynn Morrow, then a student at the University of Colorado. Morrow and Brown began to show that the sun's rotation rate at a given latitude actually remains fairly constant down through the convection zone. Past that zone, angular velocities at the poles and equator shift toward the same rate. Halfway into the sun, beyond the convection zone and into the radiative interior, the sun rotates somewhat like a rigid body. These observations confirm the suspicion that the sun's differential rotation at the surface, long a mystery, is somehow generated by convection rather than processes deeper in the interior.

Brown and Morrow's model was sustained and extended by a wealth of new data gathered by Ken Libbrecht. For six months in 1986 at Caltech's Big Bear Solar Observatory, located in the center of Southern California's Big Bear Lake, Libbrecht and his students took a Doppler image of the sun each minute, gathering a total of around 70,000 pictures. The team then extracted vibrational modes from these images after some 40 hours of supercomputer time.



Very localized Doppler motions across the face of the sun. Light regions indicate material rising from the sun's surface; darker shades indicate sinking. The side-to-side brightness variation is due to the sun's rotation. (Courtesy of Ken Libbrecht, Caltech.)

"We were interested in measuring as many modes as we could," says Libbrecht, "because each mode has its own story to tell about the medium in which it was trapped." Lastly, inversions of these modes, performed by Jorgen Christensen-Dalsgaard of Denmark's Aarhus University and others, mapped the sun's rotation down to a depth of about 450,000 kilometers, 60 percent of the way to the sun's center. Similar sets of images were taken again in 1988, 1989 and 1990 and added to the data base.

"We find that the rotation persists almost independent of radius, down to the base of the convection zone," says Libbrecht. "Then, there is a fairly sharp transition to solid-body rotation. This is one of the biggest outstanding questions concerning the sun—why does it rotate in this manner? We couldn't go down to the very core—we went down about six-tenths of the way—but, dynamically, it seems to make sense that the whole interior is rotating uniformly with about a 27-day period."

These and other measurements, particularly data taken earlier at the South Pole by Thomas Duvall of the NASA Goddard Space Flight Center, John Harvey of the National Solar Observatory, and Martin Pomerantz of the Bartol Research Institute, have served as a valuable check on the theory of general relativity, Einstein's revolutionary view of gravity. A competing theory of general relativity, introduced in the 1960s, had suggested that Einstein's calculation of a general relativistic effect that perturbs the orbit of the planet Mercury might be wrong. Supporters of this alternate theory argued that a large portion of the inner sun was spinning much faster than the solar surface, causing the sun's core to flatten.

If the solar interior is rotating very fast, Einstein's explanation for Mercury's peculiar orbital behavior would be in jeopardy, since his calculations assumed a fairly spherical sun. "The sun was rotating faster in the past than it is now. The sun is slowing down," points out Gough. "But has the inside of the sun slowed down as well? The discussion hinges on how strongly the inside is coupled to the outside." While helioseismologists are not yet able to make an exact measurement ("We can't totally rule out a fast-spinning nugget at the solar center," notes Libbrecht), the data do strongly suggest that the innermost core, a few percent of the sun's total volume, is not rotating fast enough to squish the sun and disrupt Einstein's theory.

Also affected by the changing profile of the inner sun has been astronomers' understanding of the solar dynamo, the "engine" that drives the ebb and flow of activity over a solar cycle by inducing immense electrical currents and magnetic fields. A decade or so ago, astronomers thought that the dynamo resided in and was driven by the turbulent convection zone as a whole. However, now that angular velocities are seen to remain fairly constant through the convective regions, that idea is now ruled out. In its place, theorists are suggesting that the dynamo occupies a more narrow zone between the bottom of the convection layer and the top of the deep interior, the region of transition where rotation rates change most sharply.

