

match between it and GaN in both the lattice constants and the thermal expansion coefficients, leading to the formation of cracks. Moreover, sapphire is expensive. Another candidate, silicon carbide, is even costlier, but it provides a better lattice match than sapphire wafers and is a conductor rather than an insulator.

Progress was made in the substrate problem in 1986 when Isamu Akasaki (now at Meijo University) and his colleagues at Nagoya University found a way to grow high-quality GaN on a sapphire substrate.⁵ The trick was to lay down a thin film of aluminum nitride at low temperature to serve as a buffer layer between the sapphire and the upper crystalline layers of GaN grown at higher temperatures. The buffer layer helped to decrease the dislocation due to lattice mismatch.

A second hurdle for the GaN materials was the absence of a p-type nitride. Researchers were having trouble getting acceptor ions, such as magnesium, to occupy the Ga sites. In 1989 the Nagoya University group found a way to dope GaN successfully with magnesium by irradiating the sample with an electron beam immediately after deposition.⁶ With that sample, grown on a GaN buffer layer, the Nagoya group demonstrated that one could get a p-n junction. Three years later, Nakamura and his colleagues got p-type GaN by heating the sample in a hydrogen-free atmosphere.⁷ The Nichia Chemical researchers deduced that hydrogen from the ammonia used in growing the laser devices was surrounding and deactivating the acceptors.

A third challenge in developing a GaN-based laser was to make suitable mirrors on opposite sides of the cavity to reflect the light back and forth through the active region. With many conventional semiconductor lasers, one produces mirrored surfaces by cleaving one side of the stack along a crystal face. But the cleavage plane of GaN is rotated 30 degrees with respect to that of a sapphire substrate. Instead of cleaving, then, the Nichia Chemical

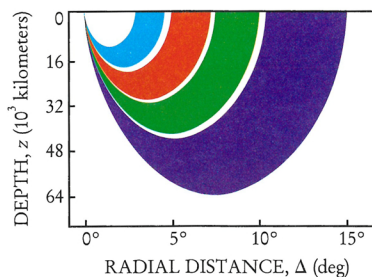
team used reactive ion etching to expose opposite sides of the stacked semiconductor layer. They then applied a dielectric coating to the etched edges to serve as the mirrors. The resulting mirror is not as smooth as that of a cleaved surface. An alternative approach with future lasers might be to fabricate a vertical cavity laser, in which the light would shine out of the top of the laser rather than emerging from the sides. John Edmond of Cree Research told us that cleaved faces are possible with SiC substrates, whose crystal planes line up with those of GaN.

Akasaki, who announced the ultraviolet laser diode last month, and his colleague Hiroshi Amano at Meijo University told us of other important steps, made by a number of research groups, in the development of a GaN laser diode. The steps included control of the conductivity in n-type nitrides, growth of both aluminum gallium nitride and gallium indium nitride alloys by metallo-organic chemical vapor deposition (AlGaIn is used in the cladding layers and GaInN is used in the quantum well structure) and fabrication of a multiple quantum well structure.

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AS SOUND RAYS PROPAGATE deeper into the Sun, they refract away from the normal until they are reflected back toward the surface at a depth, z , that depends on the phase velocity, $v_p = \omega/k$, and the initial propagation angle. Thus, by sampling waves with different wavenumbers or that emerge at different distances Δ from their starting point, one can sample the Sun to different depths. (Adapted from ref. 2.)

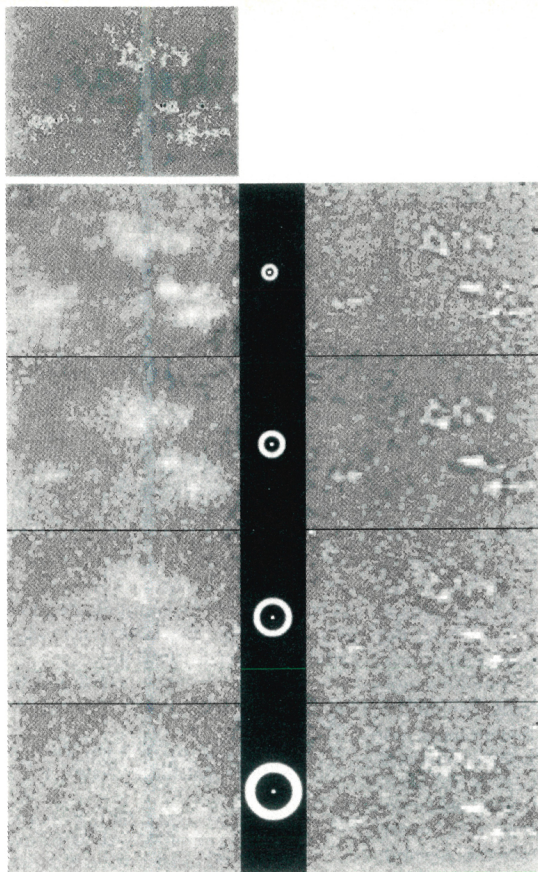
take place on a local rather than a global scale. In terrestrial seismology, local structure is usually mapped using sound-ray tracing techniques, in which one infers the properties of matter along the paths of sound rays from how the matter affects the rays' arrival times. Studying the Sun's local processes is a much more complicated undertaking. In contrast to the localized earthquakes that generate Earth's seismic waves, vibrations on the Sun are excited stochastically and uniformly across the solar surface by turbulent subsurface convective flows. Moreover, solar seismic waves are evident from Earth, 1.5×10^8 km away, only as subtle Doppler shifts of spectral lines, or as slight changes in surface brightness.

