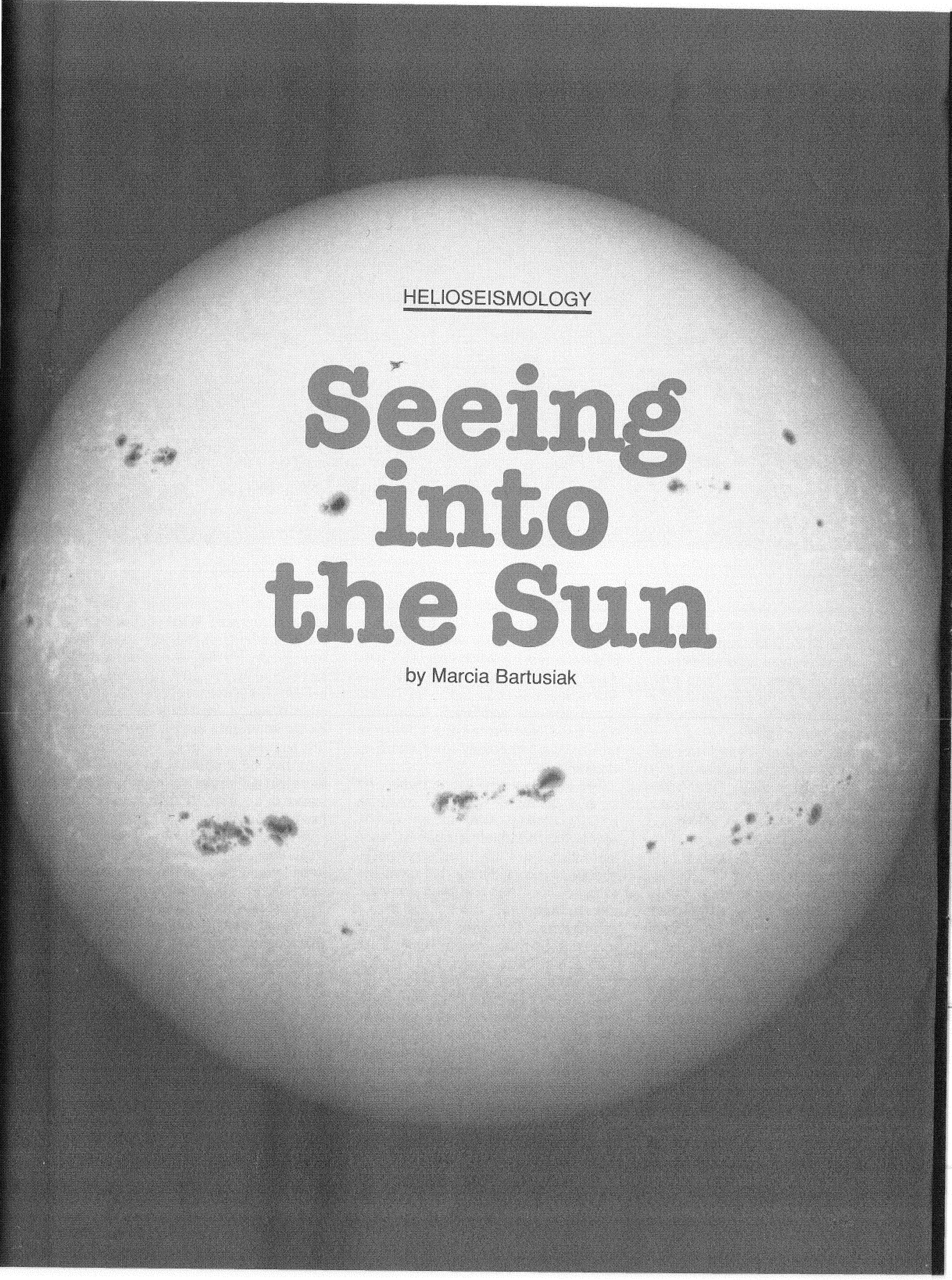


HELIOSEISMOLOGY

Seeing into the Sun

by Marcia Bartusiak

An infant discipline is forcing radical revision of long-held notions of phenomena at the solar core.

To the ancient Greek philosopher Aristotle the sun was perfect, an unblemished orb of fire. During the Middle Ages, despite reports that dark splotches occasionally appeared on the face of the sun, Aristotle's conception of a flawless solar globe held firm. Medieval theologians preferred their heavens to be untarnished.

This illusion shattered in the early seventeenth century when Galileo in Italy, as well as observers in Holland, Germany, and England, pointed a newfangled instrument, called a telescope, at the sun and confirmed that the solar surface was indeed spotted. "For the most part the spots are of irregular shape, and their shapes continually change, some quickly and violently, others more slowly and moderately," wrote Galileo of his sighting.

Since then, the science of solar astronomy has in some ways been an extension of Galileo's first effort. What is known about the sun largely comes from examination of its outer features, although modern-day instruments, both on the ground and in space, have revealed a solar surface more turbulent and varied than seventeenth-century astronomers could ever have imagined: High-speed streams of solar particles emanate from dark coronal holes; solar prominences, immense arches of brilliant gas, soar for hundreds of thousands of miles above the solar surface.

Nearly all these effects reflect complicated and tumultuous activities inside the sun itself. However, descriptions of what lies beneath the sun's fiery surface have been essentially conjecture, although bolstered by well-known laws of physics.

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, then by convection as the heated gases flow upward into the sun's outer layers. The gases release their energy at the surface, like a pot of boiling fudge, only to recirculate downward to be heated once again.

Many elements in this description are far from secure, however. Indeed, one of astronomy's most nagging mysteries lies at the heart of the sun, where a flood of ghostly particles called neutrinos is continually and copiously generated and released into space. Yet sensitive detectors on earth capture only a third of the neutrinos the standard solar model predicts.

New findings in particle physics may explain this discrepancy. Perhaps the neutrino, now assumed to be massless, does have a bit of mass. Or maybe other, undiscovered particles huddling in the sun's core somehow temper the nuclear fire. If not, solar physicists will be forced to amend their ideas on stellar structure.

"Answers that lie with particle physics are currently fashionable," solar theorists Juri Toomre of the University of Colorado and Douglas Gough of Cambridge University declare, "but if the sun really is to offer genuine evidence to particle physicists that neutrino transitions take place, it is essential to acquire precise knowledge of the conditions under which the neutrinos are produced."

