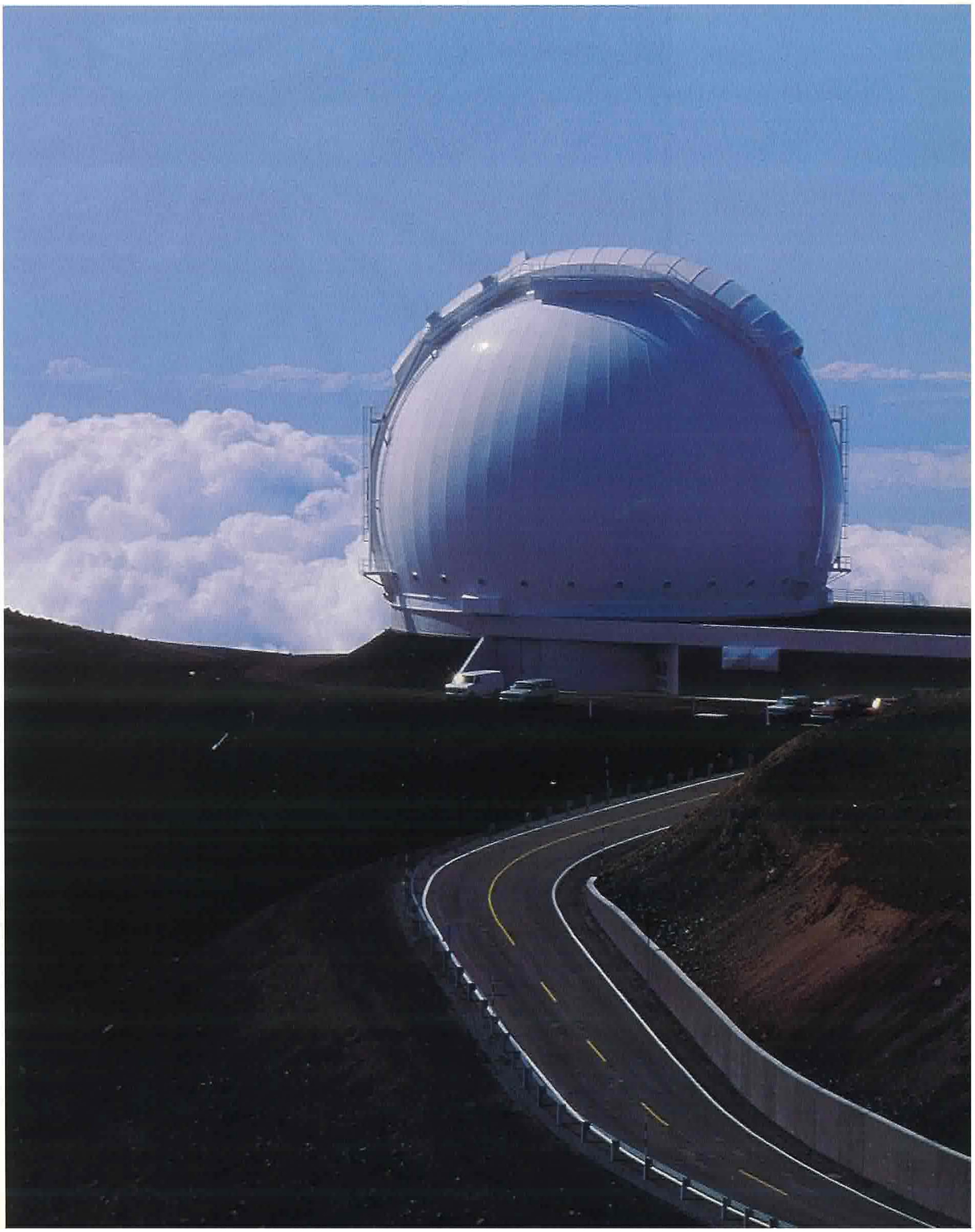
California Institute of Technology

Engineering & Science

Winter 1992



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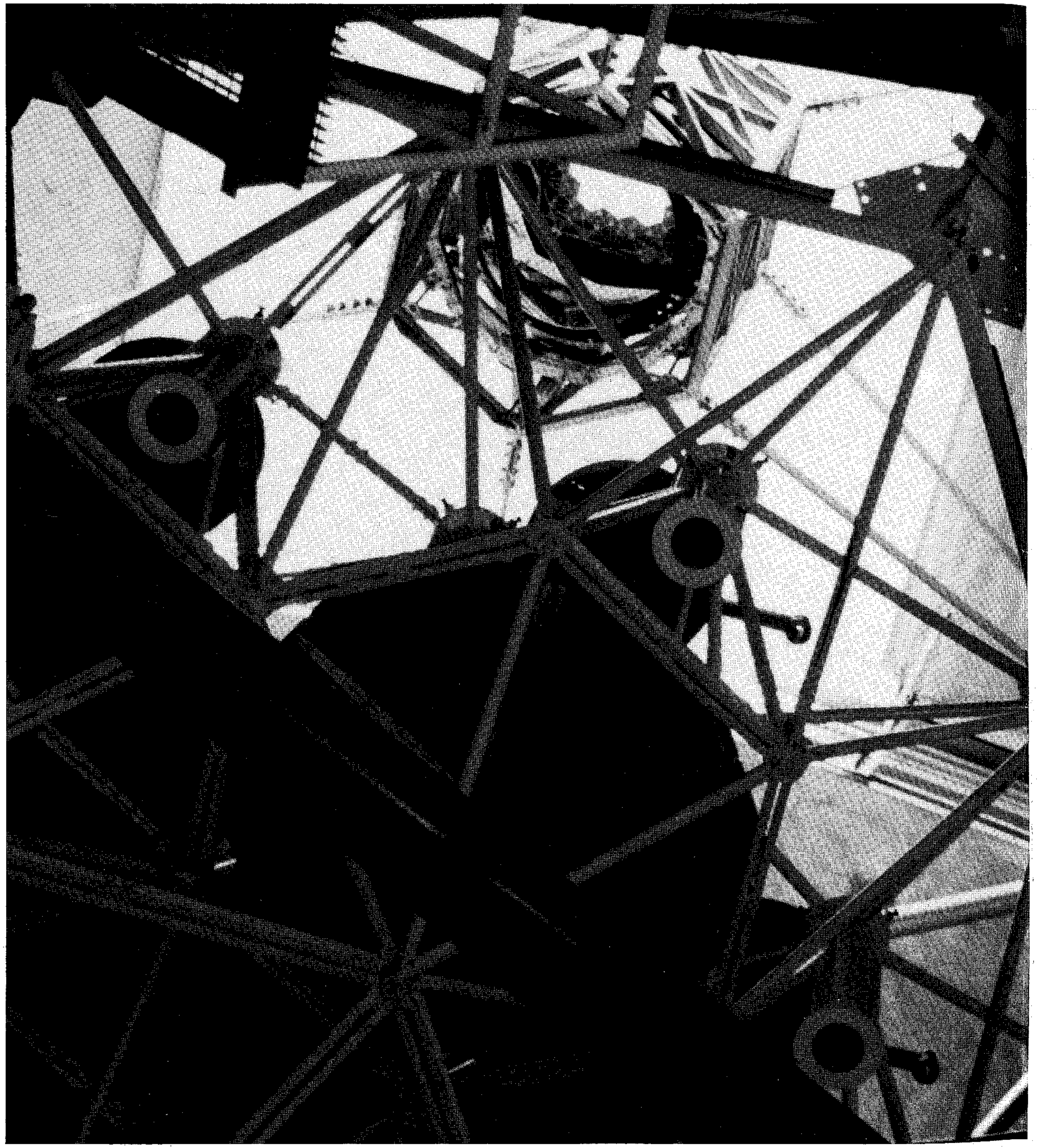

Looking out Keck I's dome through the partially completed primary mirror. The mirror and its supporting frame can be seen reflected in the secondary mirror.

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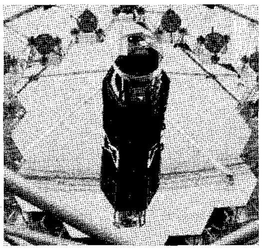

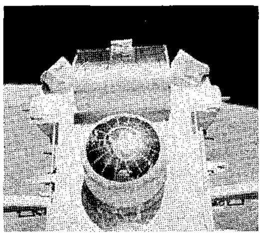

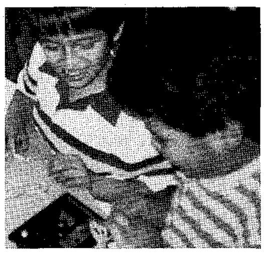

On the cover: The summit of Mauna Kea is prime telescope country. The W. M. Keck Telescope, a joint venture of Caltech and the University of California, is the latest arrival. Keck II, its twin, will be following shortly.

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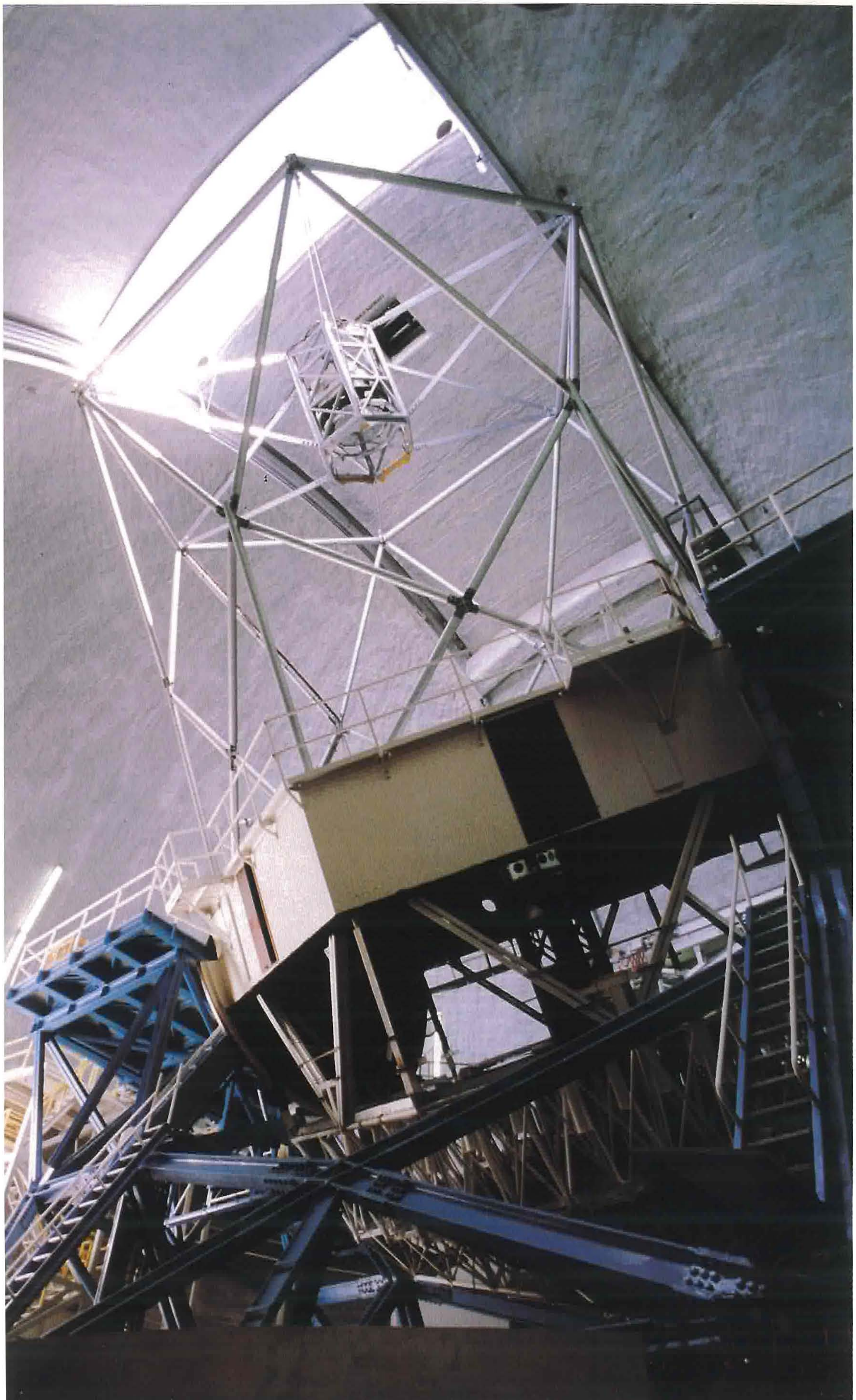


Deep Into That Darkness Peering

Keck's size and instrumentation will make the most of the view.

by Douglas L. Smith

Opposite: The Keck Telescope stands eight stories tall when pointed at the zenith.

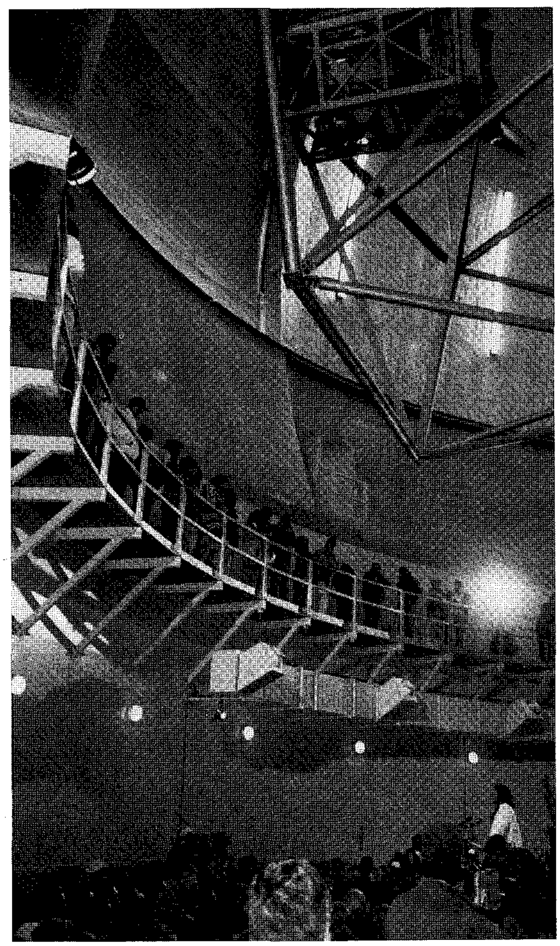
On Thursday, November 7, 1991, some 150 invited spectators from Caltech, the University of California, and the W. M. Keck Foundation joined the observatory staff to witness the dedication of the W. M. Keck Telescope and the ground blessing of the site of Keck II. The twin telescopes, collectively known as the W. M. Keck Observatory, are the latest addition to an international collection of eight others on the summit of Mauna Kea, on the Big Island of Hawaii—the world's finest astronomical site. (Mauna Kea has all the advantages of other mountains of comparable height, plus the virtue of being on an island. Wind takes the path of least resistance, going around the mountain rather than being forced over it, as happens with continental mountains. Thus the air at the summit is very stable. And there aren't any major air polluters—or even dust generators—for thousands of miles upwind, so the air is exceptionally clear.)

It was a bright, windswept day at 13,600 feet, well above the clouds that perpetually cling to Mauna Kea's slopes. Style took a back seat to comfort, as gloves, wool hats, and winter coats supplanted—or at least camouflaged—the jackets and ties normally associated with such rituals. The bulk of the ceremony took place in the telescope's dome, which shielded the crowd from the 15 mile-per-hour wind, but also blocked the sunshine that took the chill off of the 40-degree day.

If the thin, cold air wasn't enough to take one's breath away, the sight of nine tons of mirror supported by blue-painted steel trusswork worthy of a railroad trestle certainly was. At seven meters (nearly 23 feet) in diameter, Keck I was already the world's largest telescope, yet only 18 of its 36 hexagonal mirror segments had been installed. When the final segment is gently lowered into place some time this spring, the 10-meter Keck will have twice the diameter and four times the light-gathering power of Caltech's venerable Hale Telescope, the world's premier optical telescope for more than 40 years. (And when Keck II, an identical telescope sited 93 yards away, becomes operational, the Kecks' combined resolving power should be sufficient to detect warm Jupiter-sized planets, should any be orbiting Earth's closest stellar neighbors.)

