Tones of the Oscillating Sun

Helioseismology, the study of the sun's oscillations, promises new insights into solar structure and evolution, and possibly the general theory of relativity as well

By ALLAN CHEN

The sun is ringing like a bell, but astronomers are watching, not listening, to the tones it produces.

By studying this ringing — the oscillations of the sun — they hope to learn about the sun's interior without viewing it directly. "Helioseismologists" may be able to deduce from these oscillations how large the sun's core is, how rapidly the core rotates, how much helium and heavier elements the core contains, and whether or not Einstein's theory of general relativity will need revision. Helioseismology is analogous to seismology on earth, where seismic waves — earth's own ringing caused by earthquakes — are studied to learn more about the structure of earth's interior.

Robert Leighton and his colleagues at the California Institute of Technology in Pasadena first noticed in 1960, while they were studying features on the solar surface, that parts of the sun's surface were oscillating in and out. The period of the oscillation, one in-out cycle, was about five minutes. Over the next 15 years, others studied the disk of the sun, looking for evidence that the whole sun, and not just some of its parts, was oscillating.

The magnitude of the oscillation is so small that it is not possible to detect it visually — fluctuations in the earth's atmosphere cause the sun's image in earth-based telescopes to quiver more than the quivering of the solar oscillations themselves. The early helioseismologists were more successful at observing the oscillation by using the sun's Doppler shift. That is, they observed opposite points on the edge of the sun and measured the shifts in the wavelength of light leaving the edge. The light's wavelength shifted very slightly as the edge's velocity increased and decreased with the sun's oscillating edge. In this way, solar observers eventually demonstrated that the whole sun is vibrating with a period of five minutes.

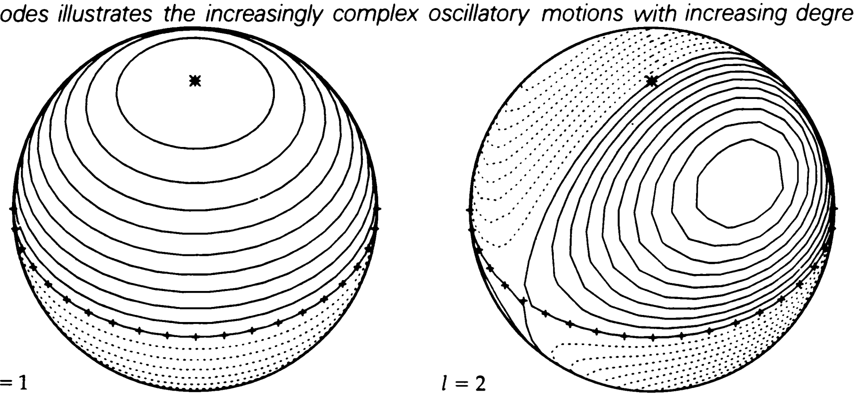
But from there the situation gets complicated. The sun does more than expand and contract uniformly. Solar astronomers found that it has many different "modes" of oscillation, from the simple uniform expanding and contracting oscillation to much more complicated patterns of motion that make of the sun's surface an intricate pulsating weave of bulges and depressions that cannot be observed visually. In the more complex modes, certain portions of the surface expand while others contract. All of the modes are superimposed on one another.

When the Doppler shift of points on the solar surface is measured over time, that measurement represents the sum of many, perhaps thousands, of different modes of oscillation as well as "noise" from local fluctuations on the sun and from within the measuring instrument. Helioseismologists have had to use complicated data processing techniques to "separate out" frequency data corresponding to each mode of oscillation. Identifying a frequency with its mode is still a problem for helioseismologists whose data are not always distinct or complete enough to make the identification possible.

Still another complication is that not all the modes have a period of five minutes. Beginning in 1966, Henry Hill of the University of Arizona at Tucson and his colleagues began to find evidence of longer-period oscillations, ranging from about 20 minutes to one hour long. By 1975 they had amassed considerable evidence that these oscillations, too, were global, not local, oscillations of the sun. And in 1976, a group working at the Crimean Astrophysical Observatory in the Soviet Union reported seeing a 160-minute oscillation. Their result was later confirmed by Phillip Scherrer and John Wilcox at the Institute for Plasma Research in Stanford, Calif., and by a French-American team using an observing station at the South Pole to watch the sun continually over several-day periods during the polar summer. Not everyone is convinced that the observations of Hill and the Crimean group truly represent global oscillations, and the significance of these data is still being debated (SN: 4/22/78, p. 253; 4/21/79, p. 270; 8/16/80, p. 100).