Probing the inner sun directly is no longer an impossible dream. In recent decades solar astronomers have noticed that the sun quivers and shakes. It continually rings, in fact, like a well-hit gong. And these reverberations are now allowing observers to begin to examine the sun's hidden inner layers, much the way seismic tremors allow geophysicists to scan the earth's interior. Appropriately enough, the name of this new field is helioseismology.

Conceptions challenged

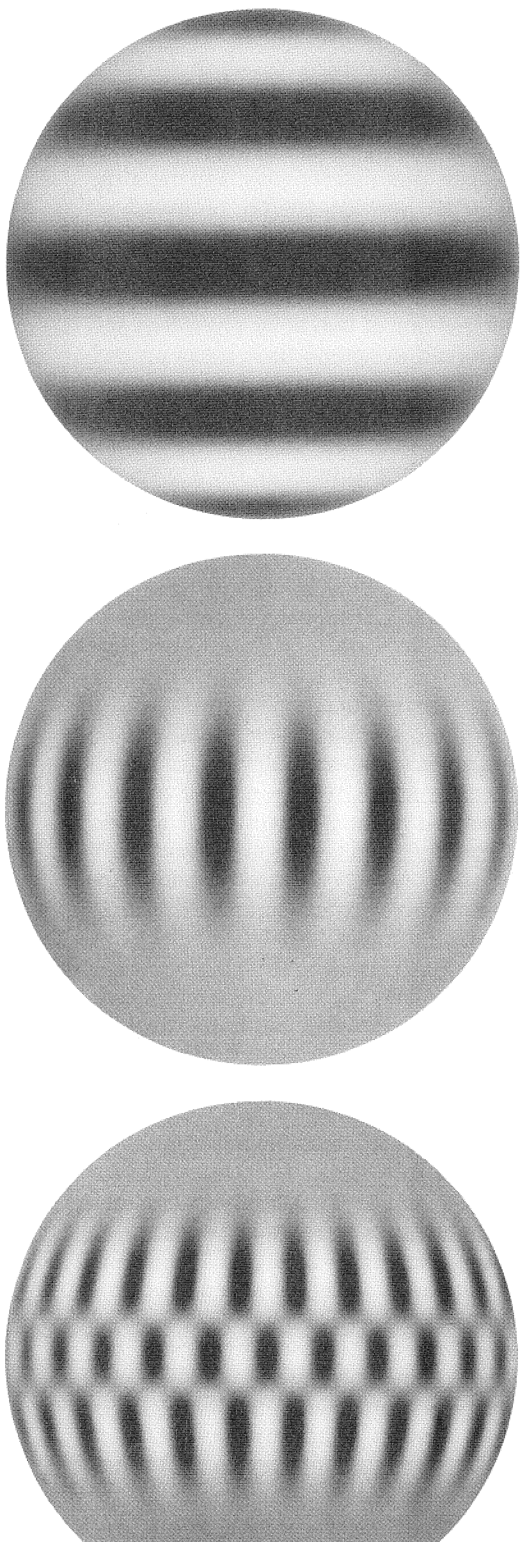
Although still in its infancy, helioseismology has already challenged and revised several long-held conceptions of the solar interior, such as the depth of the convection zone and the way in which the inner sun rotates. Astronomers expect additional revisions as an international helioseismological network, presently being established, attempts to measure the solar quivers more accurately than ever before.

"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, irreproducible on this planet, where matter is pulled apart, ionized, and fused at unearthly temperatures. It is there that the riddle of the missing neutrinos may find its solution.

Information coming from the sun's interior applies to far more than solar

National Solar Observatory

Sunspots. The continual change in sunspots, observed as early as the seventeenth century, became explicable as new observation technologies evolved.



Gough and Morrow

Standing waves. Computer modeling of the sun reveals three types of oscillation nodes as planes cutting the surface: (from top) zonal, sectoral, and tessoral.

models. "In studying the interior of the sun," says Cherilynn Morrow, Gough's colleague at Cambridge, "we can begin to connect our findings to cosmology and the grander questions of the universe." Knowledge of the sun's inner composition affects calculations of the age of the universe, as well as of the amount of helium created 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 five-minute oscillation

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, Arizona), set out to measure changes in certain solar absorption lines. The lines were observed to Doppler-shift to higher or lower frequencies as gases at the surface of the sun moved toward or away from the observers. By measuring the shift, the researchers hoped to discern the bobbing motions of individual solar granules, the cells of upwelling and sinking gases that cover the solar surface. To their surprise, the velocity patterns they found were not chaotic, as expected, but instead fairly oscillatory.

Like a churning sea, the entire surface of the sun was found to be awash with periodic waves, not discernible to the naked eye, each rising and falling with a period of about five minutes. Moving at 0.5 kilometer per second, any one patch rises and then falls more than 70 kilometers over a cycle.

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 at Michigan State University, provided a more global interpretation.

Leibacher, currently director of the National Solar Observatory, says that a bit of theoretical serendipity occurred as he was trying to simulate the five-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 five-minute oscillation was not a local effect but rather the superposition of millions of acoustic 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 as an organ pipe resonates at specific frequencies. At any given spot on the sun, the five-minute oscillation thus grows and decays as these myriad modes, each with its own period, velocity, and strength, move in and out of phase. It is as if the sun were a piano, with all the keys being pounded at the same time. The result sounds like a cacophony, but when the noise is properly analyzed, separate notes emerge.

Acoustic waves

The physics of these acoustic waves was already well understood from studies of the earth's atmosphere. The waves propagate 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. In the sun these individual modes have periods ranging from a few minutes to nearly an hour.