In spite of the difficulty of extending helioseismological techniques to the study of local solar processes, researchers have been strongly motivated by the potential payoff. Recently several studies¹⁻⁴ have tried to extract information on local solar phenomena from the preponderance of seismic signals by looking at statistical correlations between brightness at points on the Sun as a function of time and of the distance between the points. So far, these studies have focused on sunspots—relatively low-temperature (and hence dark), high-magnetic-field regions on the Sun's photosphere that have fascinated and puzzled observers for well over 2000 years. Many researchers hope that such studies will eventually allow us to understand the causes of sunspots and the connection between sunspots and a variety of other phenomena, including the 22-year solar magnetic cycle. However, the intriguing and occasionally confusing results produced to date indicate that

Sound from Sunspots Generates Heat As Well As Light

As in terrestrial seismology, helioseismological studies of the Sun's normal modes of oscillation have done much to illuminate its global structure, internal rotation and composition. (See the article by John Harvey in *PHYSICS TODAY*, October 1995, page 32.) However, as with Earth, many important processes in the Sun

Helioseismologists are just beginning the difficult task of investigating local solar features and processes. Their intriguing if somewhat confusing results to date suggest that they may eventually illuminate the dynamics of sunspots and other important solar phenomena.



FEATURES IN THE SUN affect the speeds of sound rays propagating along paths like those in the figure on page 20, causing them to arrive again at the surface at slightly different times. The photo at top left shows a portion of the Sun as it appeared during the observations. The column on the left (below the photo) shows the average excess arrival time. White features correspond to early arrivals, dark ones to late arrivals and gray ones to zero excess arrival time. The column on the right resolves flows and other directional perturbations by looking at the difference in arrival times of rays propagating out from and in toward the central point of the annuli. In the white features, outward-going waves travel faster than inward-going waves; the reverse is true for dark features. Each image in the two columns samples waves emerging in annuli of the same size as the annulus shown in the vertical black strip to its right or left. These annuli correspond roughly to maximum sampling depths of (from top to bottom) 16 000, 32 000, 48 000 and 64 000 kilometers. (Courtesy of Tom Duvall, Goddard Space Flight Center.)

much work must be done before such hopes can be realized.

Tracing the sound of the Sun

As a wave of angular frequency ω and wavenumber k propagates down into increasingly dense regions of the Sun, it refracts away from the normal until its phase velocity, $v_p = \omega/k$, is equal to the sound speed. At this point the wave reflects back toward the surface, where it is again reflected into the interior. If the Sun were homogeneous, one would expect the rays to follow identical paths repeatedly, always taking the same time to emerge the same distance from their last appearance at the surface. However, local inhomogeneities, or perturbations, in composition, temperature, flow or magnetic field along the paths of some rays may cause them to arrive early or late. Furthermore, by looking at how the perturbations affect rays propagating in different directions, one should be able to tell whether the perturbations are directional (for example, a velocity field) or not. Finally, by sampling waves with large phase velocities or steep downward initial angles, one can look at perturbations deeper inside the Sun.

Tom Duvall (Goddard Space Flight Center), Stuart Jefferies (University of Delaware), John Harvey and Sydney

face.¹ By varying Δ , the researchers could look at different depths within the Sun. (See the figure on page 20.) To look for nondirectional perturbations, Duvall and his coworkers examined the mean travel time for all rays through a region. They also looked for flows by measuring the difference in travel time for rays converging on and diverging from the center of the annulus. From their "mean" travel time map, the researchers discerned possible evidence near sunspots of a vertical magnetic field on the order of 2 kilogauss, increasing to 4 kG at a depth of 600 km. In their initial studies, they also saw bands of travel-time perturbations that varied with latitude symmetrically about the equator. Subsequent studies, made with an improved technique, showed little evidence of such a banding structure, although it remains to be seen whether the bands were purely an artifact of the original technique. (The corrected figure is shown on this page.)