No one knows why the sun oscillates. But a step was taken toward explaining how it does in 1970 when Roger Ulrich of the University of California at Los Angeles suggested that the five-minute oscillations were like sound waves in the solar gases, only more complex. In the sun, the sound waves originate in the hot gases of the sun's convection zone, a zone where heat is transferred by the movement of the gas itself, rather than by radiation. A single oscillatory mode can be "broken down" into a set of sound waves of many different frequencies. Helioseismologists characterize each member of this set by using several parameters. One parameter, the "degree," is important because it relates in a rough way a sound wave in the set to its depth range in the sun's convection zone. Different degree waves have different depth ranges. The higher the degree of the wave, the deeper the wave ranges into the sun's core, although degree alone does not determine the wave's depth range. This is important to helioseismologists who would like to observe higher-degree modes so that they can "see" farther into the core.

According to Ulrich's theory, oscilla-

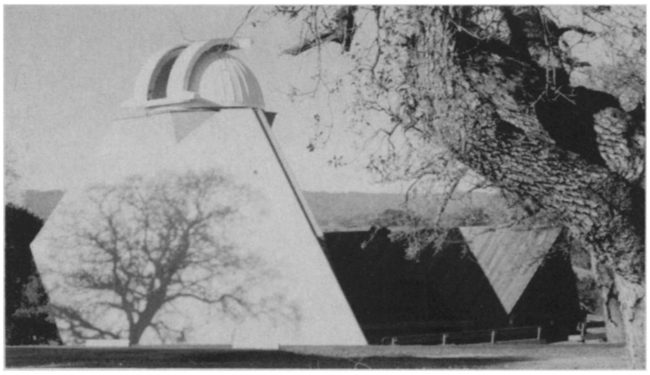


Contour plots of selected modes of oscillation of the sun. The solid lines represent zones of modes illustrates the increasingly complex oscillatory motions with increasing degree.

$l = 1$

$l = 2$

Allan Chen is a former Science News intern.



The Stanford Solar Observatory in the Santa Cruz Mountains just west of Stanford University. Observations of solar oscillations were begun here in 1975. Other teams have searched the sun from the Crimean Peninsula, the South Pole, the Canary Islands and Hawaii.

Stanford Univ.

tions of a "given" or "certain" degree will stay within certain depth limits of the convection zone. They are free to propagate within the spherical shell marked by these limits. The waves will bounce off the upper limit of the shell because the density of the convecting gases is not high enough to allow the waves to go any closer to the surface. At the lower limit, the increasing density of the gas will cause the waves to refract back toward the surface, according to the theory.

Ulrich's ideas explain all of the modes of oscillation with fairly short periods, including the five-minute modes, as acoustic waves in the convection zone. Since the energy in the waves is transferred by the back and forth motion of heated gases (just as sound is transmitted on earth), the modes with short periods of less than 30 minutes are called p-modes or pressure modes. One of helioseismology's early successes was in helping to establish the upper boundary of the sun's convection zone. Helioseismologists now believe that the zone begins at a depth of about one-third of the sun's radius from its surface, a higher figure than what was gleaned by other methods. The lower boundary of convection has not yet been fixed.

No one has been able to explain what drives the p-modes to oscillate at all. Scherrer says that one possibility is that the convection zone is "randomly exciting itself" through irregularities of its own motion.

Jorgen Christenson-Dalsgaard, currently at the National Center for Atmospheric Research in Boulder, Colo., argues that the sun's p-modes are analogous to "blowing through a flute. The [turbulent convection of the air] at the mouth of the flute excites sounds in the tube. Similarly, the turbulent convection of the sun may excite p-mode oscillations." The cavity of the flute generates tones with many different frequencies, just as the cavity of the sun excites different modes. In the flute, the fundamental tone has a wavelength equal to the length of the flute's cavity. Higher tones have wavelengths of one-half, one-quarter, one-eighth the cavity's length, and so on. Analogously in the sun, convection may excite a wave to form whose wavelength equals the length of the shell, or two waves whose length is one-half the shell, and so on. The fundamental wave plus all of the overtones together form the family of waves that make up one mode of oscillation.