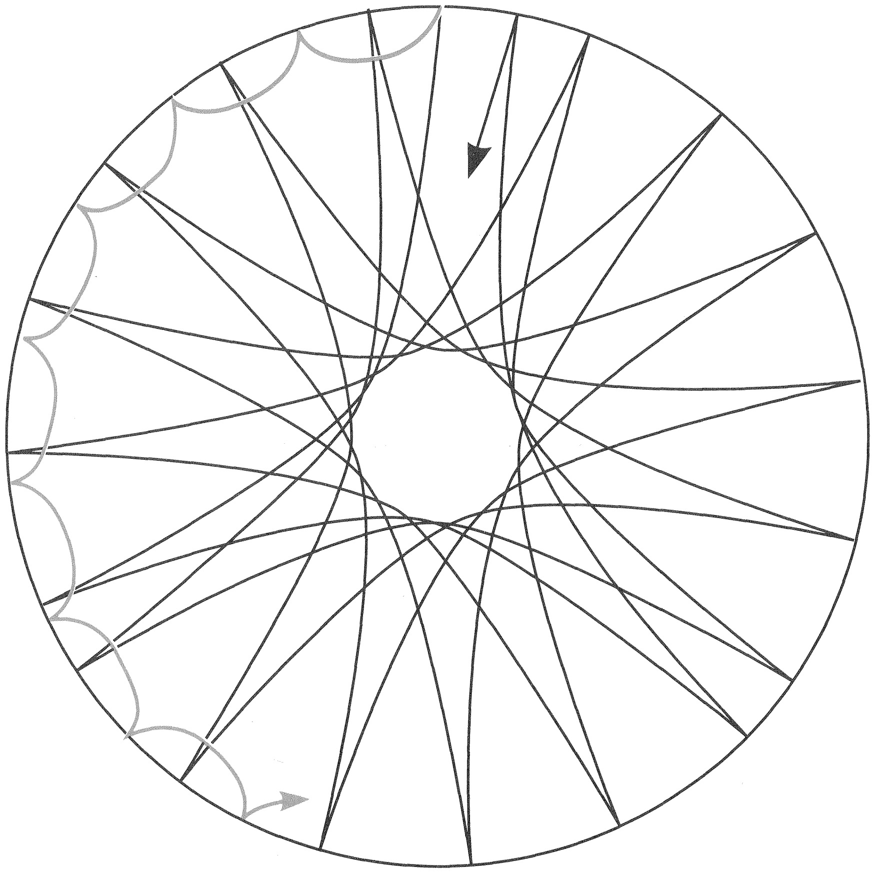
Helioseismologists recognize that as in the earth's atmosphere, the sun should also exhibit gravity waves, or *g* modes, where solar material is oscillated by the pull of gases of different density upon one another. Buoyancy is the principal restoring force. Primarily originating in the sun's central regions, these longer-period waves (40 minutes or more) do not propagate very well through the convection zone and are therefore expected to have extremely small amplitudes at the surface. So far, reported sightings of *g* modes have not been confirmed.

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 can 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, requiring a high degree number—to the entire solar circumference, a 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.

Why do solar acoustic waves exist at all? That is not known with certainty, but many solar astronomers suspect that the oscillations are driven and dampened by the vigorous turbulence of the sun's convection zone. How these waves travel around the sun is better understood.

Imagine a sound wave penetrating the depths of the sun. Both temperature and density increase as the wave travels deeper and deeper, causing it to refract, or bend, as it moves inward. 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.



Morrow and Gough

Sphere to circle. In cross-section, two of the millions of possible acoustic waves refracting within the sun. A low-degree or long-wavelength oscillation (black) penetrates to the sun's deep interior; short-wavelength oscillations (color) stay near the surface.

Acoustic waves with longer wavelengths are refracted more gradually and so propagate more steeply into the sun. In general, then, the longer the horizontal length of the wave (in other words, the lower its degree), the deeper its plunge into the solar interior. By studying a wide range of modes, from high to low degree, solar physicists can effectively "enter" the sun in a stepwise fashion, peeling away each of the star's layers as if it were an onion. 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. For example, waves traveling in the same direction as the sun's fluid material will move a bit faster, shifting their frequency upward. Conversely, waves traveling against the flow will decrease in frequency. Analysis of these splits in frequencies offer a means of mapping the sun's large-scale internal motions.

"It was realized from the outset that these modes had an enormous diagnostic capability, if the descriptions were correct," notes John Leibacher. But in 1970 the idea of acoustic modes was only one of many possible explanations of the five-minute oscillation. For some, the notion did not take hold until five years later. As Frank Hill of the National Solar Observatory says, "Helioseismology was conceived in 1960 but born in 1975." In that year, Franz-Ludwig Deubner of West Germany was at last able to separate his observations of the five-minute oscillation into neat, differentiated modes. A power spectrum of his Doppler velocity data, recorded for many hours along a strip of the solar equator, took the form of narrow and strikingly regular bands, a representation of the allowed frequency values for the resonant modes. The sum of these values was the five-minute oscillation.

Salt and pepper

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 diffi-cult, investigators at the University of Birmingham in Great Britain and the Observatory of Nice in France have 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 shifts. The wavelengths of these modes are

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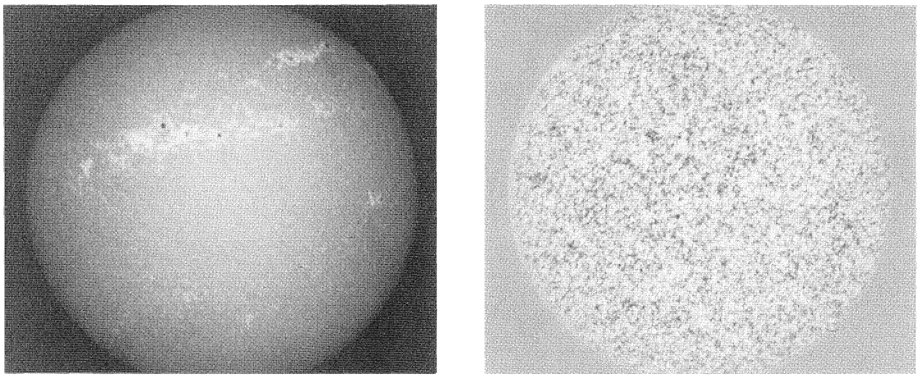
Bartusiak, the author of Thursday's Universe, *writes frequently for* Mosaic *on astronomical subjects.*



Calcium image. Variety of techniques are used while continuously photographing the sun: sequences taken in the light of calcium 394. When differentiated, they show variations in five-minute oscillations, with light patches of rising gases and dark patches of sinking.