The VIPs—a few shivering in nylon windbreakers that had seemed more than adequate at the foot of the mountain—huddled in folding chairs on the dome's floor. The observatory staff thronged the catwalk overhead, on a level with the telescope itself. The ceremony proceeded from a dais set against the telescope's concrete pedestal. The telescope was pointed at the horizon so that its primary mirror, standing vertically at the tube's far end, served as both backdrop and featured attraction. Kalena Silva, associate professor of Hawaiian studies at the University of Hawaii, gave the invocation—a Hawaiian chant, written for the occasion, blessing the telescope and all who will work there. Assorted dignitaries made congratulatory speeches, and Monsignor Charles Kekumano wrapped things up with another blessing in Hawaiian and English. And, finally, the telescope came to life. All watched in silence as 150 tons of steel and glass, floating on a few thousandths of an inch of oil, slowly began to pivot clockwise, as did the dome around them.

Above: Now properly oriented (from left), William Frazer, vice chairman of CARA; Albert Simone, president of the University of Hawaii; David Gardner, president of the University of California; Howard Keck, chairman of the Keck Foundation; Thomas Everhart, president of Caltech; and Edward Stone, chairman of CARA ply their *o'o* sticks at the ground blessing. The sticks were of *koa*, a species of acacia native to the Islands whose wood is prized for making ukuleles.



Right: Under the telescope's secondary-mirror cage, Silva chants the invocation. The ductwork below the catwalk is part of an air-handling system that can replace the entire volume of air inside the dome with outside air every five minutes. This prevents electrical equipment (and humans) from heating the dome air, making it unstable.

Applause broke out as the telescope lifted its eye toward the heavens. Then the dome shutter raised itself with a clatter far louder than any noise the telescope had made. Sunlight flooded into the dome—a flood carefully cut off before it hit the mirror, which would have acted as one of the larger burning glasses since Archimedes.

The crowd then trooped out of the dome, down the observatory hall, and out the far end of the building to a roped-off area, the site of Keck II's ground blessing. A line of *o'o* sticks—traditional Hawaiian digging implements—awaited the dignitaries, who dutifully seized them and lined up shoulder to shoulder in what proved to be the wrong direction. Confusion reigned briefly as the line re-formed under Kekumano's choreography. The phalanx of photographers, who had also been fooled, scrambled for new vantage points. The ceremony resumed and the *o'o* sticks scrabbled briskly in the rust-red volcanic cinders, halting only when Kekumano deadpanned, "That's enough dust, and there's no basement necessary." Many key members of the Keck I team have gone on to other things, but the lessons that they learned have already been incorporated into Keck II's design. Work begins this spring on "The Bride of Keck," as it is sometimes known, with completion set for 1996. The two telescopes were conceived as a single astronomical facility from the beginning, sharing utilities and support staff, and even pooling their starlight through a technique called optical interferometry.

The Keck Observatory is being built and operated by the California Association for Research in Astronomy (CARA), a partnership of Caltech and the University of California, which will get the lion's share of the observing time. Caltech is funding the construction, primarily through a $70 million grant for Keck I and a $74.6 million grant for Keck II, both from the W. M. Keck Foundation. (Each telescope actually costs about $94 million.) NASA has indicated its interest in obtaining one-sixth of the observing time in exchange for putting up a corresponding contribution toward the construction cost. UC is covering the operating expenses for the first 25 years, and funding the development of spectrographic equipment being built by Caltech and UC. The mountaintop site comes courtesy of the University of Hawaii, which operates Mauna Kea's summit as an astronomical preserve, getting a piece of the action in return.

No dedication is complete without a dinner, speeches, and an emcee—in this case Walter Cronkite, a long-time astronomy buff. At the dinner the following day, William Frazer, senior vice president for academic affairs at UC and vice

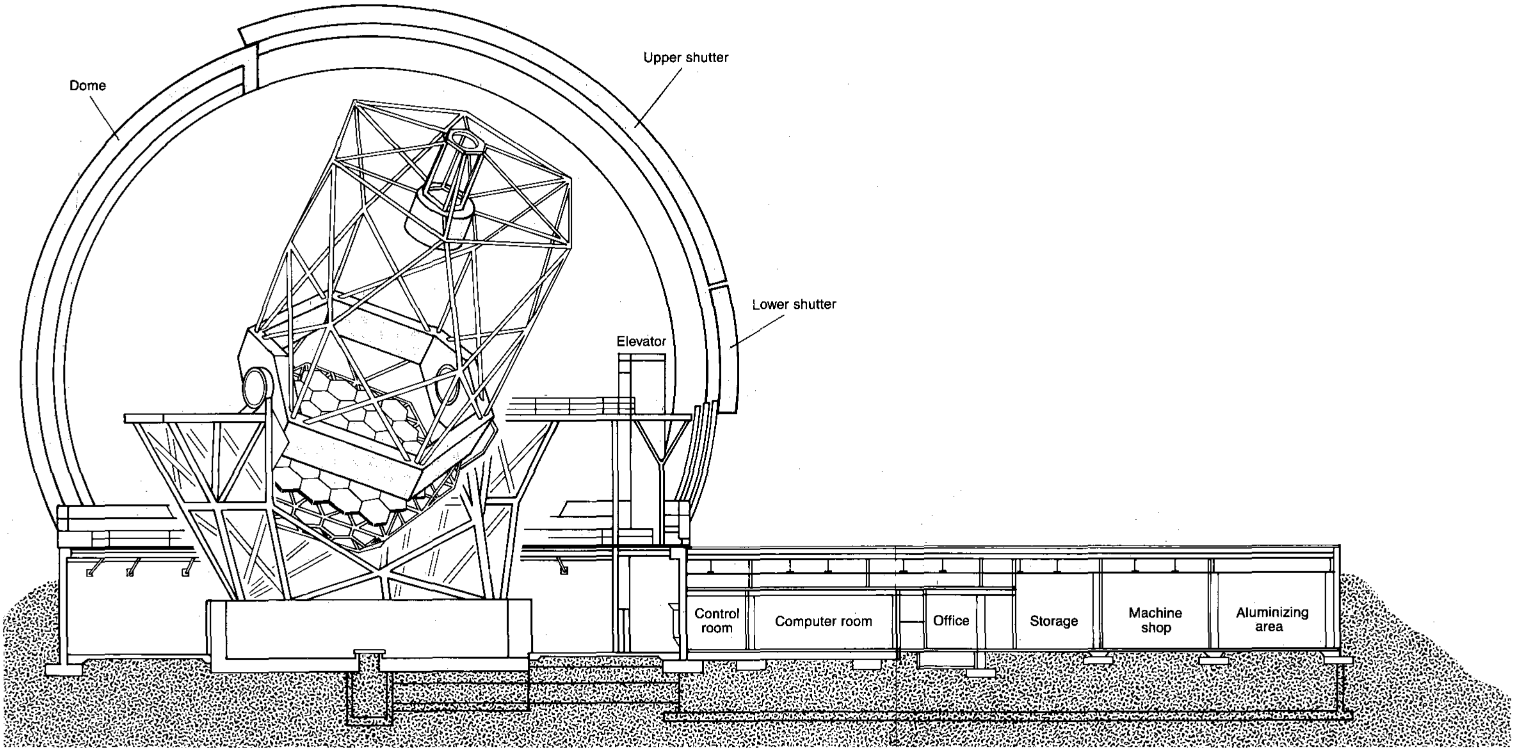


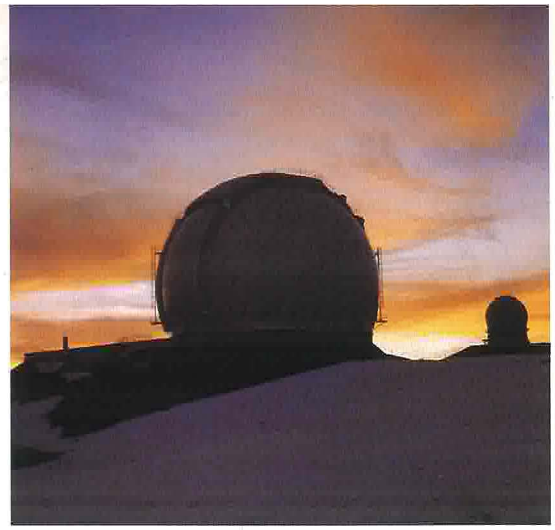
Diagram by Steven Simpson, courtesy of *Sky and Telescope*

A cutaway drawing of Keck I. Keck II will be its mirror image, and will be added to this building just beyond the aluminizing area. Starlight entering the dome falls on the hexagonally segmented primary mirror, which reflects it up to a smaller secondary mirror at the top of the telescope's openwork tube. The secondary mirror reflects the light back down through a hole in the middle of the primary mirror. Small instruments can be mounted under the primary mirror on its supporting frame. The elevator goes up to the Nasmyth platforms, where large, heavy instruments can be mounted, light being directed to them through an opening in the telescope's pivot by a small pick-off mirror. Other mirrors can direct the light down through a shaft in the telescope's pedestal, and thence into a tunnel under the building, for interferometry with the light from Keck II.

chairman of CARA, reminisced about the year of negotiations that led to its founding, including one meeting that took place "while hiking up Buckskin Pass near Aspen, Colorado, with [then Caltech President] Murph Goldberger." After midwifing CARA, Frazer jubilantly announced the birth to the faculty at Berkeley. "I was surprised when our astronomers greeted me with more complex emotions than the hero's welcome I had expected," he said ruefully. "I now understand that it was as if Chancellor Tien of Berkeley had announced to his alumni that he had just signed an agreement with President Kennedy of Stanford to build the world's greatest football team by merging the two schools' football programs." On the other hand, he added that neither school could have gone it alone, a sentiment voiced by several speakers. Frazer noted that Caltech and UC have been "scientific rivals and collaborators for most of this century, a rivalry based on mutual respect" that sometimes manifests itself in odd ways. Berkeley's 184-inch-diameter cyclotron, for example, built during and after World War II, was the "crowning achievement" of E. O. Lawrence, director of UC's Radiation Laboratory. (Lawrence won the 1939 Nobel Prize in physics for inventing the cyclotron.) "Lawrence, looking over his shoulder at Caltech, had proposed a 200-inch cyclotron to match the 200-inch Hale Telescope then under construction. Unfortunately, suitable steel was available only up to 184 inches in diameter." (Incidentally, Hale's telescope has also outlived Lawrence's cyclotron, which was recently dismantled to make way for a new particle accelerator called the Advanced Light Source.)

At one point in the proceedings, Cronkite remarked that "the mere fact of [Keck I's] construction on top of a mountain at 14,000 feet is nothing short of an engineering miracle." Building *anything* on a 14,000-foot mountaintop is an engineering miracle. Judgment clouds at that oxygen-poor altitude, so every move has to be planned in advance down below. A brisk walk across the width of the dome leaves the head spinning as if one has just sprinted up ten flights of stairs. (Some visitors even faint.) But the Keck would still qualify as an engineering miracle even if it had been built at sea level. No telescope like it had ever been built before. Says Keck Project Scientist Jerry Nelson (BS '65), "The commonly held view initially was that this was a pretty harebrained idea." The Keck's genesis goes back to 1977, when a committee of UC astronomers was pondering new ways to build big telescopes.

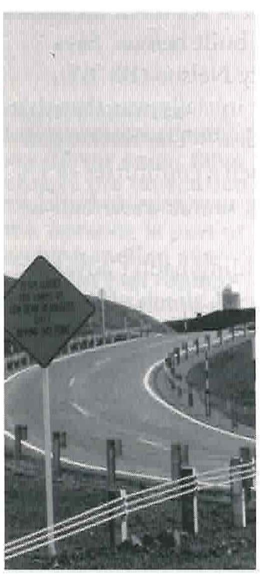
The art of telescope building hadn't advanced very much since 1908, when Caltech's George Ellery Hale built a 60-inch reflecting telescope, then the world's largest, high above Pasadena on Mount Wilson's summit. A glass disk, or "blank," the diameter of the finished mirror, is cast in a mold, then painstakingly ground and polished to a precisely calculated concave shape that focuses the incoming starlight. The blank has to be thick enough to support its own weight. The Hale's 200-inch-diameter mirror is 24 inches thick, and weighed 14.5 tons after polishing, even though it had been cast with a ribbed underside to minimize the weight.



Above: Only cinder cones and telescopes grow on Mauna Kea's summit. Rounding a bend on the approach road suddenly gives this view of Caltech's Submillimeter Observatory (left) and the Keck (right).

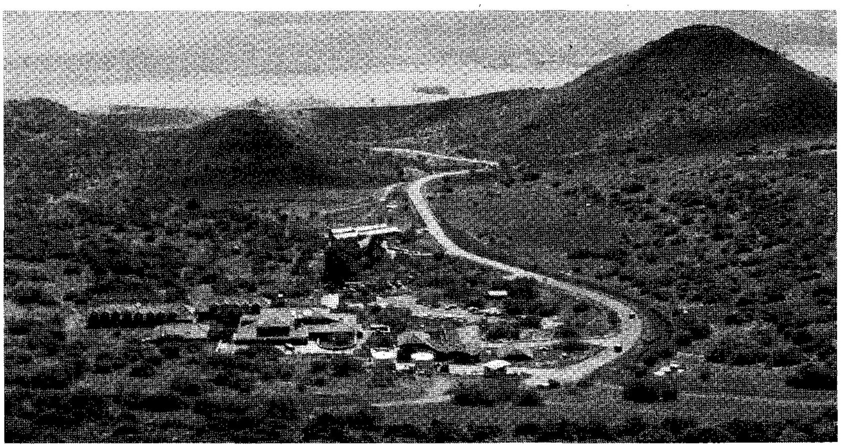
Right: Sunrise over the Keck and the Canada-France-Hawaii Telescopes.

Below: Like any sanctuary, signs warn the visitor against disturbing the protected species. An errant high beam could ruin a night's work.



Perhaps not surprisingly, the problems with making large mirrors lie not in grinding the mirror, but in handling the glass. A glob of molten glass that size takes months—the Hale's took ten—to cool, allowing ample opportunities for all kinds of stresses and imperfections to accumulate. Even after the glass cools, it never really solidifies, but subtly sags and warps as the telescope tilts to follow an object across the heavens. (A six-meter telescope on Mount Pastukov in the Russian Federation eclipsed the Hale as the world's largest telescope in 1974. The Bolshoi Teleskop Azimutal'ny, or BTA, is now on its second mirror, at least partially because of such problems.) And as the mirror bulks up, so does the weight of the steel needed to support it—more than 500 tons for the Hale, and 650 tons for the BTA—and so does the cost of the project. It's been estimated that building a ten-meter version of the Hale design would cost about $250 million; if the Hale itself were to be built today, it would run in the neighborhood of $120 million. Furthermore, such a huge mass of steel and glass holds a lot of heat, enough to keep the mirror several degrees warmer than the surrounding air for hours after sunset. Like the heat waves that dance over a blacktop parking lot in July, the air above the relatively warm mirror ripples and shimmers, blurring or obliterating the faint images of distant galaxies.

The UC committee looked at a number of ideas, but Nelson's took the pie in the sky. (Nelson, then a young astronomy professor at Berkeley, started out as a physicist. He got his first taste of astronomy as a Caltech undergrad, while helping then assistant professor of physics Gerry Neugebauer build a 62-inch telescope for an infrared sky survey.) Nelson envisioned a ten-meter mirror of hexagonal segments, arrayed like the white-tiled floor of an old-fashioned bathroom. The approach had obvious advantages. Small segments would be relatively thin and lightweight, greatly reducing the bulk (and cost) of the supporting structure. And the thinner the mirror, the less heat it and its mounting would hold. A segmented mirror would also suffer less downtime for maintenance. (Telescope mirrors owe their reflectivity to an aluminum coating some thousand atoms thick. This surface needs to be renewed in an aluminizing chamber every couple of years or so, a process that entails removing the mirror from the telescope. But a segmented mirror could be re-aluminized piecemeal, with spare segments replacing the ones in the chamber.) And, in principle, there would be no limit to how big a segmented-mirror telescope could be made. The drawbacks were even more obvious. In order to act as one mirror, the segments would have to be kept in alignment to within five percent of a single wavelength of light—within one millionth of an inch, for visible light. Radio astronomers, collecting waves several inches in length, had been building segmented dishes for years, but with tolerances measured in thousandths of an inch. This was a whole new ball game. "Radio astronomy offered a good existence proof that you could make a segmented collector," says Nelson. "But radio astronomers can position their panels once and then leave them alone. We wouldn't have that



Hale Pohaku, at 9,300 feet, is the base camp. Anyone going up to the summit spends at least an hour here, getting accustomed to the altitude. The three long buildings with dormered roofs are the astronomers' sleeping quarters. The other buildings contain the dining hall, lounge, library, offices, conference rooms, and computers. The buildings farther down the road are the construction crew's barracks.