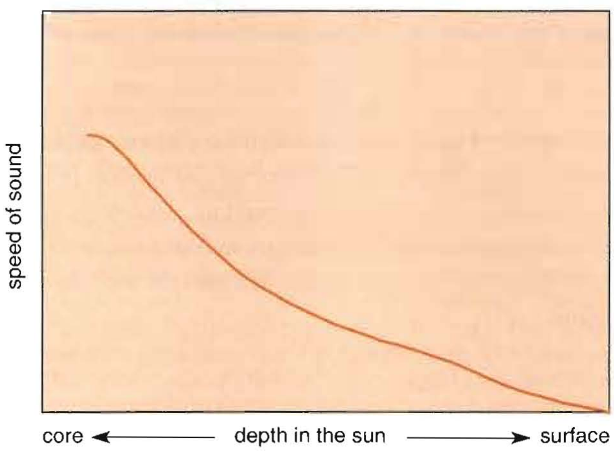
Helioseismologists are setting an ambitious agenda for themselves. A top priority is understanding the solar cycle, that 11-year period over which sunspot counts and solar flares wax and wane and solar magnetic field strengths build up and decline. Solar astronomers already suspect that the sun's magnetic fields interact with convection, indeed at times might suppress it, but helioseismology is needed to see such an effect below the solar surface.

Helioseismologists have already noticed that solar oscillations behave differently in the presence of strong magnetic fields. The stronger the field, the stronger the effect, which can be either an increase or decrease in the frequency of a mode. Moreover, investigators have seen oscillations around single sunspots exhibit an intriguing phenomenon: Up to 100 percent more vibrational power appears to move into a spot than moves out of it, as if the sunspot is absorbing *p* modes.

Such effects should provide observers with valuable tools in studying the sun's mysterious magnetic interior. For instance, how far down into the solar interior do flux tubes—threads of hot, highly magnetized gases first seen just 20 years ago—extend into the solar interior? Is the sun tunneled with these tiny sunspot-like features? And what is the vertical structure of a sunspot? Does its magnetic field branch like the roots of a bush, or does the field remain bound as one massive trunk that extends more deeply?

Since the propagation of acoustic modes is dependent on temperature and density, helioseismologists are also using the modes to follow the sun's temperature changes. After dissecting modes for nearly a decade, observers have now seen temperature gradients shift over the length of a solar cycle. Having analyzed this effect with helioseismic observations extending back to 1980, Jeffrey Kuhn of Michigan State University suspects it to be a reflection of changes in large-scale magnetic fields as the sun's activity waxes and wanes every 11 years.

Modal frequencies, too, appear to change synchronously with the solar cycle, a modulation that may also be slowly driven by varying magnetic fields. In analyzing his four large data sets, taken over the last half of the 1980s, Libbrecht saw the modal frequencies shift by one part in 10,000, due to changing magnetic activity on the sun's surface as the solar cycle progressed. Moreover, the shape of the sun's acoustic cavity itself appears to alter subtly over a full cycle. All of these observations suggest that the solar cycle may have deeper roots than previously suspected. Some even speculate, although it's very controversial, that the very core of the sun, where thermonuclear reactions take place, may somehow participate in the solar cycle.



The speed of sound increases (right to left) *as temperatures increase toward the center of the sun. The rise diminishes near the core, where hydrogen is being converted into helium, because the speed of sound decreases in denser material. (Courtesy of Douglas Gough, Cambridge University.)*

Solar astronomers have long assumed that the sun's convection zone is lined with giant cells that act as monstrous conveyor belts, transporting solar material to and from the sun's fiery interior. But no hint of these massive structures has yet been found on the surface. To discern such a detailed solar topography, helioseismologists need long uninterrupted views of the sun, especially with instruments that resolve the high-degree modes.

With that need for high-degree data in mind, helioseismologists established the Global Oscillation Network Group, or GONG for short, a reminder of the acoustic qualities of the solar tremors. (As an additional reminder, a small gong is struck at the start of each annual GONG meeting.) Initiated by the U.S. National Solar Observatory in 1984, this international project now involves more than 100 observers and theorists from 61 institutions in 16 countries.