National Solar Observatory

relatively small compared with 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 detect parcels as small as 1,000 kilometers across, about the width 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 are rising or moving toward the earth. These oscillations are differentiated into the high-degree components.

This method has enabled observation of modes up to a few thousand degrees, although atmospheric distortion plays havoc with degrees that measure above 400.

Analysis of these 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 developed mathematical techniques known collectively as inversion, which extract the solar parameters directly from the modes themselves.

This second approach is far more challenging than the first. "It is only too easy to swamp supercomputers when dealing with up to a million modes," Colorado's Juri Toomre and Cambridge's Douglas Gough report.

Interpretation of the *p* modes began soon after their discovery. Franz-Ludwig Deubner, for example, reported that the modal frequencies he had uncovered were actually lower than theoretical predictions. Additional observations led Edward Rhodes, now at the University of Southern California, Roger Ulrich, George Simon, and Gough to deduce that the sun's convection zone must be deeper than previously estimated, which would account for the unexpected signal. "It had been assumed that the convection zone's depth was 20 to 25 percent of the solar radius. Now, it's more like 30 percent," says Gough. This larger number means that convection can transport heat from the bowels of the sun more efficiently than once thought.

Some solar researchers hoped that the neutrino problem would resolve itself in a similar manner, through an adjustment in the sun's abundance of helium. If the sun's core contained more hydrogen and less helium, the core temperatures required to maintain the sun's current luminosity could be lowered, which would cut back on the number of neutrinos generated in the core. So far, however, analysis of the acoustic modes comports with an initial solar helium content of some 25 percent by mass, a figure that agrees with current cosmological theory. The dearth of solar neutrinos thus remains unexplained.

A pressing question

For many, a more pressing question was the exact nature of the sun's internal rotation. A competing theory of general relativity, introduced in the 1960s, suggested that Einstein might have been wrong. Supporters of the new 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 so, Einstein's predictions would be in jeopardy, since his calculations assumed a fairly spherical sun.

While an exact measurement cannot yet be made, current helioseismological data suggest that the innermost core, a small percentage of the sun's total volume, may be rotating, at most, a few times faster than the surface—in other words, not fast enough to flatten the sun and disrupt Einstein's theory.

The view that has changed dramatically is the overall profile of the sun's internal rotation, which is turning out to differ considerably from that surmised by theorists from computer simulations. 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.

"With this information from the surface," explains Cambridge's Cherilynn Morrow, "numerical simulations developed a picture of the sun's differential rotation commonly referred to as 'constancy on cylinders.'" The sun in this picture, at least through the convection zone, is composed of a set of nested cylinders that extend from pole to pole, aligned with the sun's rotation axis. The inner cylinders, which surface at the higher latitudes, rotate more slowly than the outer ones, which meet the surface at the more rapidly rotating lower latitudes. The angular velocity at a particular latitude should therefore gradually decrease with depth.

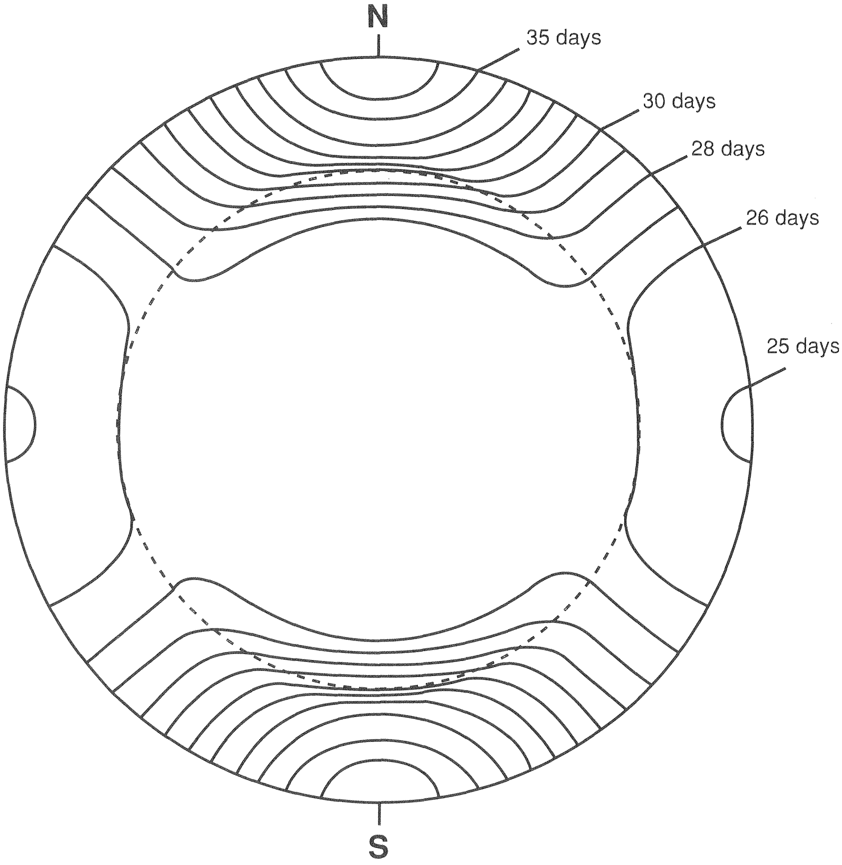
This picture failed to fit the observations of a number of helioseismologists, including Morrow and Timothy Brown of the National Center for Atmospheric Research (NCAR) in Colorado. Morrow, while a student at the University of Colorado, and Brown began to show that the sun's rotation rate at a given latitude actually remains fairly constant down through the convection zone. Past that zone, angular velocities at the poles and the 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. (As mentioned earlier, the innermost sun may rotate a bit faster.) 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 far deeper in the interior.

"My thesis title was 'A new picture for the internal rotation of the sun,'" says Morrow, "and almost as soon as it came out it was an old picture," a testament to the fast pace of this burgeoning field. Actually, Brown and Morrow's model was sustained and extended by a wealth of new data gathered by Ken Libbrecht of Caltech.

For four months in 1986 at Caltech's Big Bear Solar Observatory, Libbrecht and his students took a Doppler image of the sun each minute, for a total of 60,000 pictures. The team then extracted vibrational modes from these images after some 40 hours of supercomputer time. Finally, inversions of the modes, performed by Jorgen Christensen-Dalsgaard of Denmark's Aarhus University and others, mapped the sun's rotation down to a depth of 260,000 miles, 60 percent of the way to the sun's center.