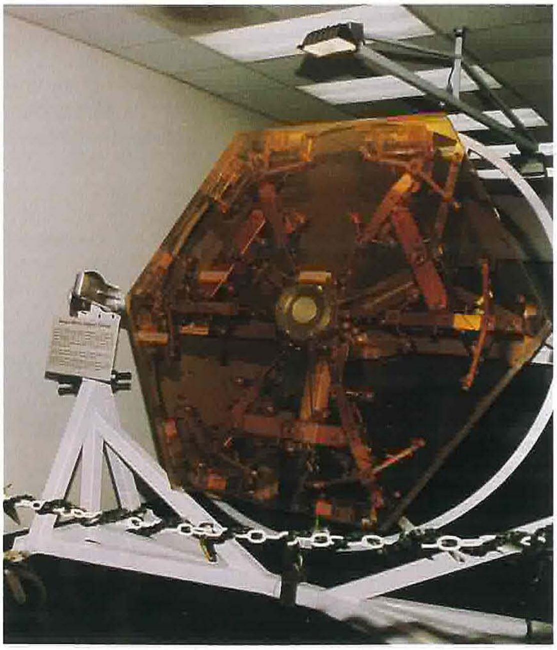
Even after the glass cools, it never really solidifies, but subtly sags and warps as the telescope tilts to follow an object across the heavens.

luxury." And with thinness comes flexibility—the segments would be even more vulnerable to gravitational warping and other stresses that could deform the mirror and blur its focus. Furthermore, while precisely polishing a symmetric mirror like the Hale's is easy, creating an accurate asymmetric surface is not. And not only would each mirror segment have an asymmetric curve, the way the pieces of a salad bowl would if you cut it up into hexagons, but the curvatures would vary, depending upon where each piece belonged. Each segment would have taken a year to polish using the technology then available.

Nelson was persuasive enough that the committee gave him the go-ahead to develop his idea, while authorizing another group to study scaling up existing mirror-making technology, just in case. Bit by bit, he and a growing group of coworkers at Berkeley and at UC's Lawrence Berkeley Laboratory demonstrated that all of the undoable things can be done. Attaching the mirror segments to the telescope frame in such a way that they hold their shape and stay in alignment with their neighbors, no matter which way gravity tugs them, takes several support systems. A "passive" system holds the segments to the telescope frame while minimizing mechanical strain on them. An "active," computer-controlled system keeps the segments aligned into one reflective surface. And a new optical technique, called "stressed-mirror polishing," enables the mirrors to be, if not exactly mass produced, at least turned out at the rate of one every five weeks instead of one per year.

One of Nelson's first recruits was fellow physicist Terry Mast (BS '64). As undergraduates, "Terry and I were alley mates—he lived next door to me—in Ruddock House for a year and a half," says Nelson. "Then we both went to graduate school at Berkeley, and kept running into each other. We started working together as postdocs, and we just gradually evolved from particle physics to astronomy to telescope building. He did an awful lot of mathematical analyses of the active control system during its design, and at the same time he was working on the passive supports. Properly supporting the segments turned out to be a surprisingly difficult problem that took us several years to solve."

The team wound up needing two sets of passive supports. One set resists forces in the plane of the mirror, while the other counteracts forces perpendicular to the mirror's surface. Acting in concert, the two systems can neutralize a force from any direction. Each mirror segment sits on a central support post, like a toadstool on its stem. The mirror actually rests on a "flex disk" of stainless steel 0.011 inches thick—less than half as thick as this article. The disk, which is bolted to the top of the post, fits tightly into a depression ground into the mirror's underside. The disk prevents the mirror from moving sideways, keeping it centered over the support post, but has enough "give" to allow the mirror to tilt or move vertically. These perpendicular forces are held in check by "whiffletrees"—systems of levers on pivots that move horizontally (or, rather, in the plane of the mirror segment) but not vertically. There are three whiffletrees per segment, each branching out to twelve attachment points spread



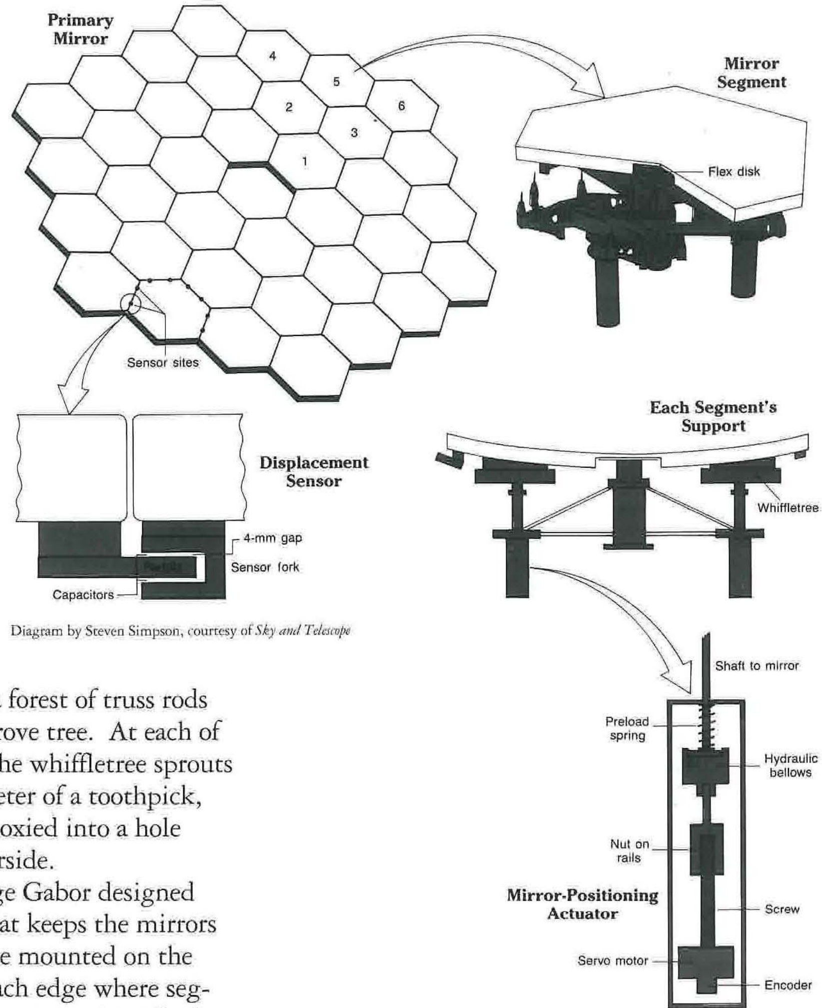


Diagram by Steven Simpson, courtesy of *Sky and Telescope*

Above: A mirror segment, ready for the aluminizing oven, stands in its custom-built cart. The mirror's central flex disk and radiating whiffletrees are clearly visible. Each segment is 1.8 meters (5' 11") at its widest point. The mirrors' Zerodur glass was cast by the Schott Glassworks of Mainz, Germany. Zerodur has an ultralow thermal expansion coefficient, one-thirtieth that of the Pyrex glass used in the Hale.

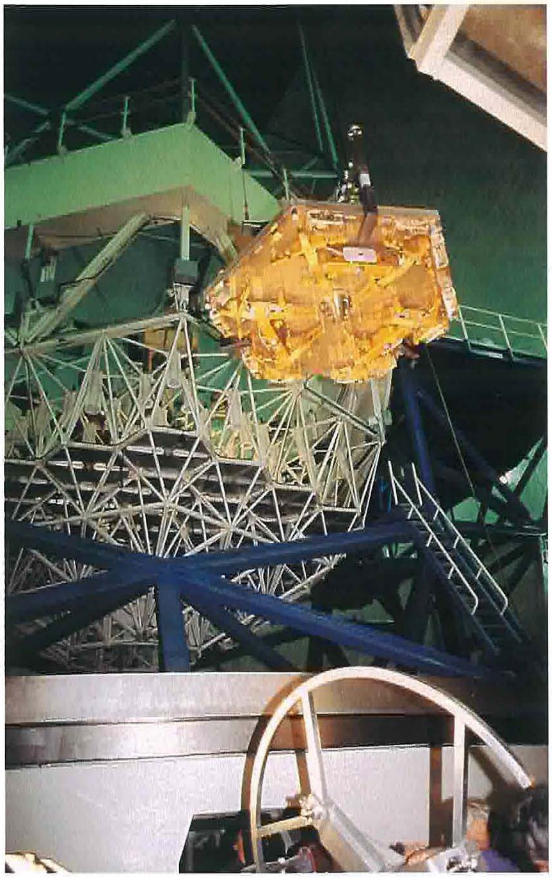
Right: The 36 segments come in six different curvatures, depending on their position in the mirror. (One spare in each curvature is also being made.) There's no central segment, allowing focused light to pass through the mirror's plane to the instruments below. The other diagrams show the various systems that support each segment. The complete active-control system will have 168 sensors and 108 actuators.

across the mirror, creating a forest of truss rods not unlike a metallic mangrove tree. At each of the 36 attachment points, the whiffletree sprouts a short metal rod, the diameter of a toothpick, that threads into a sleeve epoxied into a hole drilled in the mirror's underside.

Nelson, Mast, and George Gabor designed the active control system that keeps the mirrors aligned. Position sensors are mounted on the mirrors' undersides along each edge where segments meet. A flat paddle on one mirror fits between two parallel plates on the adjoining mirror, with a four-millimeter gap separating the paddle from each plate. The plates and the paddle are of the same glass as the mirror, in order to share its thermal expansion characteristics, with a thin plating of gold along the surfaces forming the top and bottom of each gap. An electric charge turns the gold-plated gaps into a pair of capacitors. As a mirror segment moves up or down relative to its neighbor, the paddle gets closer to one plate and farther from the other. The capacitance increases in the shrinking gap, while dwindling in the growing one. Twice every second, computers measure all the capacitances, calculate to the nanometer how much each segment has moved, and issues instructions to the actuators that keep the mirrors in position. The actuators are motor-driven screws that turn within nuts that press against hydraulic bellows. One complete turn of the screw moves its nut one millimeter, and the screw can be turned by as little as 1/10,000th of a rotation, moving the nut 100 nanometers (about four millionths of an inch). Impressive as this might seem, it isn't the 30-

The mirrors can be adjusted in increments of four nanometers—roughly the thickness of seven of the thousand layers of aluminum atoms on the mirror's surface.

nanometer precision the astronomers need. So the bellows reduces that motion by a factor of 24 before passing it on to the mirror segment. The mirrors can be adjusted in increments of four nanometers—roughly the thickness of seven of the thousand layers of aluminum atoms on the mirror's surface. The system has proven very stable. Now that the mirrors are aligned, the computer can be turned off, then on again, and the alignment remains unaffected.



Right: A mirror segment is lifted into place. This brief crane ride is the last leg of a journey whose previous steps included a 747 flight from the mainland to Honolulu, a seagoing barge to Hilo on the Big Island, a layover at Observatory headquarters in Waimea, and then a bumpy drive up the mountain.

And then there was the mirror-polishing problem. It's very easy—or at least a straightforward, well-known process—to polish a symmetrical, or "spherical," concavity into a mirror. So Jacob Lubliner (BS '57), a professor of civil engineering at Berkeley, used the mirror segments' thinness and flexibility to advantage by calculating just how each mirror segment would have to be warped so that the warped segment, if polished spherically, would rebound to give the correct, aspherical shape when the warping stress was removed. The mirror blank is mounted in a holder, called a jig, for polishing. All around the jig, levers loaded with adjustable weights warp the blank to the calculated shape for polishing. The polishing had to be done to a very high degree of accuracy. When opticians grind a single mirror for a telescope, they have a little room to fudge. The mirror only has to focus light to within one percent of the designed focal length, and the rest of the telescope's optics are simply adjusted to compensate. But just try adjusting one set of optics for 36 different mirrors! Each one of the Keck's mirrors had to focus light to the same point to one part within 100,000—a thousandfold more accurately than the astronomical mirror-making norm. The entire optical setup had to be designed with that level of accuracy in mind—a feat that required the use of theodolites and other tools of the surveyor's trade. The mirrors are being polished by Itek Optical Systems, of Cambridge, Massachusetts, and Tinsley Laboratories, in Richmond, California.

Below: Jacob Lubliner with a 35-centimeter (13.7-inch) aspherical mirror prototype created by stressed-mirror polishing.

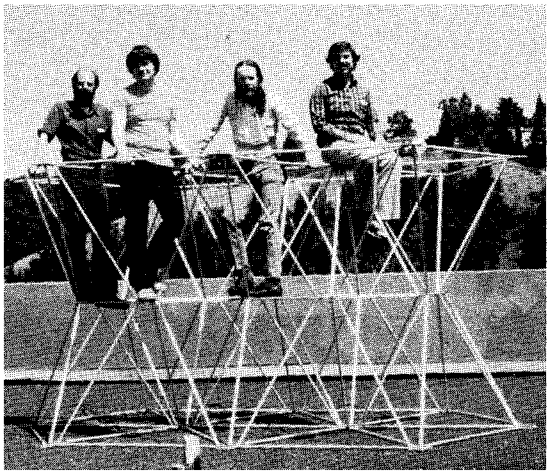
In the end, stressed-mirror polishing proved rapid and efficient, although there were some scares along the way. When the polished disks are trimmed into hexagons, their shape changes ever so slightly in an unpredictable way. Apparently, cutting the edges off of the disk alters the internal balance of forces within the glass. The telescope makers cope by installing a set of aluminum leaf springs, adjustable to 1/25,000th of an inch, on the whiffletrees. This "warping harness" gently nudges the mirror back into shape.

The committee officially adopted the segmented-mirror approach in 1980, authorizing Nelson to proceed with the R&D needed to design the

Right: Mast (far left), Nelson (far right) and friends appear to be monkeying around in this full-sized prototype of the supporting frame for a mirror segment. In fact, they're seeing how easy it will be to get at the mirror's underside, or to instruments mounted in the frame. The design's geometry gives it considerable strength, even in a mock-up made of electrical conduit.

Far right: The frame gets a bit more complex when multiplied by 36.

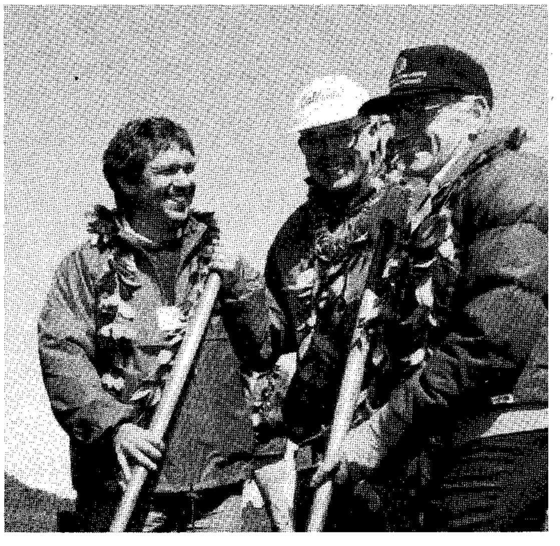
Below: Nelson and Gabor standing in the prototype built to demonstrate the active-control system. This telescope contains one full-sized mirror segment and the edge of another, adjoining one (visible on the left, in front of Nelson).