In the "difference" map, Duvall and his collaborators saw strong evidence that seemed to indicate downdrafts below sunspots. Studies of models suggested that their data could be explained by a cylindrical downflow with a diameter of about 6000 km and a depth that depended on the velocity of the downflow: If the velocity is 1 km/s,

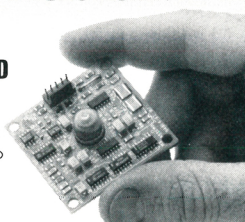
the model would require a depth of 10 000 km to fit the data; if the velocity into the downflow were 2 km/s, the downflow would have to be only 2000 km deep. Eugene Parker of the University of Chicago had previously predicted that such a downflow might be necessary to hold together the magnetic field in a sunspot against its magnetic pressure.

Alexander Kosovichev of Stanford has developed a tomographic inversion technique that divided the Sun into rectangular blocks whose properties were assumed to be homogeneous and constant.² Upon inverting the travel-time observations to determine the sound speed for each block, Kosovichev saw evidence of downflows extending more than 16 000 km below the sunspots.

On the other hand, the time-distance results obtained by Kosovichev and by Duvall and his collaborators are difficult to reconcile with those of the Doppler acoustic diagnostic technique developed by Charles Lindsey and Douglas Braun (Solar Physics Research Corp), Jefferies and Martin Woodard (University of Delaware), Yu Hong Fan and Yeming Gu (National Solar Observatory) and Seth Redfield (Tufts University).³ This technique measures local perturbations by the shifts they cause in the wavenumbers and phases of rays propagating through the solar interior. Instead of downflows below sunspots, Lindsey and his coworkers observed evidence for extended outflows around the sunspots. These outflows typically had speeds on the order of 250 meters per second and were strongest below a depth of about 16 000 km, weakening substantially at shallower depths and essentially vanishing at the surface. The outflows seemed to evolve rapidly and to sink as the sunspot aged. At depths of less than 4000 km, Lindsey

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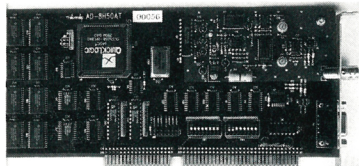
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and his collaborators also saw evidence of extended 200-m/s flows from the solar equator, which had almost no sunspot activity, into latitude bands with higher sunspot activities.

In another analysis,⁴ Braun, Fan, Lindsey and Jeffries used a technique called Fourier-Hankel decomposition to look at the frequency shifts of sound rays in an annulus converging on and diverging from the center. By looking at the magnitudes of the shifts as a function of the wavenumber, they concluded that the velocity of the outflow increases nearly linearly with depth, ultimately having a magnitude of 200 m/s at a depth of 20 000 km.

Resolving differences

The seeming disagreements among these investigations are reminiscent of a proverb: A person with one watch always knows what time it is; a person with two is never sure. However, the existence of multiple independent techniques offers hope that they all might be improved by resolving the differences among them. Researchers are now investigating whether different techniques might be sampling different depths within the Sun, or whether additional effects need to be considered. Of course, there is always the possibility that flow around sunspots could be extremely complex, with closely associated downdrafts and outflows. However, according to NSO's Harvey, "My approach to these things is always to blame the observations or the analysis before falling back on the last resort of blaming it on the Sun."

Many of these seeming conflicts may be resolved by improved data that will soon be available. Helioseismology de-

pends critically on obtaining long, uninterrupted observations of the Sun. Up to now, the best available data for local helioseismology have been those taken at the South Pole during the austral summer. However, the GONG network, inaugurated last year with six helioseismological observatories scattered over the globe, is providing almost continuous solar observations, largely uninterrupted by diurnal cycles or bad weather. The SOHO spacecraft began gathering continuous solar seismic data from its position at the L₁ Lagrangian point between Earth and the Sun on 31 March. These data, undistorted by Earth's atmosphere, are expected to have significantly better spatial resolution than any previously available data. Once sunspot activity increases from its current minimum level in the 11-year cycle, such data should help helioseismologists isolate and quantify the effects of sunspots and other local processes.

RAY LADBURY

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