Most 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.

"There is no question that the model of the solar dynamo is changing," says Peter Gilman, director of the High Altitude Observatory in Colorado. Ten years 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, Gilman and others suggest 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.



Caltech, Big Bear Solar Observatory

Rotation rates. A longitudinal section shows that, while the sun's rotational velocity increases from pole to Equator, it consistently persists through to the limit of the convecting layer (dashed line).

The chicken or the egg

Interpretation of helioseismological data resembles, in some ways, that old conundrum "Which came first, the chicken or the egg?" Theorists turn to current models of the sun to differentiate and analyze the various acoustic modes; the modes, in turn, help to refine the standard model of the sun.

It is a tricky business. Yale helioseismologist Pierre Demarque says that a number of uncertainties are incorporated in the standard model of the sun. For example, estimating the sun's opacity, a feat that requires massive computing, generates uncertainties of several percent or more, and this affects how modal frequencies are calculated from the Doppler information.

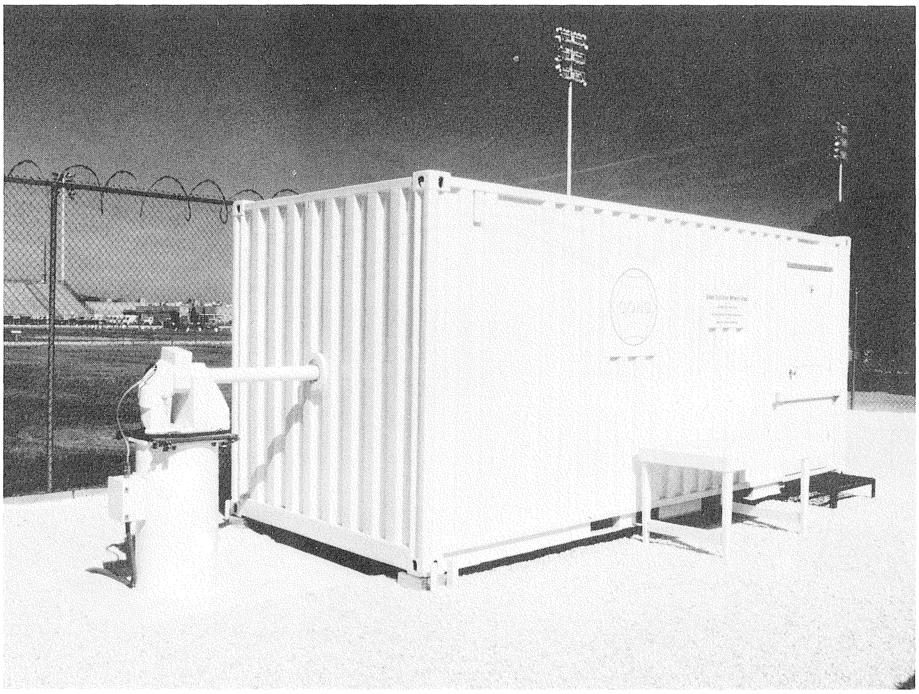
"Convection near the surface, the structure of the sun's atmosphere, nuclear reaction rates, and the resultant element abundances—all these things affect our interpretations of the oscillations," adds Jorgen Christensen-Dalsgaard. Theorist and observer thus work hand in hand, each responding to the findings of the other in the search for the correct model of the sun.

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 the strengths of solar magnetic fields 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. The relationship is "complicated and challenging," says Ellen Zweibel of the University of Colorado.

Zweibel and others have recognized 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, Barry LaBonte and Douglas Braun of the University of Hawaii and Thomas Duvall of the National Aeronautics and Space Administration's Goddard Space Flight Center in Maryland have shown that 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. "It's as if sunspots absorb *p* modes," says Zweibel.

Such effects, according to Zweibel, should provide observers with valuable tools for answering questions about the sun's mysterious magnetic interior. For example, Zweibel wants to know how far flux tubes—threads of hot, highly



National Optical Astronomy Observatories

High-tech cargo. Prototype field station contains sensitive automated instruments to record one complete image per minute over a planned three-year solar observational period.

magnetized gases first seen just 20 years ago—extend into the solar interior. Is the sun tunneled with these tiny sunspotlike 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?

Helioseismologists also use the acoustic 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.

Deep roots

Teodoro Roca-Cortez of the Instituto de Astrofisica in the Canary Islands reports that modal frequencies, too, appear to change synchronously with the solar cycle, a modulation that may also be slowly driven by varying magnetic fields. Also, the shape of the sun's acoustic cavity itself appears to change subtly over a full cycle. All of these observations suggest that the solar cycle has deeper roots than previously suspected, with the very core of the sun, where thermonuclear reactions take place, possibly participating in the cycle as well.

For Colorado's Juri Toomre, the composition of the core, convection-zone dynamics, and the origin of the excitation and damping of the oscillations themselves are key areas of concern. Adds Jorgen Christensen-Dalsgaard, "If we can get a handle on the abundance of elements from core to surface, we would obtain a history of the sun." This information might also help to solve the mystery of solar neutrinos.