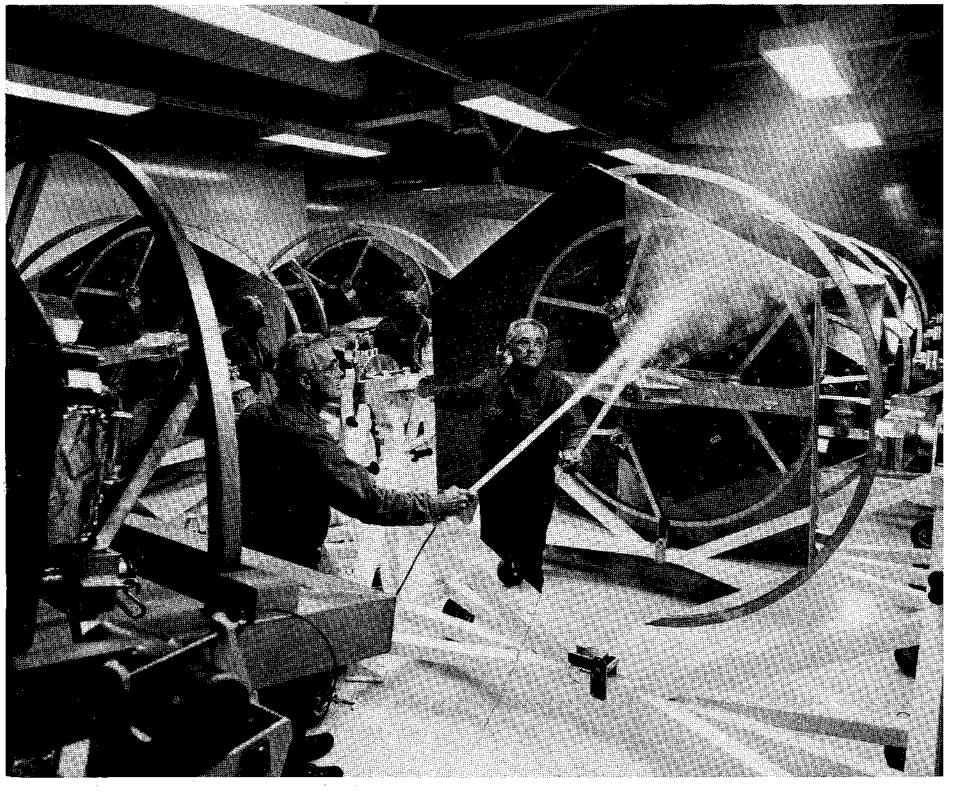
as-yet unfunded telescope. In the meantime, Caltech astronomers were also pondering the large-telescope question. As Nelson's team grappled with the problems of transforming desktop-sized prototypes and scale models into a real-life scientific instrument, some of these Caltech astronomers were drawn in. They, too, got hooked on the idea, making the ultimate joint venture that much easier. By 1984, the work had advanced to a salable stage, and the search for donors was on. The rainbow that Caltech followed led to the biggest private gift ever made to a scientific project; CARA's birth was announced in January 1985 as the ink was still drying on the Keck Foundation's letter of intent. After nearly a decade of engineering work and demonstration projects, culminating in the fabrication of a full-sized mirror segment and part of an adjoining one, complete with support systems and alignment controls, the real telescope building was set to begin.

The first order of business was to find someone capable of building the thing. Back in 1983, UC had "borrowed" Gerald Smith from Caltech's Jet Propulsion Laboratory to prepare a cost estimate and plan the observatory's construction. At JPL, Smith had been project manager for the Infrared Astronomy Satellite (IRAS), which had just finished its highly successful mission to create the first map of infrared sources for the entire sky. He'd earlier been manager of JPL's Space Instruments Systems Section—the outfit that built the cameras for the Voyagers, Mariners, and Vikings—and had then gone on to manage construction of NASA's Infrared Telescope, also on Mauna Kea. As CARA formed, Smith was asked to pick up where he'd left off. From a basement office in Caltech's Bridge Laboratory, he began assembling the core engineering and administrative team, which ultimately numbered 24 when it moved to Hawaii four years later. The team included engineers of all persuasions: electrical, mechanical, software, systems, and civil. Some were JPL recruits, while others came from a bit farther afield—the chap who designed the equipment needed to transport the mirror segments and lift them into place had previously designed roller coasters. (He now works on theme-park rides for an organization whose mascot is a rodent.) Due to the telescope's revolutionary design, practically everything had to be engineered from scratch, from the honeycomb that supports the mirror to the software that runs the telescope. "Everything was a challenge," says Smith. "The dome is a bit smaller than the Hale's, to minimize construction costs, yet the aperture and its shutter had to be twice as wide, making a much harder structure to design. Even some of the dome's cranes had to be designed especially for this project."

The detailed design work started in August 1985, with construction beginning in September. The dome, telescope, and support structure were all fabricated off-site, shipped in pieces to Hawaii, trucked up the mountain, and assembled at the summit. Crucial parts were test-fitted before shipping—citizens of Tarragona, near Barcelona, Spain, were treated to the sight of the half-built telescope yoke and tube on the grounds of the Schwartz–Hautmont ironworks. The dome arrived in May 1987, and was completed by October the following year. "We were lucky," *As Cronkite remarked at the dinner, "These two men have given us a new, apposite definition of the phrase, 'jerry-built.'"*



Right: Tom and Jerrys. Everhart looks on while Nelson (left) and Smith rest on their laurels, or rather, their *o'o* sticks, at the ground blessing.



Below: Ron Laub, facilities manager for the Keck Observatory, is the only person in this picture as he cleans off a mirror segment. *How* many mirror segments were there again?

Smith remarks. "It was a mild winter that year, and we were able to work straight through. Some years it gets really bad up on the summit, and you can't work outdoors for months." The telescope's mounting arrived in July 1989, and the first mirror segments were installed in October 1990. First light—with nine segments of the mirror installed (*E&S*, Winter 1991)—followed in November. This working demonstration of the telescope's elements stands as vindication of Nelson's vision and testimony to Smith's ingenuity. As Cronkite remarked at the dinner, "These two men have given us a new, apposite definition of the phrase 'jerry-built.'"

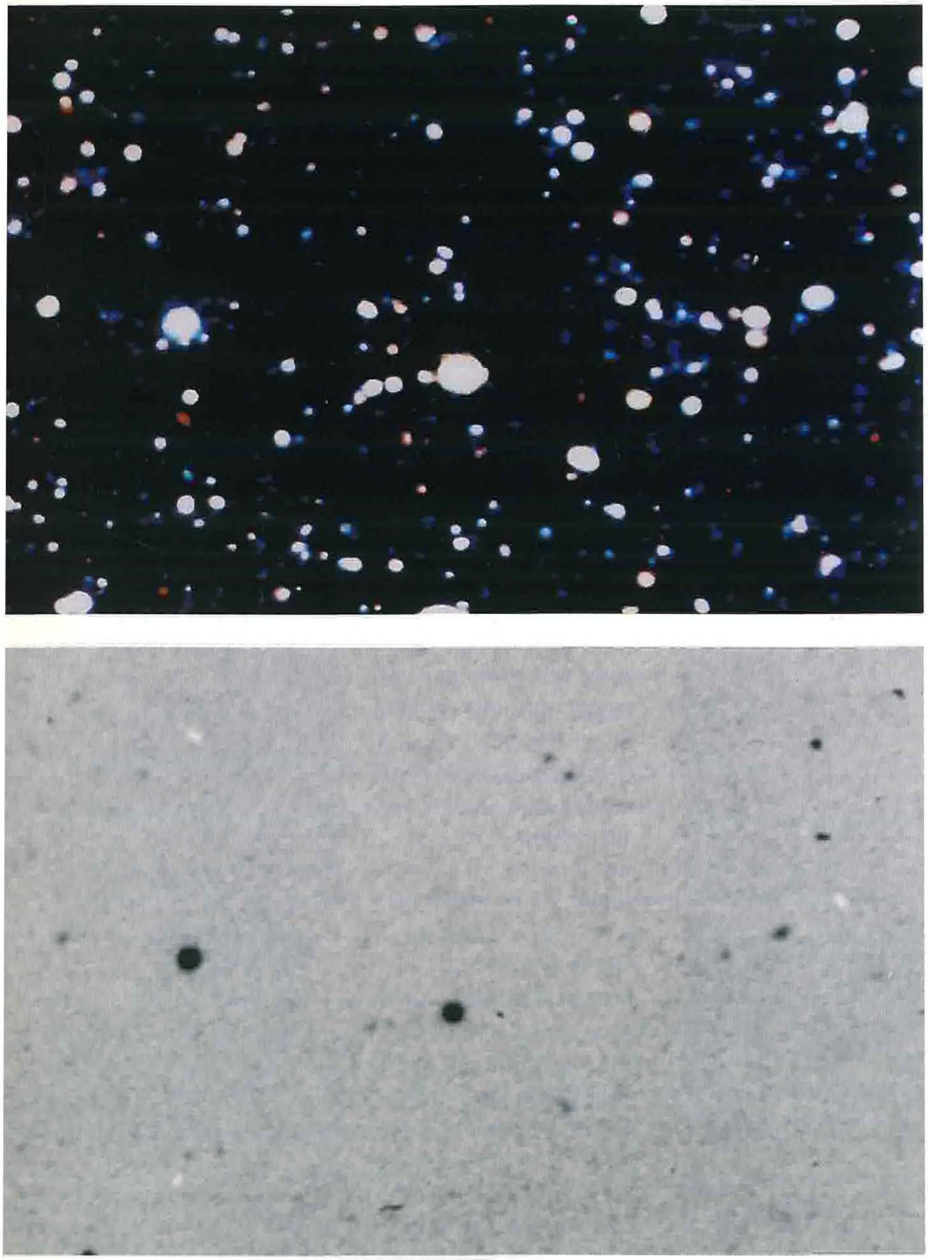
The dinner's keynote speaker was Ed Stone, Caltech vice president and professor of physics, director of JPL, and chairman of CARA. Stone prefaced his remarks by noting, "There are as many interesting questions [about the universe] as there are astronomers—in fact, there are probably more. In the interests of time, I'll stick to two." These two were questions of origin: the ultimate question, "What caused the universe to become what it is today?" and a penultimate one, "How do solar systems form?"

A telescope is really a time machine, although its physical being remains as solidly fixed in the present as any other object within our ken. The universe is so vast that even light, traveling at 186,000 miles per second—5,878,000,000,000 miles per year—takes a long, long time to get anywhere. The Andromeda Galaxy, our nearest neighbor, is roughly two million light-years away. Thus the light from Andromeda shining in at your window tonight took two million years to get here, and you see Andromeda as it was two million years ago. Andromeda could have blown itself into oblivion before the first homo sapiens stared up at the night sky in wonder, and the news still won't reach his descendants for another million and a half years.

Astronomers put the age of the universe at 15 billion years, give or take 5 billion. So if one wants to see the universe as it was in the beginning, all one has to do is look at objects 15 billion light-years away. The catch is that the further away an object is, the dimmer it appears to be and the bigger the mirror you need to gather enough light to see it. The Hale's 200-inch mirror can collect enough light to fingerprint galaxies some seven to eight billion years old. When Keck I's mirror is completed in the spring of 1992, it will push the galactic limit back to some 12 billion years. And when Keck II joins Keck I, the two together will be able to sift starlight from galaxies dating to within a billion or two years of the universe's birth, the time when most

Top: What Tyson saw when he pointed his souped-up CCD toward the South Galactic Pole at a seemingly blank patch of sky. Each blue speck is a galaxy. (Photo courtesy of Tony Tyson and Patrick Seitzer.)

Bottom: A one-hour photographic exposure of the same region.

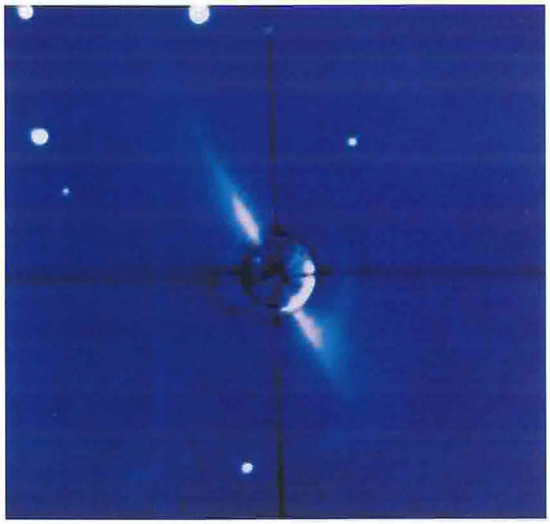


These might even be the primordial galaxies, caught in the act of formation some 13–14 billion years ago—an invaluable source of knowledge about the early universe.

astronomers believe that galaxies began to form.

Astronomers may have already gotten a glimpse of what they might see way back then. In 1983, Tony Tyson of Bell Labs began experimenting with methods to boost the sensitivity of CCDs—very sensitive electronic cameras—even further, in hopes of discovering new types of objects too faint to be seen any other way. When pointed at what a one-hour photographic exposure had shown to be a dark, relatively starless patch of night, the souped-up CCD revealed faint, blue galaxies littering the sky—a hundred or more of them in a field of view encompassing two percent of the area covered by Earth's moon. They're presumably out there in all directions, because there's nothing particularly special about where Tyson was looking. There are two likely explanations for these galaxies. They might be relatively nearby dwarf galaxies, in which case they're perhaps half as old as the universe. The other, far more exciting possibility is that they are galaxies more like our own Milky Way but seen from a great distance. If so, we're seeing them as they were when they—and the universe—were very young. "These galaxies might be so blue because of their great rate of star formation," explains Stone. "Stars are always bluer when they're young, because they're hotter, so a very young galaxy would also be blue." These might even be the primordial galaxies, caught in the act of formation some 13–14 billion years ago—an invaluable source of knowledge about the early universe.

To settle this issue, astronomers need to analyze the galaxies' spectra, dissecting each galaxy's



Right: The disk surrounding Beta Pictoris (here seen edge-on) may encircle unseen planets.

If planetary systems are as common as astronomers have every reason to presume they are, then there's no need to search too far.

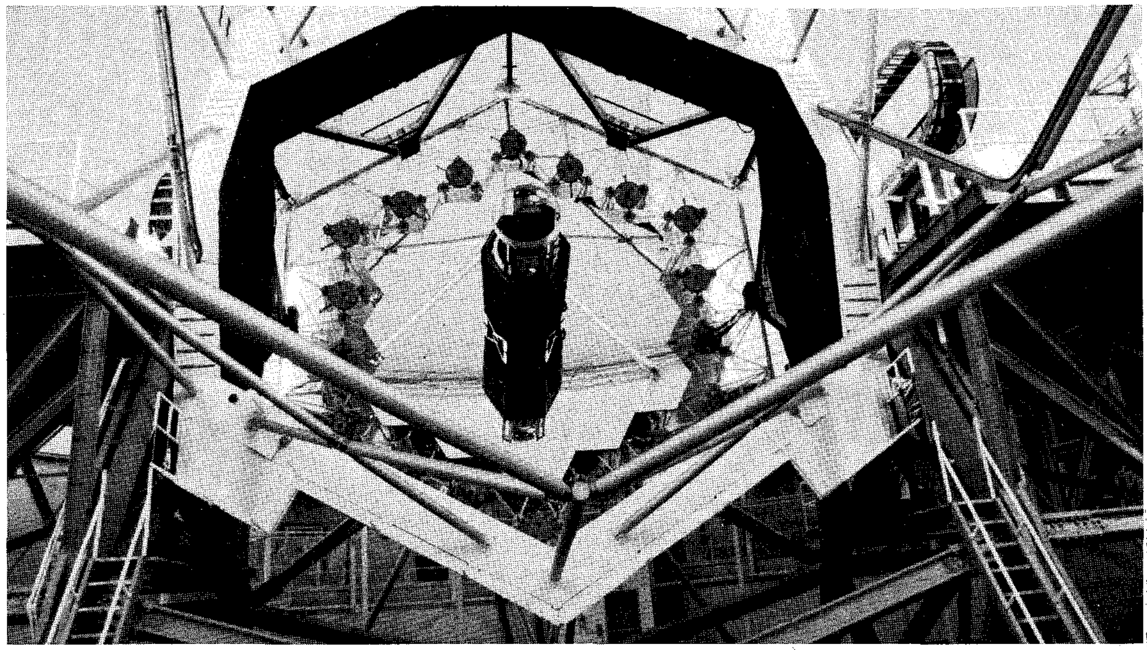
Top: T Tau as seen by the Hale.