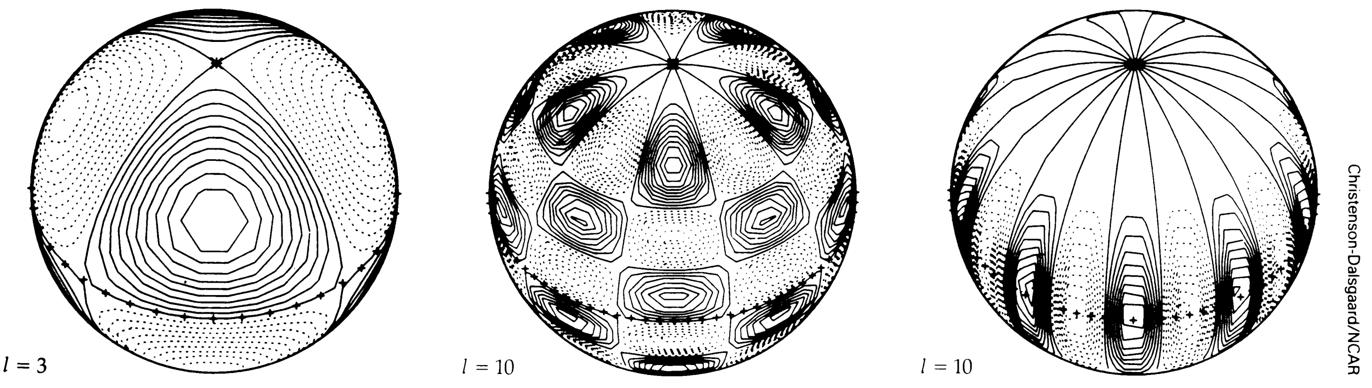
A second type of solar oscillation is the gravitational or g-mode, with periods of more than 30 minutes. Here, the force that maintains the oscillation is the force of gravity itself. Closer to the sun's center, the density of its hot gases increases. When higher-density gas moves up into the lower-density region, a restoring force called "buoyancy" tends to pull the high-density gas back in. The result is an oscillation of the gases within the sun's core maintained by the differential pull of gases of different densities upon each other.

According to Thomas Duvall of the Laboratory for Astronomy and Solar Physics of the Goddard Space Flight Center in Greenbelt, Md., "G-modes are more concentrated at the core...[they] don't propagate in the convection zone." However, because they can't get through the convection zone from the core, they should be difficult to observe. Nonetheless, some helioseismologists, including Scherrer at Stanford and Hill at Tucson, believe that the longer-period oscillations are g-modes. Duvall says, "There's a certain range of frequencies above which g-modes won't exist. The shortest-period g-modes should be around 30 minutes." Scherrer believes that g-modes can be observed because the motions of the sun's core could lift the whole convection zone up and down, and this motion would be visible at the surface. There is still no general agreement that g-modes have ever been observed.

With information about the sun's oscillatory modes, solar physicists can mathematically infer the solar core's size, rate of rotation and composition. But to effectively use the modes, helioseismologists say they need more observations of them, as well as observations of the weaker, higher order modes that they have not yet identified. The problem is that solar observers cannot observe the sun continuously at one station for longer than the length of the day. Scherrer explains, "What you need is to observe [the sun] for several [of its] rotational periods continuously for two to three months without gaps. ... In theory, by combining observations at two stations, you can get 24-hour coverage." In practice, instruments at two stations cannot yet be calibrated accurately enough to work in tandem, he says. "Right now, what the modes are is the main question...until observations can be replicated, we can't do any more physics."

Continued on page 395

expansion, the dotted lines, contraction. Only five of thousands of possible modes are shown. l is the degree of the mode. This selection of



Christenson-Dalsgaard/NCAR

track in the sky will have shifted more than that in declination since the petroglyphs were made. (The angle between the sun's track in the sky and the earth's equator — that is, the sun's declination — changes 0.12° per millenium. In one millenium or so that is not enough to destroy the sun-petroglyph relations at these sites.)

At other times observations may be made on a day close to the desired day, and predicted or observed motion of the sun's position be used to compensate. Finally, the moon may be used when it happens to stand at an important solar position. "The moon has just reached the declinations of the summer and winter solstice sun for the first time in nine years," Preston and Preston point out. "This will happen every month for the next nine years."

Even so, time was short, and many sites had to be investigated. The program depended, therefore, on accurate prediction of which petroglyphs were likely to be solar markers. Nevertheless, the Prestons say, "no solar interactions have been claimed unless we observed them."

Their work now indicates that solar observatories of the sort were numerous and widespread in Arizona, and they refer to related findings in California and the Baja California peninsula. One of their comparisons of sites at opposite extremes of the territory they searched runs:

"[At the Painted Rocks site] 45 days before or after winter solstice two pointers move from left to right across the rockface. The leading tip of the first pointer brushes tangent to the lizard's body. The leading tip of the second pointer intersects the center of the cross....

"On this same day in the Cave of Life, 350 km to the northeast, the trailing tip of a pointer dies in the center of a cross at sunset. In both instances, the cross interactions happen only on that day."

The petroglyph makers seem not to have altered the natural rock configurations. They seem to have taken note of fortuitous plays of light and shadow on the appropriate days, and drawn in their markers to fit.

"Archaeologists are going to be busy," says Curtis Schaafsma, director of the Laboratory of Anthropology at the Museum of New Mexico in Santa Fe and State Archeologist of New Mexico. As a result of the Prestons going around and finding empirical correspondences of this sort, they have provided a large data base, he says. Archaeology "has to assimilate a large block of information," and produce meaningful and coherent models to explain it, possibly hypothesizing a prehistoric religion that would account for it.