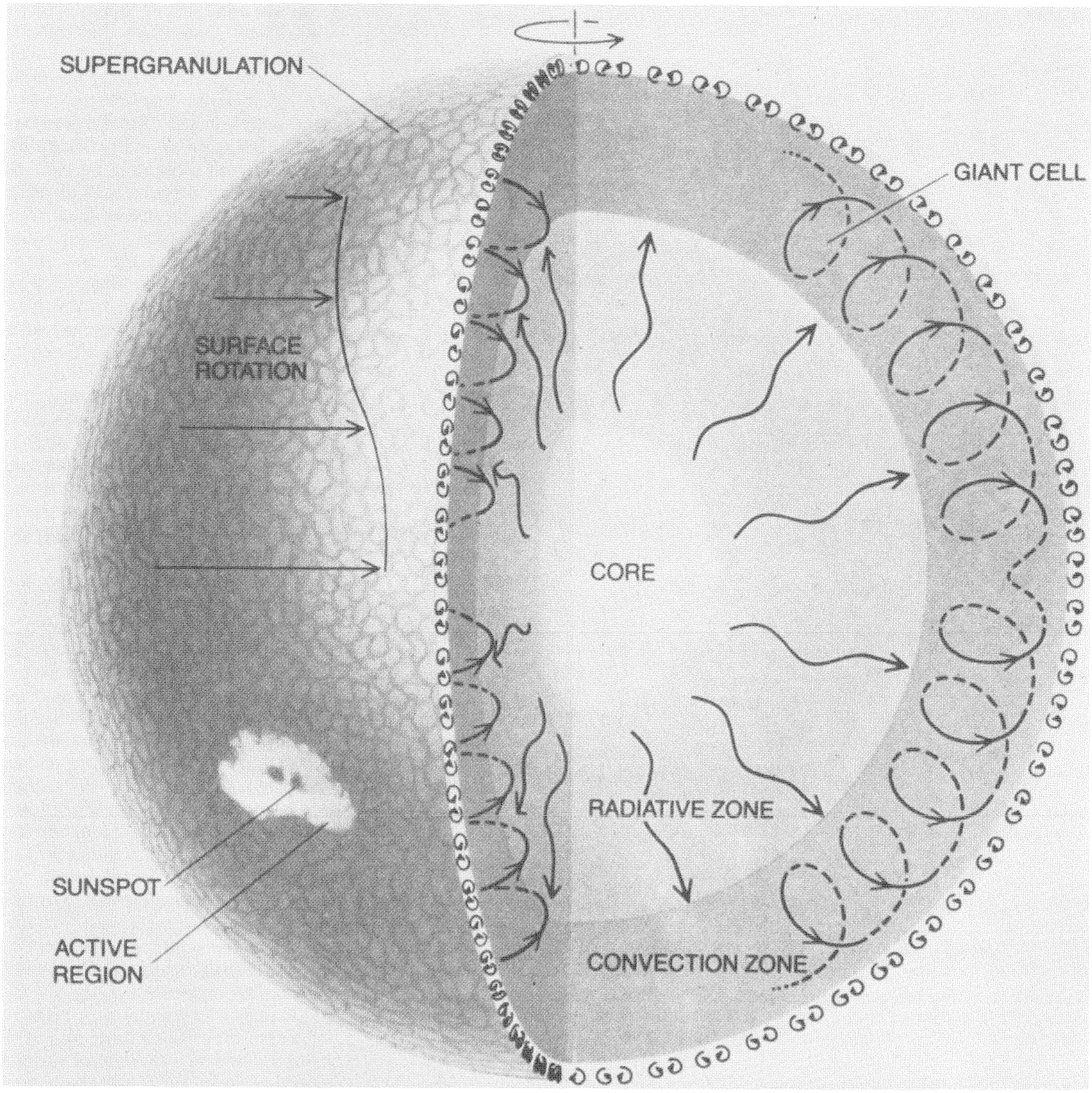
The potential uses of helioseismology are legion. Some observers hope to study surface features, such as supergranules, and to follow their movements over days and weeks. Others are hunting for large-scale convective flows. Solar astronomers have long assumed that the convection zone is lined with giant 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 is found on the surface. "It's as if we knew that clouds should exist in the earth's atmosphere," explains the National Solar Observatory's John Leibacher, "but didn't yet know how to describe them."

To discern such a detailed solar topography, helioseismologists need long, uninterrupted views of the sun, especially with instruments that resolve the high-degree modes. (The worldwide networks set up by Birmingham and Nice do not image the sun and so distinguish only low-degree modes.) With this need in mind, helioseismologists have established the Global Oscillation Network Group, or GONG, 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 meeting.) Initiated by the United States' National Solar Observatory in 1984, this international project now involves more than 100 observers and theorists from 61 institutions in 16 countries.

The $42-million project, principally funded by the National Science Foundation, will place six helioseismological field stations—identical and highly sensitive Doppler-imaging instruments—around the globe at roughly equal distances. Fourteen locations are now under study, including sites in Arizona, California, Hawaii, Australia, and China, as well as India, the Canary Islands, Chile, Saudi Arabia, and Morocco. "Lots of sunshine, of course, is a prime requirement for a good site," notes GONG project manager James Kennedy, "and it must also have access to power, transportation, and local technical support. However, contrary to many astronomical sites, a lack of air turbulence, or good 'seeing,' is not a prime consideration at our resolution."

Data flow

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, where the first station has been erected for testing. 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. With each station recording some two gigabytes a week, one-and-a-half trillion bytes of data will be acquired after three years of continuous sun watching, the project's planned lifetime. "It will be one of the largest data sets in astronomy, after the Hubble Space Telescope," says Juri Toomre. Funding levels will determine