Bottom: T Tau as seen by the Hale via speckle interferometry becomes two companion stars.

light into its individual wavelengths. By measuring the intensity of light at each wavelength, a galaxy's life history—its age, its distance from us, and the average composition, density, and temperature of its stars—can be read. But collecting light from a faint galaxy is like weighing marbles in a bucket, where the bucket has to contain a few marbles before the scales register. A visual image puts all the marbles into a single bucket, but spectral analysis sorts the green marbles into one bucket, red ones into another, and so forth. And there just aren't enough marbles to sort, in this case. These galaxies are so dim that hardly enough light reaches Earth to make decent images, much less spectra, without an unconscionably long exposure time. But the Keck's large light-gathering area, coupled with its state-of-the-art detectors and Mauna Kea's unsurpassed visibility, should speed up the time needed to make an exposure by a factor of 20, putting spectra of these faint galaxies within reach. Taking such a spectrum now would take a solid ten hours of telescope time—more time than most astronomers get on a big telescope in a year. The Keck should be able to knock one off in half an hour.

The folks working on the other question—the origin of solar systems—will be looking closer to home. If planetary systems are as common as astronomers have every reason to presume they are, then there's no need to search too far. What matters here is not light-gathering power but resolution—the ability to distinguish two objects very close to each other. To get a better feel for the problem, consider this: A telescope capable of seeing a planet the size of Jupiter orbiting one of our nearest stellar neighbors would have the resolving power to see, from a distance of seven and a half miles, that a grain of salt and a dust mote sitting ten inches apart are two distinct objects, according to JPL planetary astronomer Richard Terrile (MS '73, PhD '78) in "Prospecting for Planets," *E&S,* Spring 1989.

When Keck II joins Keck I in 1996, the twins can combine their light through a process called interferometry, acting as a single telescope the size of the distance between them. (The new telescope's light-gathering power won't increase in proportion—it's just the sum of the surface area of the two mirrors—but the resolution will be that of a 280-foot mirror.) In effect "we get two small pieces of a mirror 280 feet in diameter," says Stone. Radio astronomers have been doing interferometry for a long time, but applying the technique to the far-shorter wavelengths of visible light remains a challenge. According to Nelson, "People have demonstrated that it's possible, but there's still a lot of work to be done." (The only working interferometer to use visible light has been built atop Mount Wilson by JPL's Michael Shao, and has mirrors some three inches in diameter and about 35 yards apart.) The same problems of aligning large objects to tiny tolerances that attended segmented-mirror design also pertain to optical interferometry. But even before those problems have been fully solved, the method's promise beckons. Recently, Andrea Ghez, a graduate student of Neugebauer's, used the Hale to make some images of an object called T Tau, located in a nearby—slightly less than 500 light-years away—region where stars are forming.



With only 18 of its 36 segments installed, Keck I was already the largest telescope in the world. The Nasmyth platforms can be seen to either side.

Longtime astronomy buff Walter Cronkite presided at the dinner, held at the Mauna Kea Beach Hotel.

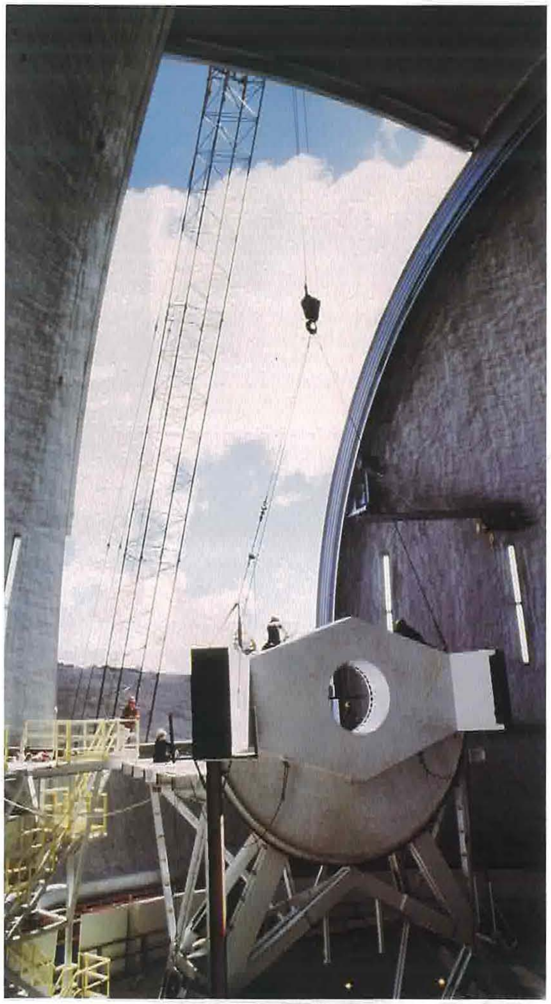
Ghez used a technique called "speckle interferometry," in which the atmospheric shimmy that makes stars twinkle and drives astronomers bonkers is put to good use. Multiple images of a patch of sky, taken faster than the atmosphere moves, are combined in a computer that uses the stars' apparent motion between successive images to produce an interferometric effect whose baseline is the width of the telescope. Ghez was able to resolve T Tau into two stars, 102 astronomical units (AU) apart, orbiting each other. One AU is 93 million miles—the mean distance between Earth and the sun. At T Tau's range, speckle interferometry should enable the Hale to resolve objects 15 AU apart. Fifteen AU is the distance from the sun to halfway between the orbits of Saturn and Uranus. Keck I will be able to resolve 7.5 AU—from the sun to midway between Jupiter and Saturn—at that range without resorting to interferometry, while Keck I and II, working interferometrically, will make out one AU.

Nobody has yet seen a planet in orbit around another star. (There have been recent reports of planets discovered around pulsars, but these detections were made indirectly—inferred from wobbles in the pulsars' rotation. In any case, the observations are still awaiting confirmation.) But if we already have the capacity—at least in terms of resolution—to see a not unreasonably large planet in a not unreasonably large orbit around nearby stars, why hasn't anybody found one?

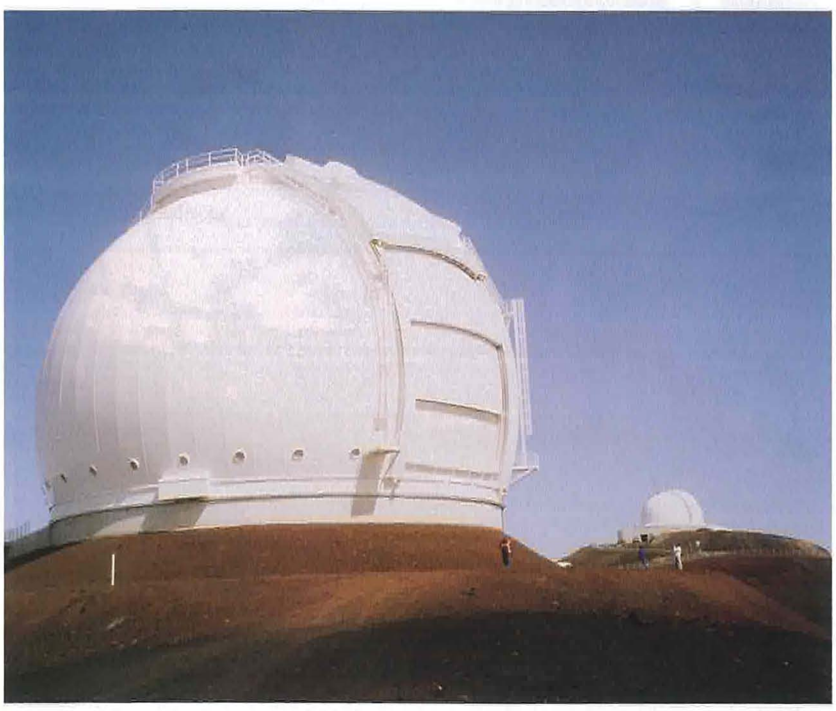
Even the twin Kecks won't be able to photograph planets on other solar systems directly, according to Stone. A star and its planet are right on top of each other by celestial standards, and the one is an awful lot brighter than the other. To a distant observer, the sun would appear a billionfold brighter than Jupiter—radiant enough to cause Jupiter to vanish altogether in the glare. This problem can be licked by suspending an occulting mask—a plastic dot, smaller than the period at the end of this sentence—in the telescope's optics at just the right spot to keep the light from the star itself from reaching the detector, allowing the fainter companion to be seen. But there's always one more problem, it seems. Even with the star's direct light gone, subtle imperfections in the mirror's surface will scatter a few thousandths of one percent of the starlight around the mask, more than enough to obliterate a planet one-billionth as bright as its star. (Several astronomers, including Terrile, are working to make super-smooth mirrors.) The Keck will, however, be able to spot a planet by the wobble that the orbiting mass imparts to the star. As the star wobbles toward Earth and then away from us, the Doppler effect will shift the lines in the star's spectrum upfrequency and then downfrequency ever so slightly—just as an oncoming train's horn has a higher pitch than one that's receding in the distance.

But where the Keck will really shine, if you'll pardon the pun, is in the infrared. A planet warmed by its star will re-radiate that warmth as infrared light. Astronomers know exactly how much infrared radiation at a given wavelength a normal star of a given temperature should emit. But if that star has a warm planet, or a warm disk of dust from which planets might be forming, the star will appear to be emitting more infrared at certain wavelengths than it ought to. Unfortunately, atmospheric water vapor absorbs most of the infrared light that reaches Earth from space. Mauna Kea's summit, by virtue of being above the clouds, is also above the bulk of the water vapor, affording as good a look at the infrared as can be had without a spacesuit. Keck's size and instrumentation will make the most of the view.

The first candidate for intensive scrutiny has already been identified this very way. In 1983, the IRAS mission found that one of the thousand or so stars closest to us—Beta Pictoris, a mere 50 light-years away, practically looming over our back fence—sits in the middle of a disk of gas and dust just like those from which planets are supposed to condense. In 1984, Terrile and Bradford Smith of the University of Arizona used the 100-inch telescope at the Las Campañas Observatory in Chile to get a picture of the disk. It proved to extend out to the equivalent of about 30 times Neptune's orbit, much farther out than planets should form, and consists of particles ranging from dust-sized to perhaps as big as a brick. Closer in to the star, the particles appear to have been swept away, indicating that the material may have condensed into planets—"a tantalizing suggestion" of planets, in Stone's words.



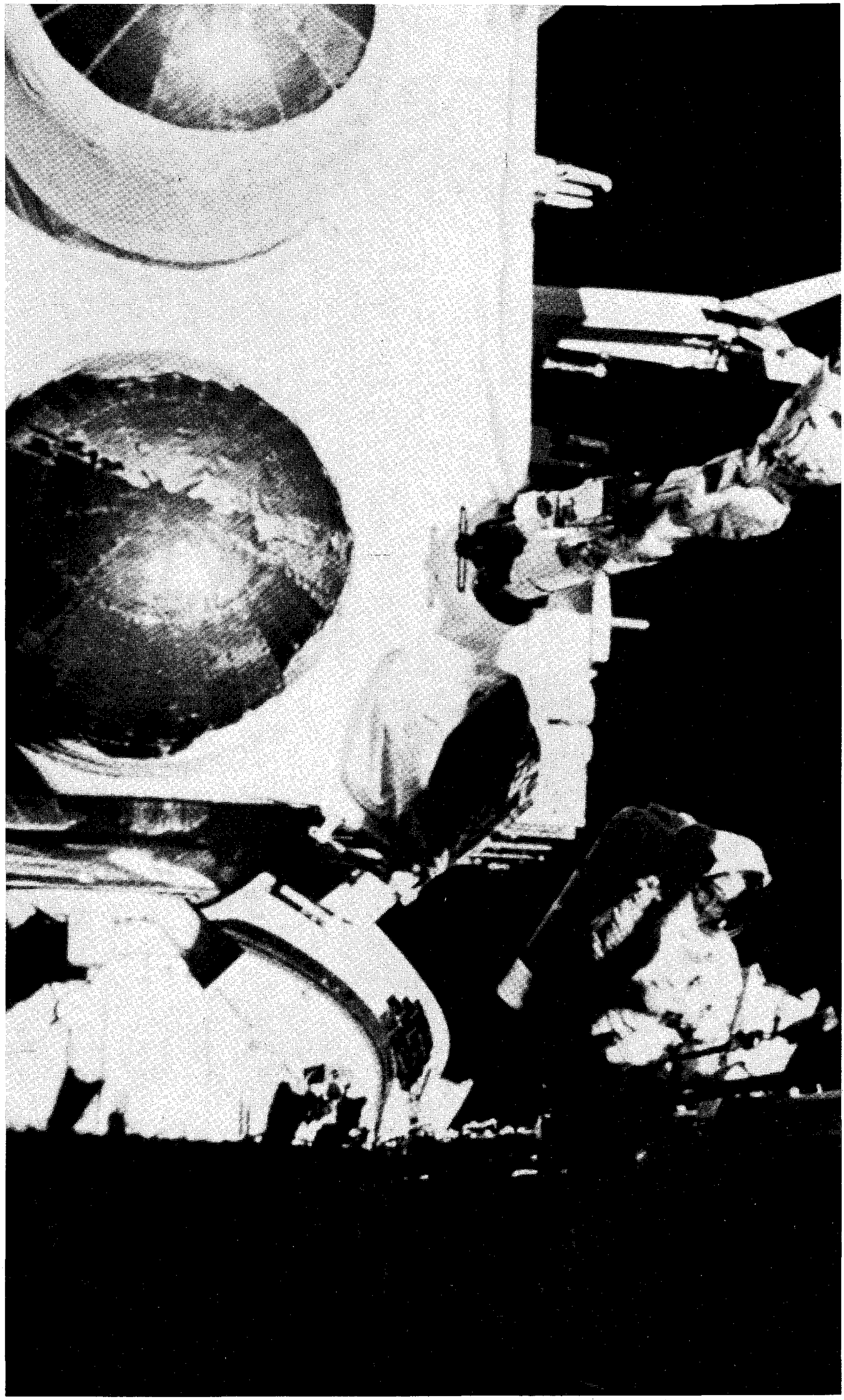
Right: Part of the telescope yoke being hoisted into the dome.



Below: The Keck's dome, looking like a cross between a natural-gas storage tank and a UFO, dwarfs its photographers. The "portholes" are part of the air-handling system. NASA's Infrared Telescope Facility is visible in the background.

Smith and Terrile expect to have a go at Beta Pictoris with Keck I this year. The first instruments to harvest the mirror's laboriously gathered starlight should begin arriving on the mountain about the time that the last mirror segment does. These five instruments include two infrared cameras, being built by Caltech and Berkeley, an infrared spectrometer from UC San Diego, and two spectrometers that analyze visible light, built by Caltech and UC Santa Cruz. Light-sensing technology is improving so fast that the Keck's infrared cameras are 20 times more sensitive than the one installed on the Hale just a few years ago. New instruments will be built over the years, so the maturing Kecks will be able to see farther and more clearly as they get older. The last of the first five instruments won't arrive until December, but Christmas will come earlier for the first astronomers to use the other four.

"And that's the way it was," intoned Cronkite after the last toast had been drunk, the ceremonial souvenirs presented, and the legions of coworkers thanked. The gathering dispersed into the night as "Charlie on the MTA" wafted faintly across the bay from a pavilion on the far shore, where the Kingston Trio was playing for an attorneys' convention. The dinner guests went to bed, the lawyers partied on, and in the clear, moonless sky Mauna Kea stood silhouetted against the stars. □



Exploring the Gamma Ray Sky

We've all looked at the night sky, and we know, visually, about stars and planets and galaxies, but very few people have a feel for what the gamma ray sky actually looks like.

by Thomas A. Prince

Astronaut Jay Apt stands on board the space shuttle *Atlantis* as the Gamma Ray Observatory (in the background), the heaviest scientific payload ever launched into orbit, prepares to begin its mission. At this point it is still in the grasp of the remote manipulator system.