The Prestons' work "has considerable value," says Fred R. Eggan, retired head of the Department of Anthropology at the University of Chicago, now a resident of Santa Fe. Eggan thinks it particularly important that the data were compiled "out of [Robert Preston's] astronomical knowledge."

The modern Hopi and Zuñi, whom Eggan has studied for decades, also do a lot of sunwatching. They have a lunar calendar that has to be fit to a solar year, because the sun governs their agriculture, which is precarious. Eggan points out that the Hopi and Zuñi must live with a season of about 130 days to grow corn, "caught between last and first frost." In a situation as tight as that, they "have to predict when to start planting in order to get through." The sun is more accurate for that than the daily vagaries of the weather. In the same region, with very little climatic change over the last thousand years, the Anasazi would have been under similar constraints.

In modern Zuñi and Hopi society, each pueblo is autonomous, and each does its own sun-watching and keeps its own calendar. If the Anasazi were organized like their modern descendants, they too would have needed a lot of fairly simple sunwatching sites, one for each group or pueblo. (Schaafsma, too, stresses the need for a lot of observatories to serve each independent pueblo.) This is just what the Prestons have found, Eggan points out: "a whole series of simpler models [than Fajada Butte]. There's no doubt that they are genuine and culminated in a more sophisticated observatory on Fajada Butte." □

Continued from page 393

Recent work by Duvall, and J.W. Harvey at Kitt Peak National Observatory in Tucson, Ariz., and by Duvall, Harvey and Martin Pomerantz of the Bartol Research Foundation in Newark, Del., at the South Pole, may provide some of these observations. Reporting on their preliminary results in the March 3 Nature, Duvall and Harvey say they have observed p-mode oscillations for the first time from degrees 6 to 140. The higher the degree of the oscillation, the deeper within the sun the oscillation penetrates, and the more information about the sun's interior it brings.

One question on which these data may shed light is the abundance of helium and heavy elements in the sun's core. How the sun burns hydrogen to form helium and heavier elements is poorly understood. There exists a model of the process that depends on knowing the hydrogen, helium and heavy element content. But this model is in doubt because other solar physicists, using a different approach to studying the sun's interior, have not been able to detect a sufficient number of neutrinos, massless elementary particles, that should be produced by the sun's burning core (SN: 6/30/79, p. 420; 2/17/79, p. 103). To explain the lower neutrino count, the theorists may have to assume there is less helium in the sun than supposed by the model. However, Christenson-Dalsgaard believes that Duvall and Harvey's data support the current model's higher helium abundance, in opposition to the neutrino evidence. Further study of the solar modes may help resolve this contradiction.

The solar oscillation data may also solve the riddle of the sun's rotating core, and whether or not Einstein's theory of general relativity will need revision if the core is found to be rapidly rotating. Physicists first suggested in the 1960s that the theory, which concerns the nature of gravity, might need to be revised. Robert F. Dicke of Princeton University and his colleague Carl Brans developed an alternate theory of gravity. They argued that the orbit of Mercury would be affected in a slight but measurable way, if the sun's core were rotating more rapidly than had been assumed when Einstein developed his theory. The core's rapid spinning should cause the sun to flatten out slightly, and the flattening's gravitational influence on Mercury's orbit could be measured. The magnitude of the gravitational effect should be different from what Einstein's theory predicted.

Since 1966, Hill and his colleagues have been trying to determine if a modification of general relativity is necessary by studying the sun's flattening and its oscillations. Hill's team recently published data concerning the long-period oscillations (20 minutes to one hour) in the January Solar Physics and the Dec. 13 Physics Review Letters that Hill feels call general relativity into question. "These are gravity modes with periods that are large. This is information about the deep core," he says. The team has calculated that the sun's core rotates very rapidly, about once every four days. (The sun's surface rotation varies with position on the surface. It ranges from 27 to 35 days per rotation.)

Dicke, meanwhile, began to change his views around 1973. He now argues that the five-minute oscillations (not the longer-period oscillations of Hill) indicate the sun is rotating only about once every 12.5 days. Still other theorists have also come out with different interpretations of the data. Everyone working in the field contacted by Science News agreed that no one agrees on how fast the sun's core is rotating. Dicke says, "Anything as fundamental as a [modification of relativity] requires a more strongly based set of measurements than what we have available."

Hill, by contrast, is optimistic that the available and soon-to-be-available data will lead to new developments in the field. He likens the state of helioseismology today to spectroscopy (the branch of physics that probes matter by observing the electromagnetic radiation it absorbs or gives off) in the 1940s. Spectroscopists then had "hundreds of [observations] and 10 models, but only one of those models will fit. This decade is going to be a really exciting one because we have a lot of observational data. The important thing is not whose model is correct, but that we are on the threshold of a new understanding about the sun." □