National Optical Astronomy Observatories

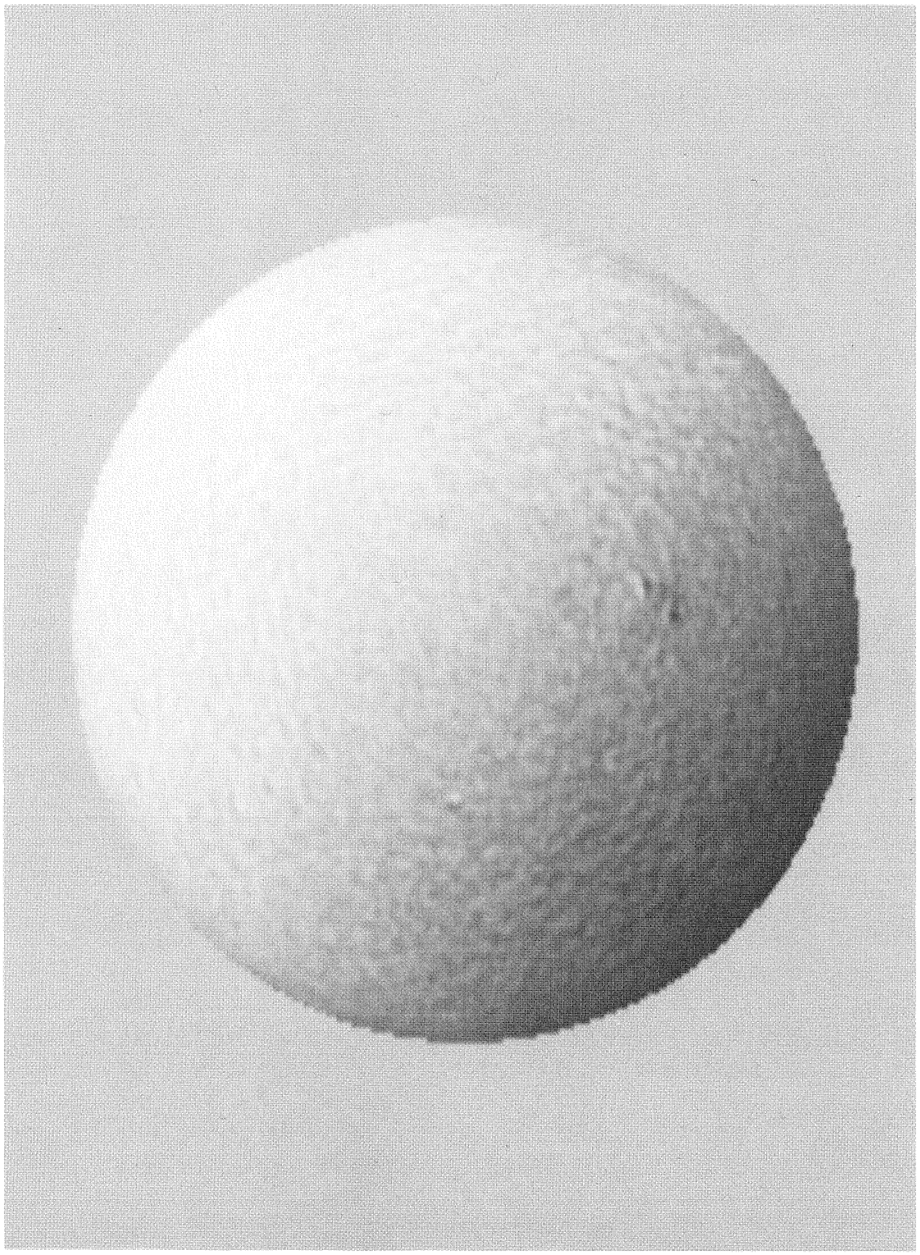
Still questions. Models produced over the last decade propose that nuclear energy radiating from the sun's core induces convection cells which result in supergranulation at the surface. Magnetic and thermonuclear surges erupt as sunspots and solar flares.

when this network is fully in place; project scientists are aiming for 1992.

Helioseismologists use a number of techniques to take high-resolution Doppler measurements. GONG scientists have chosen Fourier tachometry because of its ability to measure Doppler velocities quickly and accurately. Kennedy calls the tachometer "the most sophisticated piece of equipment of its kind—and it needs to be."

A given mode, one of many that make up a solar oscillation, moves some ten centimeters per second or less. To get a good signal above the noise, a GONG instrument should detect movements over the sun with a precision as small as one centimeter per second. "At times we didn't think it would work at all," recalls GONG instrument scientist Jack Harvey, who has been assembling a prototype at the National Solar Observatory. "But now we're reasonably sure that we'll get the data for high-quality science." A so-called breadboard model has already seen first light and detected the historic five-minute oscillation.

Timothy Brown of NCAR pioneered Fourier tachometry; the GONG instrument, says Harvey, is a product of the evolution of that technology. Sunlight first enters through an eight-centimeter



National Optical Astronomy Observatories

GONG output. Velocity image produced by proto-GONG breadboard optical system. Lighter shades indicate gas rising from the sun's surface; darker shades, sinking. Shade gradient is caused by solar rotation; anomalous texture shows supergranulation and sunspots.

telescope, or light-feed, that automatically tracks the sun over the course of a day. This light passes through a filter that isolates a specific spectral line, in this case the nickel I absorption line at 6,768 angstroms. These red rays then enter the heart of the Fourier tachometer, a compact Michelson interferometer in the form of a cube 2.5 centimeters on each side.

As with many interferometers, this cube splits the incoming light into two parts, routes each beam along a different pathway, and then recombines the two beams. If the light waves are in phase, or in step (peak matching peak), the two beams will add up to a bright signal; out of phase (peak matching trough), the two waves will combine to produce a dark image.

The Fourier tachometer's keen ability to detect small Doppler shifts on the solar surface results from the makeup of the cube: one pathway or arm is solid glass; the other is air. With such different pathways (the glass arm is 30,000 wavelengths longer than the air arm), a tiny change in the wavelength of light entering the interferometer results in a measurable change of phase when the two beams are recombined. These phase shifts thus indicate the way in which motions on the sun are increasing or decreasing the original 6,768-angstrom wavelength.

The output image of the interferometer, which encompasses the entire solar disk, will ultimately be focused on an electronic detector with an array of more than 65,000 pixels. Each pixel will record the signal intensity and phase at that point on the sun. At the field stations a complete image will be recorded once a minute. In this way, GONG scientists should detect any solar oscillations of durations of three or more minutes.