The following article is adapted from a recent Watson Lecture on gamma ray astronomy.

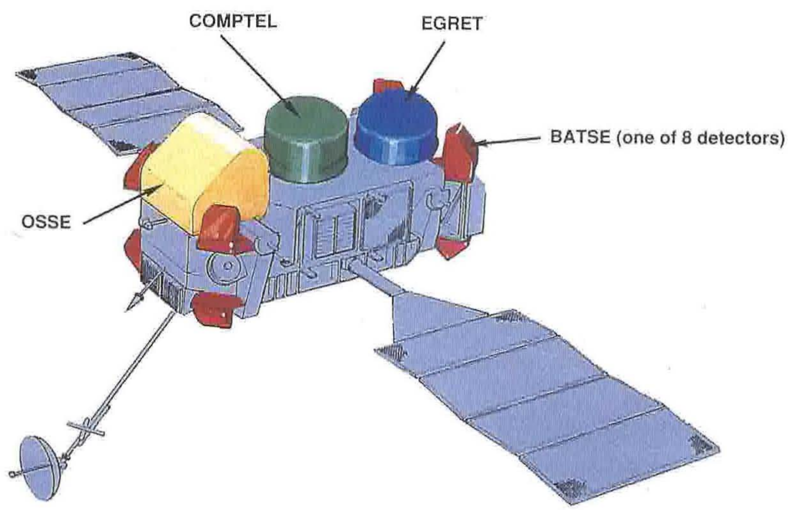
Traveling back and forth to Washington, D. C., for Gamma Ray Observatory meetings, I usually try to do a little work on the airplane. Every so often I'll be sketching some drawings of neutron stars and writing down equations, and all of a sudden I get the distinct feeling that the person in the seat beside me is watching. Then, invariably, a few minutes later they'll ask, a bit sheepishly, "Are you an astronomer or something?" I answer, "No, I'm not an astronomer; I'm a physicist, but I do a lot of work with NASA's space astronomy missions." Then their eyes light up and they say, "Oh, you must be working on the Hubble Space Telescope." I say, "No, I work with the Gamma Ray Observatory," and they say, "Oh, what's that?" So perhaps with this article, which was adapted from a recent Watson Lecture, I can explain to a larger audience, as well as to all potential airplane-seat neighbors, just what the Gamma Ray Observatory is and what we are learning from it.

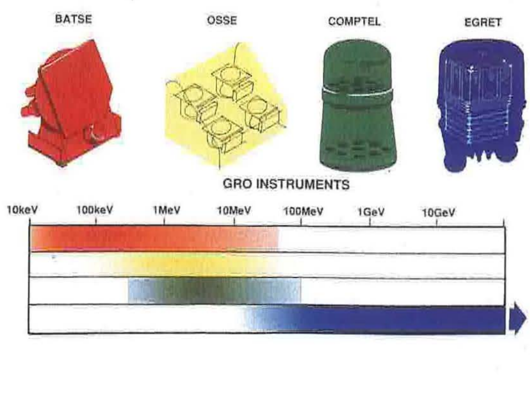
The Gamma Ray Observatory, or GRO, is the second in NASA's program of "Great Observatories" that will observe the sky at various wavelengths. So far, the Hubble Space Telescope, which covers the visible wavelengths, and the Gamma Ray Observatory have been launched. Scheduled for the future are the AXAF telescope, which works in x-ray radiation, and the SIRTF, which operates in the infrared.

Actually, it is understandable why people are more familiar with the Hubble than with GRO. We've all looked through telescopes or binoculars and intuitively have a good feel for what a visual or optical telescope is. But how many of us have a gamma ray detector in our homes? And how many of us know what our pet dog looks like at gamma ray energies? We've all looked at the night sky, and we know, visually, about stars and planets and galaxies, but very few people have a feel for what the gamma ray sky actually looks like.

Gamma rays are radiant energy of the same form as radio waves, infrared, visible light, and x-rays. We can distinguish among these different forms of radiant energy, called electromagnetic radiation, in one of three ways—by wavelength, by frequency, or by energy. Radio waves have long wavelengths; gamma rays, on the other hand, have very short wavelengths—smaller than an atom. Radio waves are relatively low frequency; gamma rays are ultrahigh frequency. Gamma rays have very high energies compared to radio and visible light. For example, visible light has an energy somewhat larger than one electron volt; gamma rays span the range from about 10,000 electron volts—that is, about 10,000 times more energetic than light—to about 10 billion electron volts. Because gamma rays are so energetic, and because their wavelengths are so short, they interact more like particles than like waves, so I'll be discussing them as if they were particles. While visible light essentially has to do with atomic transitions (that is, when you look at a fluorescent light you're really looking at the excitation of atoms), gamma ray radiation often comes from the excitation of nuclei. So visible light is used to learn about the atomic physics of

GRO's four instruments all record the energy and arrival time of each gamma ray although they cover different, but overlapping, energy ranges and provide different views of the gamma ray sky. BATSE can look in all directions; OSSE has a narrower field of view. COMPTEL and EGRET are imaging instruments.





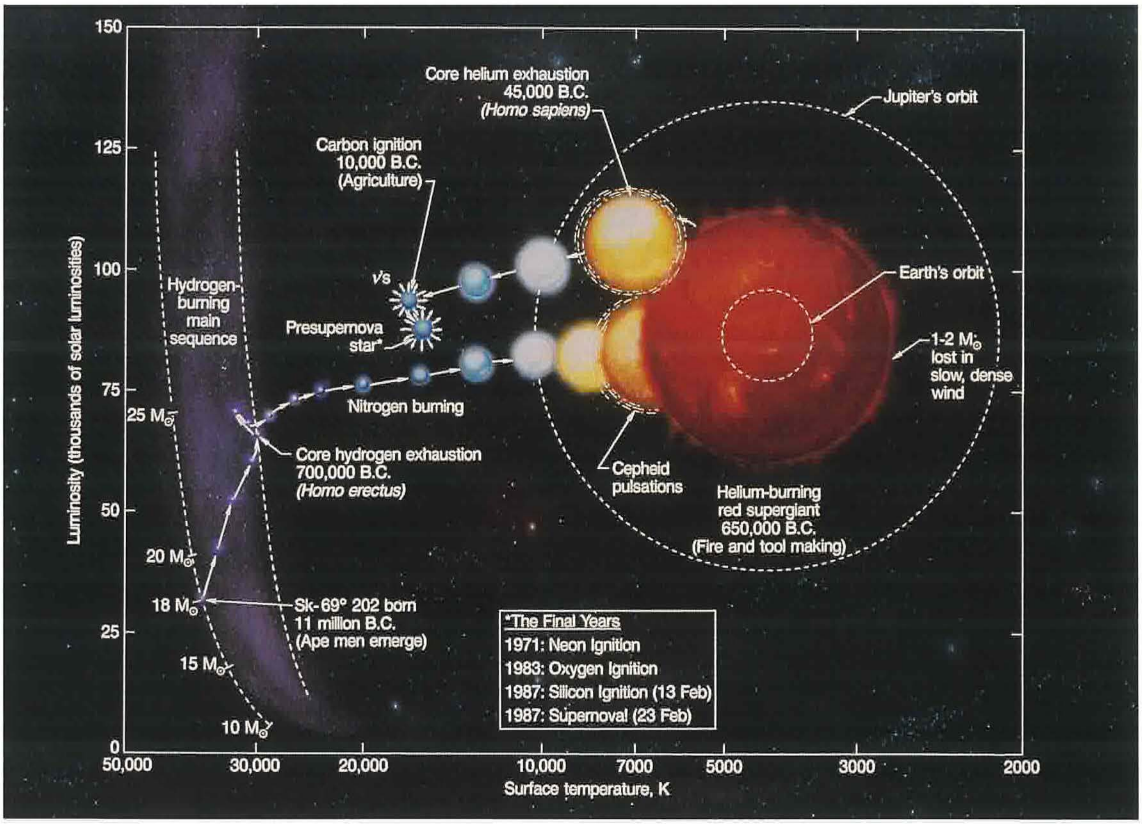
astrophysical sources, and gamma ray radiation will tell us about nuclear processes such as radioactive decay in those sources.

If humans had gamma ray eyes, we wouldn't be able to see much. The air in a room would glow faintly because of trace radioactivity. If we had only gamma ray eyes, we would pretty certainly starve to death. Plants and animals don't show up very well at all, and it would be a lousy way to hunt. But in astronomy, not being able to see gamma rays and learn what they can tell us, is starvation of a different sort. Even gamma ray eyes wouldn't help much, because gamma rays, although they are very energetic, don't penetrate the Earth's atmosphere at all. So we have to send instruments above the atmosphere to observe the radiation. The Arthur Holly Compton Gamma Ray Observatory (its official name) is the most ambitious attempt so far to observe the sky at gamma ray energies.

The Gamma Ray Observatory was launched April 5, 1991, from the space shuttle *Atlantis*. The satellite weighs 35,000 pounds, the heaviest scientific payload ever put into orbit from the shuttle. The GRO has four instruments on board, all of which record the energy and arrival time of each gamma ray, but each with a different scientific goal. Although the instruments are often called telescopes, they're very different from conventional optical telescopes; there are no lenses or mirrors for the gamma ray range. BATSE (Burst and Transient Source Experiment), covering the lowest energy range, consists of eight detectors on the corners of the satellite to look in all directions at all times. OSSE (Oriented Scintillation Spectrometer Experiment) looks at a much smaller field of view at somewhat higher energies. Neither of these two produces an actual picture of the gamma ray sky. But COMPTEL (Compton Telescope) is an imaging instrument. It looks at a still higher energy range and has about a 40-degree field of view, while EGRET (Energetic Gamma Ray Experiment Telescope) is an imaging instrument, which holds down the most energetic end of the gamma ray range.

Now that I've described the GRO instruments, I'd like to turn to the observations. Many of the interesting results I'll be discussing are quite new, some as recent as this winter.

Probably the most familiar gamma ray source is our own sun. But although the sun dominates our sky in the visible wavelength, it's almost completely dark at gamma ray wavelengths, even if we observe it from space. Occasionally, though, a solar flare erupts, suddenly releasing magnetic energy in a loop on the sun. That



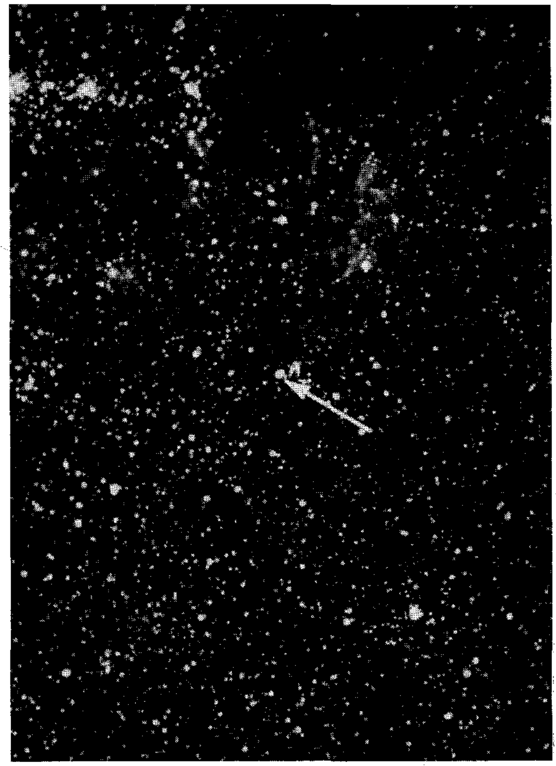
The life history of the star that produced Supernova 1987A began 11 million years ago with a blue star about 20 times the mass of our sun. First it burned hydrogen, then swelled up into a helium-burning red giant. When it ran out of helium and started burning carbon 12,000 years ago, it shrank back into a blue star. Ignition of the next elements—neon, oxygen, and silicon—took place only in the last 15 years before the supernova explosion. (Illustration courtesy of Tom Weaver and Stan Woosley.)

energy accelerates particles, which bombard the nuclei in the sun's atmosphere, causing emission of gamma rays. The four instruments on GRO have studied some of the most intense solar flares ever observed on the sun. These studies have shown that the sun, although a very normal star, can accelerate gamma rays up to almost the highest energies observable by the Gamma Ray Observatory. This brings up the question of whether, if the sun can throw out gamma rays like this, other normal stars can also be seen at gamma ray energies. Unfortunately the answer is no. We can see the sun because it's so close to us, but not any other ordinary stars. Instead, the GRO will be looking for sources of gamma rays from much more exotic objects: supernovae, neutron stars, and black holes.

The study of supernovae was one of the primary scientific objectives of the Gamma Ray Observatory, in particular of the OSSE and COMPTEL instruments. A supernova is, quite simply, the death of a star, and in that death a tremendous amount of energy is released. A star that explodes in a supernova can suddenly become brighter than the entire galaxy that it's in. A particularly important supernova occurred five years ago (precisely at 7:35 a.m. on February 23, 1987). Supernova 1987A was the closest, brightest, and best studied supernova since the invention of the telescope.

It takes a star, for example one about 20 times the mass of the sun, a long time to get into a state where a supernova can occur. The life history of that star is pretty much a story of the struggle between gravitation, which is trying to collapse the star into a tiny ball, and the nuclear reactions burning in its core, which create the energy and pressure that puff the star up. The star starts out by burning hydrogen into helium, the fusion reaction in its core. But of course it has to run out of hydrogen eventually, so it starts burning helium, making carbon in the process. When it runs out of helium, it starts burning the carbon; when it runs out of carbon, it starts burning neon, then oxygen, then silicon. And then it stops, because when you burn silicon in a nuclear reaction in the core, you create iron. Iron is a very stable nucleus, and you can't get any net energy from burning it to form heavier elements. This is the state that the star is in just before going supernova. It has a core of silicon and iron that weighs about twice as much as the sun. It's roughly the size of the Earth and is just sitting there accumulating iron, which it can no longer burn.

Above is a picture of what astrophysicists think is the life history that led to Supernova 1987A. The star started out about 11 million years ago as a blue star roughly 20 times the mass of the sun, then began burning hydrogen, swelled up, and became a red giant star that would have fried any earthlike planet near it. At that time it was burning helium. When it ran out of helium, it started burning carbon, ending up as a blue star again. The neon-oxygen-silicon burning took place very fast—forming the core of silicon and iron in only about the last 15 years before going supernova. When enough iron accumulat-



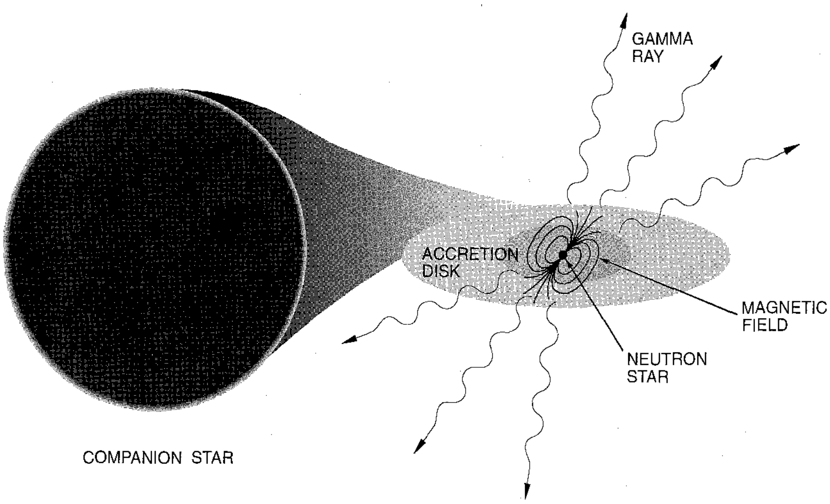
Supernova 1987A—before and after. Before, it was an ordinary blue star in the Large Magellanic Cloud named Sanduleak -69°202. On February 23, 1987, it died in an explosion that released a tremendous amount of energy, mostly in the form of neutrinos. A fraction of a percent of the energy goes into producing radioactive elements that are identifiable by gamma ray detectors. (Photograph from the Anglo-Australian Observatory by David Malin.)

ed, the core could no longer hold up its own weight, the atoms got crushed, and the entire core collapsed in less than a second to an object about 25 miles across. So here's something that weighs a little less than twice as much as the sun collapsing into an object about twice the size of Pasadena. As you might expect, in that process it releases a tremendous amount of energy—more energy than our own sun has emitted in its entire lifetime as a normal star.