The project is setting up six helioseismological field stations—identical and highly sensitive Doppler imaging instruments—around the globe at roughly equal spacing. "We will be able to increase our resolution 10 times over by observing, not at one site for 6 months, but at several sites around the world," points out Libbrecht. "Going beyond a basic understanding of the structure of the sun, these new helioseismological measurements are expected to turn the sun into a precision laboratory for learning about the physics of high-temperature plasmas and magnetohydrodynamics, neutrino oscillations, radiative transfer, and the dynamics of large-scale stratified convection and rotation."

The GONG instruments are being placed in California, Chile, the Canary Islands, India, Australia, and Hawaii. Each station will be housed in a refurbished commercial cargo container and automated to the fullest extent possible, as if it were a spacecraft on the ground. "Mission Control," in this case, will be the National Solar Observatory in Tucson. Much like the system already established for global radio-telescope arrays, data taken at each station will be recorded on videocassette tapes, which will be mailed periodically to the central data-analysis center in Tucson. Prolific data gathering will make it one of the largest data sets in astronomy, after the Hubble Space Telescope.

Ultimately, atmospheric fluctuations prevent observers from studying the highest-degree modes, which are tinier and require very good resolution. Therefore, the field of helioseismology will soon take to space, free from turbulent air, as well as disruptive day/night gaps. Helioseismic instruments will be included on SOHO, the Solar and Heliospheric Observatory, a joint project of the European Space Agency and the National Aeronautics and Space Administration. Scheduled for launch later this decade, SOHO will be placed at a Lagrangian point 1.5 million kilometers sunward from the earth. There a variety of detectors will be trained on the sun for at least two years, although the observatory could operate for six years, a major slice of the solar cycle.

SOHO scientists are developing an instrument called the Michelson Doppler Imager, or MDI, which will perform both long-term Doppler scans and daily readings. In this way SOHO investigators hope to measure solar vibrational modes with degrees from 1 to 3,000. With such long-term high resolution, MDI's data could enable helioseismologists to focus on the topography of active regions, zoom in on granulation, and track the movement of sunspots.

Other detectors aboard SOHO will concentrate on low-degree modes and possibly *g* modes, whose extremely tiny amplitudes on the sun's surface make them the most elusive of the sun's oscillations. Years of data collection, either in space or by GONG, may be needed to discern the faint *g*-mode signal above the noise. But the payoff will be big if *g* modes are firmly discovered, for the detection will enable solar astronomers to peer directly into the sun's core. "The very core of the sun where nuclear reactions take place, that's the biggest prize in helioseismology," declares Gough. At the sun's core, helioseismologists will find a laboratory that is irreproducible on this planet, where matter is pulled apart, ionized and fused at unearthly temperatures.

The potential uses of helioseismology are legion. And helioseismologists are not stopping at the sun. Already a few adventurous observers have looked for seismic quivers in other stars, which offers astronomy the chance to plumb other stellar interiors. Analogues to the five-minute oscillations of our sun have been reported in such stars as Alpha Centauri A, Procyon, and Epsilon Eridani. For the moment, however, the sun remains the top priority for specialists in this pioneering discipline.

Recommended Reading

Gough, D.O., and J. Toomre. 1991. Seismic observations of the solar interior. *Annual Review of Astronomy and Astrophysics* 29:627–684.

Harvey, J. W., J. R. Kennedy and J. W. Leibacher. 1987. GONG: To see inside our sun. *Sky & Telescope* (November):470–476.

Leibacher, J., R. Noyes, J. Toomre and R. Ulrich. 1985. Helioseismology. *Scientific American* (September):48–57.

Libbrecht, K. G., and M. F. Woodard. 1991. Advances in helioseismology. *Science* 253 (July 12):152–157.

Combining an advanced degree in physics with a career in journalism, Marcia Bartusiak has been covering the fields of astronomy and physics for more than a decade. She is a contributing editor at Discover magazine and the author of Thursday's Universe, a guide to the frontiers of astrophysics and cosmology, and Through a Universe Darkly, a history of astronomers' centuries-long quest to discover the universe's composition. In 1982, Bartusiak was the first woman to receive the Science Writing Award from the American Institute of Physics. She lives in Massachusetts.