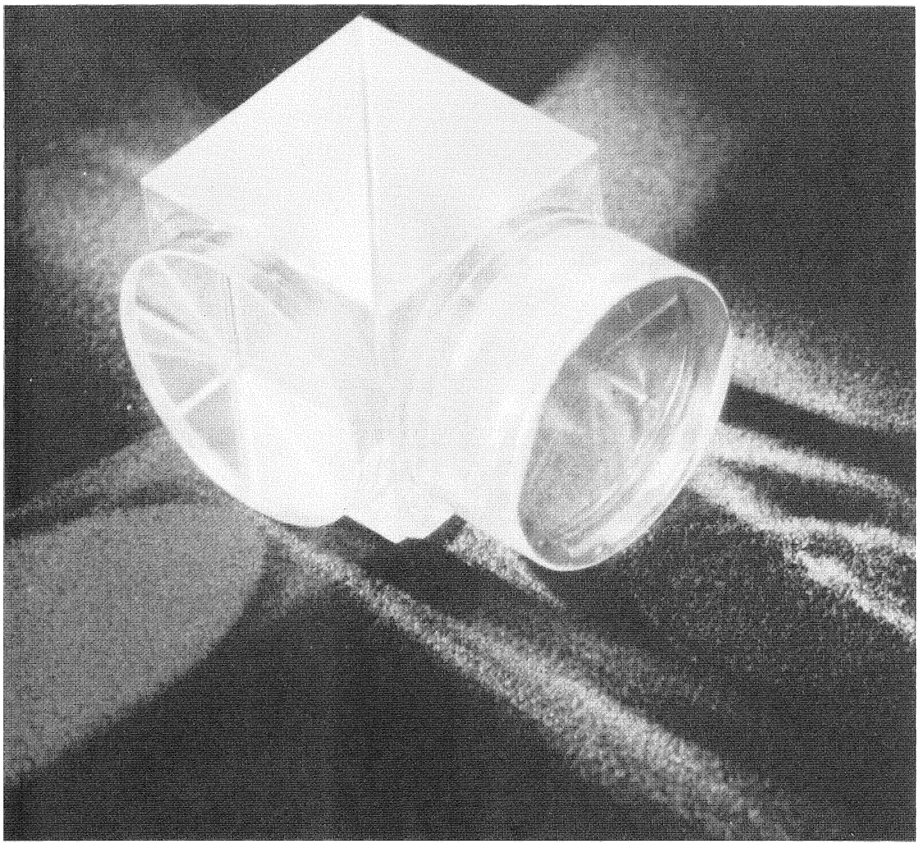
GONG software specialists are now developing a special program called GRASP, for GONG Reduction and Analysis Software Package. This software will allow users to browse, view, and select the data sets they wish to interpret within the archives. A major challenge, though, still confronts the software analysts: determining a way to merge the data from six separate sites to achieve a continuous record of measurements. Every image from each station must be adjusted, pixel by pixel, to reconcile differing instrumental, geometric, and photometric effects.

Meanwhile, GONG theorists must learn to invert the overwhelming sets of data anticipated. To hone their skills, they have been conducting a series of hare-and-hound exercises. A leader (the hare) selects a set of data mimicking an observation of the solar vibrations and sends it out to participating theorists (the hounds). Each theorist, in turn, tries his or her preferred procedure to arrive at the correct interpretation of a particular solar parameter.

This playful competition is allowing helioseismologists to determine the strengths and weaknesses of various inversion schemes. "It also tests whether we're skillful enough," says Toomre, "to ferret out hidden bits of information about the sun from the frequencies. It's a lively detective hunt."

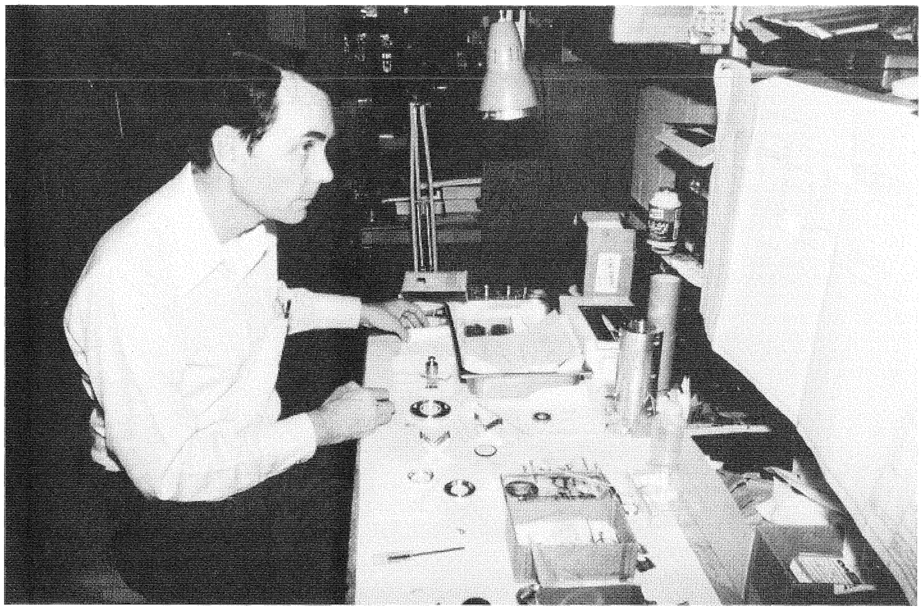
Tremor-hunting in space

Ultimately, atmospheric fluctuations prevent observers from studying the highest-degree modes, which are tinier and in need of 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



National Solar Observatory

Heart of the GONG. The Michelson interferometer at the heart of the tachometer receives sunlight and splits the beam into two paths, one of which passes through glass and one through air. When recombined, beams in phase will produce a bright signal; any others will appear dark.



National Optical Astronomy Observatories

Hands on. Jack Harvey assembles a prototype of the GONG instrument for the global network.

included on SOHO, the Solar and Heliospheric Observatory, a joint project of the European Space Agency and NASA. Scheduled for launch in 1995, SOHO will be placed at a Lagrangian point one million miles sunward from the earth. 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.

At Stanford University, Philip Scherrer and a 14-member international group, along with collaborators at the Lockheed Palo Alto Research Laboratory, are developing a SOHO instrument called the Michelson Doppler Imager, or MDI. It will perform both long-term Doppler scans, up to two months of continuous coverage at one image per minute, as well as daily readings.

Scherrer and his group hope to measure solar vibrational modes with degrees from one 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 surface make them the most elusive of the sun's oscillations. "I was one of the few brave ones to report on *g* modes in 1983," says Scherrer, "but I wouldn't bet on that finding now." Later observations failed to support the reported sightings to everyone's satisfaction. In fact, years of data collection, out 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," says Scherrer, "for the detection will enable us to peer down into the sun's core."

Helioseismologists are not stopping at the sun. Already a few adventurous observers have looked for seismic quivers in other stars, a technique which offers astronomers the chance to plumb other stellar interiors. Analogues to the five-minute oscillations of the earth's sun have been reported in such stars as Alpha Centauri A, Procyon, and Epsilon Eridani.

"The observational data from the solar interior have expanded tremendously," Jorgen Christensen-Dalsgaard, Douglas Gough, and Juri Toomre say. "As a result we can now study the sun at a level of detail that would have seemed hopelessly out of reach only a decade ago." John Leibacher concurs. "Helioseismology is an area ripe for discovery, and in ways we may not be able to anticipate." •

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