Most of this energy from a supernova, 99 percent in fact, shoots out as a form of radiation called neutrinos. Neutrinos can pass through matter very easily. Supernova 1987A is so far away that its light took about 170,000 years to reach us. But even from that unimaginable distance, more than a trillion neutrinos produced in that event passed through each one of us. These neutrinos, the 99 percent of a supernova's energy, are a story in themselves, but I want to track the other 1 percent, because that's the energy that's interesting to gamma ray astronomers. That 1 percent explodes out in a shock wave, which first heats up the material of the overlying star that *hasn't* collapsed—heats it up so much that it can start producing nuclear reactions and radioactive material and heavier elements. Then the rest of the energy goes into blowing all that stuff out into interstellar space. This material has elements in it such as carbon, oxygen, nitrogen, and traces of metals—precisely the elements that we're all made of. This is no coincidence. The stuff we are made of was once cooked up inside a massive star and ejected in a supernova explosion. The same material condensed to form our solar nebula, and here we are. We would not be here if it weren't for supernovae.

But meanwhile, back to the gamma rays, it turns out that the nuclear processes that occur when the shock wave passes through the materials in the star create a lot of radioactive elements or radioactive tracers, such as nickel, cobalt, titanium, sodium, and aluminum. The radioactive material produced in a single supernova is equivalent to a mass that's about 25,000 times the mass of the Earth. Because so much radioactivity is created, it's observable by gamma ray detectors. When a nucleus of, say, cobalt 56 decays radioactively, it emits a gamma ray of a very specific energy. When we see increases in intensity at that particular energy, we can say we have detected radioactivity, and we can measure how much cobalt 56 was actually produced.

One of the long-term objectives of the Gamma Ray Observatory is to detect radioactivity from elements produced in supernovae, be they a couple of months old, a couple of years old, or even a couple of million years old, and from that to map out the distribution of radioactivity that has been produced by supernovae in our galaxy. Because Supernova 1987A, however, offered such an unparalleled opportunity to observe the radioactivity of a supernova in progress, it became one of the Gamma Ray Observatory's first targets. Just this January, GRO scientists discussed the possibility that the OSSE detector may for the first time be seeing direct evidence of the rare isotope cobalt 57. We think that right now, at this stage of its evolution, the supernova is being powered by the decay of cobalt 57 instead of



When a neutron star resulting from a supernova happens to have a companion star that has swelled into a red giant, the neutron star's strong gravitational field can suck material from its companion into an accretion disk. A neutron star with a strong magnetic field can pull some of the material in the disk onto its poles, creating hot spots of radiation that show up as the star rotates. The neutron star is then detectable as a pulsar.

Probably 100 million or more neutron stars have been produced in our galaxy over its history. But we don't see that many of them; why not?

cobalt 56, which powered the supernova early on. The detection of this isotope will be fundamental to the understanding of the supernova at these late stages, four to five years after the explosion.

Now I'd like to consider not what was ejected, but what was left behind. When the core collapsed, it left a very condensed, very hot blob sitting there. Eventually it cooled and became an object about 12 miles across, about the size of Pasadena, 1-1/2 times the mass of the sun. Because it's composed, not of atoms, but almost purely of nuclei (and in particular neutrons), we call it a neutron star. GRO data are being combed very agressively right now, searching for radiation signatures of the neutron star that was born out of Supernova 1987A. It hasn't been detected so far, but it will be an exciting discovery when and if it is.

How many neutron stars are produced by supernovae like this? Predictions say that perhaps two or three occur per century in a galaxy like our own. That doesn't seem like much, but in astrophysical terms time is fairly long—for a galaxy that has been around for billions of years, two or three per century adds up pretty quickly. Probably 100 million or more neutron stars have been produced in our galaxy over its history. But we don't see that many of them; why not?

An old neutron star just sits out there; it's dark; it's relatively cold; it's not producing any energy of its own, so it's essentially unobservable. But in rare instances the neutron star can be detected. Sometimes a star that goes supernova happens to exist in a binary system with a companion star. This companion star can start out as a blue star and then gradually swell up to be a red giant. When it does so, the neutron star resulting from a supernova can literally suck the material off the companion star with its strong gravitational field, and put it into an accretion disk, where it spirals in toward the neutron star. Some neutron stars have very strong magnetic fields, very much stronger than anything we're used to on Earth, which can catch material in the accretion disk and funnel it down onto the star's polar caps. Since the neutron star is only the size of Pasadena, this stuff actually falls on a surface about the size of the Caltech campus. The matter hits the surface of the neutron star at speeds approaching the speed of light, dumping a tremendous amount of energy onto that surface and heating these spots up to temperatures as much as 10,000 times greater than the temperature of the sun. If the rotation axis of the neutron star is misaligned with the magnetic axis, then the hot spots that are being created at the polar caps of the neutron star rotate in and out of our field of view. What we can see are pulses of radiation coming at us—one pulse for each time the hot spot circles around. Hence, this type of neutron star is called a pulsar, and it's something we *can* detect.

With detectors such as BATSE on GRO a group of us at Caltech (including John Grunsfeld, a senior research fellow, and grad students Deepto Chakrabarty and Bill Detlefs) are looking for very regular pulses of radiation. We're searching a broad range of periods and frequencies of this radiation. We've been quite successful so far, and have detected 11 pulsar systems. Because these

Probably the most interesting results to come out of GRO so far involve gamma ray bursts.

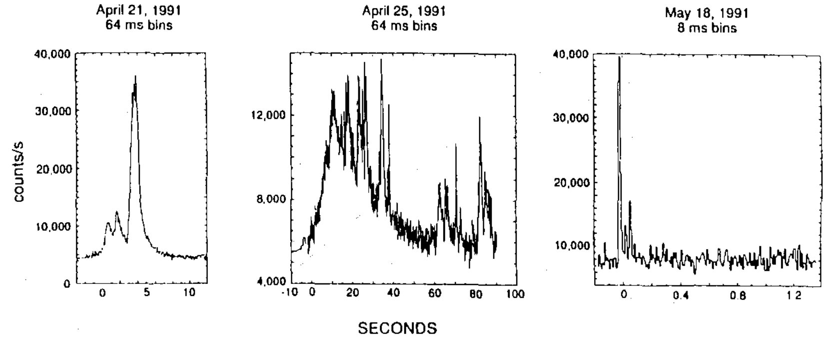
Seen from the shuttle Atlantis before final launch last April, the Gamma Ray Observatory glides over the coast of Mauritania and Senegal in West Africa.

systems turn on and off irregularly, on time scales of days, weeks, and months, they're hard to catch in the act. You might watch in a particular direction for one of them with a telescope for a long time and not see anything, and then a month later, after you got tired of looking, it might turn on. The beauty of the BATSE detectors, which look in all directions at once, is that you can detect a pulsar as soon as it turns on and study it for the entire time it's active. By doing such studies we hope to determine such things as the magnetic field of the neutron star, and perhaps its mass. And we certainly want to know the details about how mass can be sucked off the companion star and onto the neutron star.

Another target for the Gamma Ray Observatory is black holes. The same type of process that leads to the formation of neutron stars can also create black holes, with the difference that a neutron star can form from a star about 20 times the mass of the sun, while a black hole requires a star that's more than 40 times the mass of the sun. Because it has a more massive core, when a star this size goes supernova, there's more mass compacted in that dense blob that forms when it finally collapses. If enough matter gets packed in there, it will have such a strong gravitational field that a black hole is produced. But how can we see a black hole? It has the same type of visibility problems as a neutron star—it's just sitting out there in space, and it's *black*. If the black hole happens to be in orbit around a companion star, however, just as with a neutron star, matter can be sucked onto the black hole to form an accretion disk and spiral in. As the matter spirals toward the black hole, it gains energy and heats up, emitting radiation in the process. It turns out that it's very hard to tell a black hole, which has no magnetic field, from a neutron star that happens to have a very weak magnetic field. Scientists have spent a lot of time trying to tell the difference between them, and some of us think that the Gamma Ray Observatory may be able to detect one distinct signature of a black hole. We think that black holes may be able to produce a very hot bubble of electrons and positrons close by. As the hot bubble expands because of its high temperature, the electrons and positrons can combine and annihilate each other (because they are matter and antimatter). When this occurs, they produce gamma rays close to an energy of 511 thousand electron volts. By looking for radiation at that energy we can determine whether or not systems that we think might be black holes are really emitting this signature of electron-positron production. The Gamma Ray Observatory's OSSE is the best detector yet with the potential to observe this phenomenon, and with it we hope to learn a lot about discriminating between black holes and neutron stars.

Probably the most interesting results to come out of GRO so far involve gamma ray bursts. These were discovered in the late sixties by a series of satellites monitoring the nuclear test ban. They were searching for evidence of clandestine nuclear weapons tests, evidence that included gamma ray bursts. Indeed, they *did* see gamma ray bursts, but, it was determined eventually that they weren't coming from Earth

Gamma ray bursts come in all shapes and sizes, from less than a second long to tens of seconds long. These are three that BATSE detected early in the GRO mission.



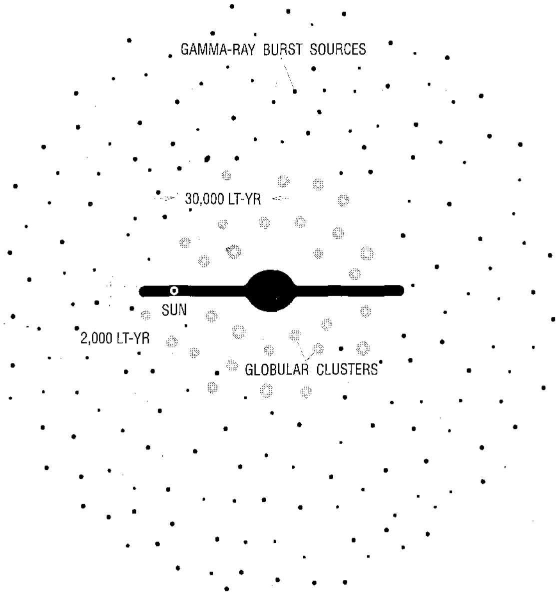
—rather, they were coming from space. Since that information was declassified in 1973, the astronomical community has proposed and carried out a large number of experiments to determine the origin of these gamma ray bursts. The bursts come in all shapes and sizes—some less than a second long, and some tens of seconds long. The largest of them can be the brightest source of gamma rays in the sky for the brief time that they occur.

The Gamma Ray Observatory has given us the best data yet on these bursts. Gamma ray bursts, as observed by the BATSE detectors (which look out from the observatory's eight corners), happen about once per day. Both BATSE and COMPTEL can determine the rough arrival directions of the gamma rays. In addition, by comparing the time of arrival of the burst at the Gamma Ray Observatory with its time of arrival at very distance spacecraft (for instance, Ulysses, which is out near Jupiter), we can tell very accurately the direction where the burst actually came from. Oddly enough, when astronomers look at the spot where a burst came from, they find nothing astounding whatsoever. It's almost invariably a patch of sky empty of any interesting objects.

Oddly enough, when astronomers look at the spot where a burst came from, they find nothing astounding whatsoever.

What could these bursts be, and where do they come from? Before the launch of the GRO, the general consensus of the scientific community was that gamma ray bursts were due to old, dead neutron stars, which are normally dark. Astrophysicists had proposed various models by which dead neutron stars could actually create gamma-ray bursts—neutron star-quakes, collisions with asteroids or comets, or release of magnetic field energy, analogous to solar flares. Before the GRO, detectors were able to see only the brighter gamma ray bursts, which were randomly scattered in every direction across the sky. Using our visible-light intuition, such a random distribution is what you would expect from objects in our own galaxy—relatively close to us. When you look, for example, at the brightest stars (that is, the closest ones), they seem to be sprinkled randomly about, but as they get fainter and fainter (that is, farther away), you start seeing them line up with the plane of the galaxy. The plane of the galaxy is familiar to us as the Milky Way that we see in the night sky.

Analogous to what we see in the visible, we expected that the Gamma Ray Observatory's sensitive detectors would reveal a deficit of the faintest (farthest away) bursts, namely in directions out of the galactic plane, and that the observable faint bursts, like faint stars, would lie along the galactic plane. Very early in the GRO mission it was indeed found that there was a deficit in the number of faint bursts. But the chief surprise is that the prediction concerning their distribution was *not* borne out. Rather than being lined up in the galactic plane, the faintest bursts are distributed all over the sky. The fact that we see a deficit of faint bursts clearly means that we are seeing out to the edge of their distribution. But the fact that the faint bursts that we do see are uniformly scattered across the sky means that there is no preferred direction and that, therefore, their distribution doesn't seem to have anything to do with the plane of our galaxy.



GRO data show that gamma ray burst sources may be distributed in a halo around our galaxy, which, if the bursts are indeed from old neutron stars, provokes a mystery as to how the neutron stars might have gotten out there.

Many bursts and their positions have been cataloged, and yet we have no firm idea where they really are, how far away they are, or what they are.

This has put astrophysicists in a quandary. We've known about these bursts—the brightest objects in the gamma ray sky when they go off—for almost a quarter of a century. Many bursts and their positions have been cataloged, and yet we have no firm idea where they really are, how far away they are, or what they are. I don't think there's any other object in astrophysics that has been studied so intensely but about which so little is definitely known.

Three theories have been suggested to explain the new data from GRO: that the bursts are very close to us; that they are moderately far away; and that they are very, very far away. The first is probably everybody's least favorite choice. In this instance it's been proposed that perhaps the gamma ray bursts are coming from a uniform and randomly distributed crowd of comets around the solar system. Unfortunately no one has come up with a good explanation of how you can make gamma ray bursts with nearby comets.

The second possibility involves old neutron stars, which was also the pre-GRO favorite explanation. We are, however, forced to the conclusion that if there is an edge to the distribution of gamma ray burst sources, then it must be uniformly distributed across the sky. So instead of having all the burst sources lined up in the plane of the galaxy, we may have to put them out in a halo around it. The immediate question that arises is that if old neutron stars are creating the gamma ray bursts, why are they way out in a halo when presumably they were all produced via supernova explosions from massive stars in the plane of our galaxy? Were they ejected out of the plane into the halo? Was there at one time a halo of massive stars around our galaxy that produced lots of neutron stars?

I'm still betting on the galactic halo model, but a lot of scientists favor the idea that puts these gamma ray bursts very far away—way outside of our galaxy. We know from the GRO data that there is an edge to their distribution; where is there a natural edge once you go outside of our galaxy? Well, there's the "edge" of the universe—the Big Bang. When you look out with powerful telescopes, you're looking further and further back in time, toward the beginning of the universe. How far out do the gamma ray bursts have to be in order to explain all the data? It turns out that they would have to be distributed over a good fraction of the entire universe. That means that the gamma ray bursts would have to be truly cosmological in origin. Some suggestions for the kind of objects that could possibly put out enough energy to do this include a neutron star orbiting another neutron star or even a neutron star orbiting a black hole. In certain cases the neutron star orbiting another neutron star emits gravitational radiation, spiraling the two stars closer and closer to each other until they merge. Such an event would release as much energy as a supernova. Quite a few people are excited about this explanation, but I am skeptical. It's going to take a lot more work on the data from GRO and on new types of data to unravel this question, but so far the distribution of gamma ray bursts has been the Gamma Ray Observatory's most exciting discovery.

The second most important discovery from

GRO concerns quasars—quasi-stellar objects that can be ten billion light-years or more away from us. It's generally thought that quasars are powered by black holes, not ones that weigh perhaps 10 times as much as the sun, as I discussed earlier, but black holes that might be as much as 10 million times the mass of the sun, or even larger. Quasars are very efficient emitters of radiation. EGRET, the highest energy telescope on the GRO, was trained on the site of the quasar nearest to us, called 3C273, which had been detected at gamma ray energies before. EGRET did detect a very definite peak of gamma ray emission, indicating clearly that it had seen a source in the general direction of 3C273. But although the Gamma Ray Observatory was pointed directly at 3C273, the location of the strong source was quite a bit off it. In fact, this was an entirely different quasar, called 3C279, which is far more distant than 3C273. It turned out to be the farthest, brightest, and most luminous gamma ray object ever detected. Just recently the EGRET telescope detected four more quasars. So it seems that the massive black holes that may lurk in the centers of quasars are very efficient gamma ray producers. I anticipate further interesting GRO results on quasars in the future.

The GRO mission, not even a year old, has already been highly successful, yielding new discoveries and raising some intriguing questions. It is giving us our first really good look at the gamma ray sky.

Perhaps this article will help make gamma rays more familiar, although they will never beat visible light in a popularity contest. But at least if you ever end up sitting next to me on a plane, you won't have to wonder what a gamma ray observatory is. Rather, you can ask, "Have they found out where those gamma ray bursts are coming from yet?" □

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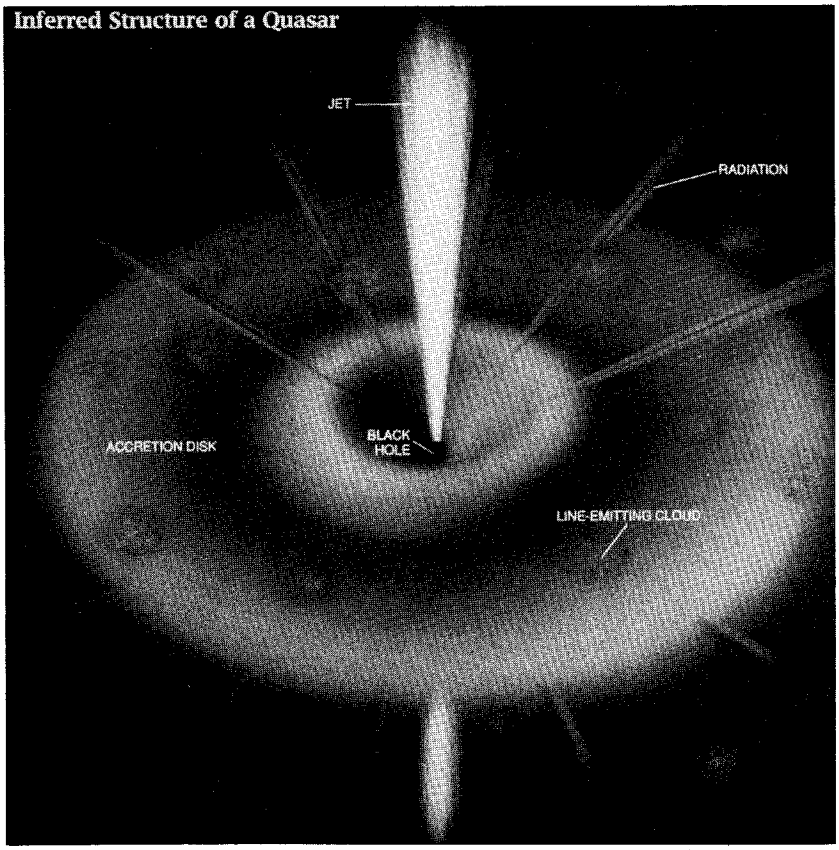
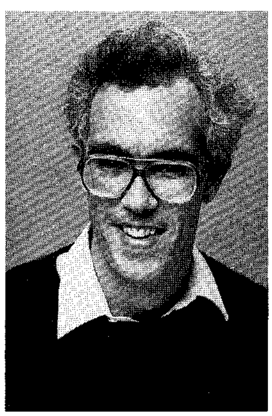


Recent GRO data may provide clues to the nature of quasars (quasi-stellar objects), which are thought to be powered by black holes 10 million times the mass of the sun. These black holes are thought to produce jets that can be intense sources of gamma radiation.



Tom Prince, associate professor of physics, has been a member of the Caltech faculty since 1979, after receiving his BS from Villanova in 1970 and his PhD from the University of Chicago in 1978. His group has been active in the development of imaging gamma ray telescopes. Currently he's chairman of the NASA GRO Users Group, and also has been instrumental in the growth of parallel supercomputing at Caltech.

Planting SEEDs

"We've tended to turn kids off to science in about the third grade. But if science is made exciting, kids want to know more about it. They want to learn."

by Winifred J. Veronda

How aggressive is a crayfish? Fifth graders at Field Elementary School learn about animal behavior by observing their own crayfish, as part of Project SEED, a science-education program begun by two Caltech professors.

Ten-year-old Ralph is trying to think of a new name for his crayfish. Ralph has discovered that the animal, originally christened David, is actually a girl. "Susan" has a pleasant sound, Ralph thinks, but he listens intently as his classmates offer suggestions.

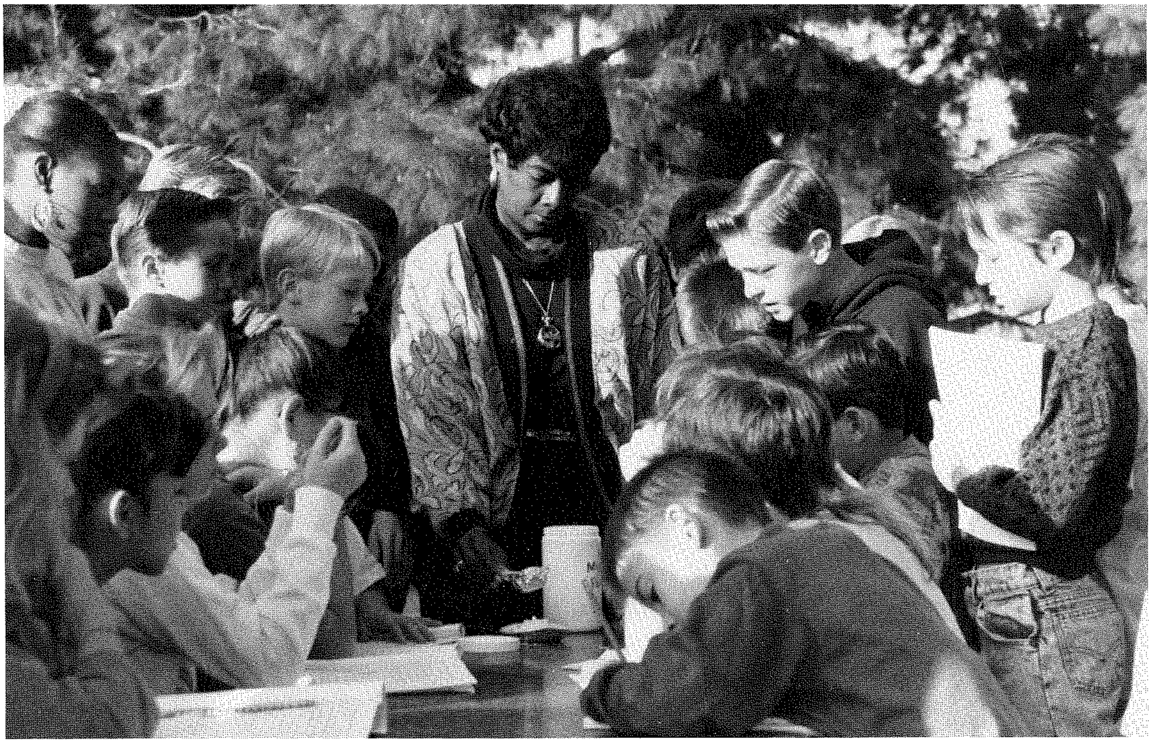
Excited chatter fills the fifth-grade classroom at Cleveland Elementary School in Pasadena, where students are enthusiastically examining their crayfish and observing their behavior. A science lesson is under way, and at Cleveland School that means hands-on science exploration through Project SEED. Leila Gonzales (BS '79), a Project SEED staff member, is a visitor today. A group of children cluster around her as she discusses the varying degrees of aggressiveness in the crayfish the children are holding. One student tells Gonzales that she took her crayfish home, and that it became so gentle she could kiss it.

Project SEED (Science for Early Educational Development) has come a long way since it began as an experimental pilot project in Field Elementary School in 1984—a project focused on teaching students through immersion in the scientific process. Through hands-on inquiry and computer simulations, the kids learn to pose a scientific question, collect data, reach conclusions, develop hypotheses, and invent experiments to test them. Now, thanks to a $645,200 grant from the National Science Foundation, and the unstinting efforts of its creators, Project SEED is expanding over three years to include all 22 elementary schools in the Pasadena Unified School District, (so far it has been established in 20 of them), and additional teachers are being trained each year at every grade level. For kindergarten through fifth grades, it has become the school district's official science curriculum, and this spring the program is being extended to sixth grade in 10 schools. It will eventually reach more than 10,000 children in Pasadena.

For its creators, Jim Bower, associate professor of biology, and Jerry Pine, professor of physics, all this is only the beginning. Already they're looking at ways to extend the program through middle school and high school. Meanwhile, through the interest of Micheal Boughton, BS '55, former president of the Alumni Association, Project SEED has become a part of the curriculum of the Lihikai Elementary School on Maui, and requests for information are coming in from districts located all over the country. As of January it also has an official home—a two-story, 1922-vintage, Caltech-owned house on South Hill Avenue. Institute funds have refurbished the downstairs as a first step, and the house is already being used as a training center for teachers and principals.

"Caltech is doing what it has always done—using its resources, imagination, and energy to develop new approaches," says Bower. If the dream of Bower and Pine comes true, then SEED as an approach to early science education will become a model for raising the scientific abilities of students across the United States.

Both Bower, the biologist, and Pine, the physicist, do research on the biophysics of the nervous system, studying neural networks in brains and in cell cultures. They both are involved in Caltech's interdisciplinary program



Left: Dorothy Hall's class at Sierra Madre Elementary School pays close attention to a science experiment.
Below left: Grad student Scott Strobel conducts Pasadena elementary-school teachers on a tour of Caltech laboratories.
Right: As a group of teachers watches by Baxter Hall, Jerry Pine demonstrates shadows and sundials, part of the fifth-grade unit on daytime astronomy.

"Scientists have tended to go into outreach programs disguised as priests. They give sermons, but the teachers don't buy in."

in Computation and Neural Systems. But the development of elementary science education programs has become a kind of second career for Bower and Pine, both of whose commitment to educational service goes back a long way. Almost 20 years ago, when he was a high-school student in Rochester, New York, in the late sixties, Bower was involved in education policy and curriculum reform at the high-school level, as well as in teaching emotionally disturbed children. As an undergraduate intern at Antioch College, he taught kindergarten through third grade. Later he worked as an aide at a state institute in Montana for profoundly retarded children. "I believe everybody owes it to the community to contribute to the education of its children," he says with emphasis.

Pine's commitment dates to the early 1960s, when he was a part of the National Science Foundation-sponsored team that developed the first elementary-school hands-on science kits. In Pasadena, he was instrumental in conceiving Caltech's Saturday high-school education program.

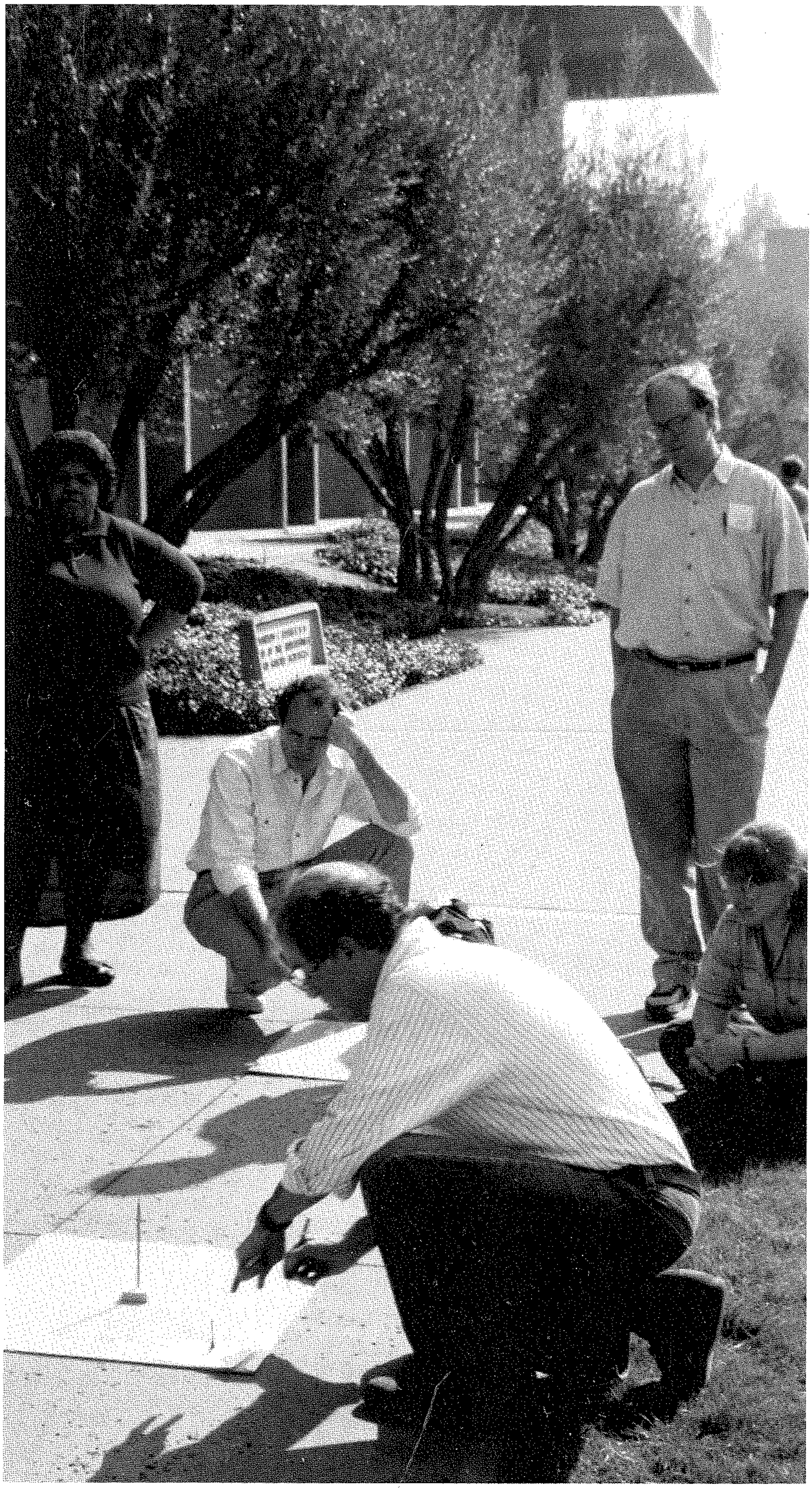
The two linked up in the early eighties. "We were disheartened to see kids in kindergarten and first grade who were more excited about science than they would ever be in their lives because of what would happen to them through the educational system," says Bower, as he reminisces about SEED's inception. "We wanted to maintain their creativity and inventiveness. Children have a natural tendency to explore. Our object was to build a sense of order and direction into that process."

Some schools had experimented with "hands-on" science in the sixties, but most abandoned it as "back to basics" became the mode. The Mesa, Arizona, district was one that had stuck with the use of the NSF science kits in elementary-school classrooms, and 14 of these kits were replicated for classrooms at Field Elementary, Project SEED's pilot school.

The science kits don't work on their own; teacher training has been a vital component. Before the pilot program began, the Field School teachers who would be Project SEED participants met at Caltech with faculty members, graduate students, and postdocs for instruction in the use of hands-on kits and computers. Teachers who showed special promise became mentor teachers and, in subsequent years, helped to train their colleagues.

As SEED has grown, so has teacher training. Last summer, 115 elementary-school teachers participated in a five-day workshop at Caltech. By the end of 1993, Bower estimates, 420 Pasadena teachers in grades kindergarten through fifth will have been trained in the use of Project SEED materials. All sixth-grade teachers at the 22 elementary schools will have been trained as well.

Unique to the program has been the role of scientists in the training process. "Scientists have tended to go into outreach programs disguised as priests," says Bower. "They give sermons, but the teachers don't buy in. At Caltech, the scientists have worked side by side with teachers on the curriculum materials, modeling the process involved in scientific reasoning and



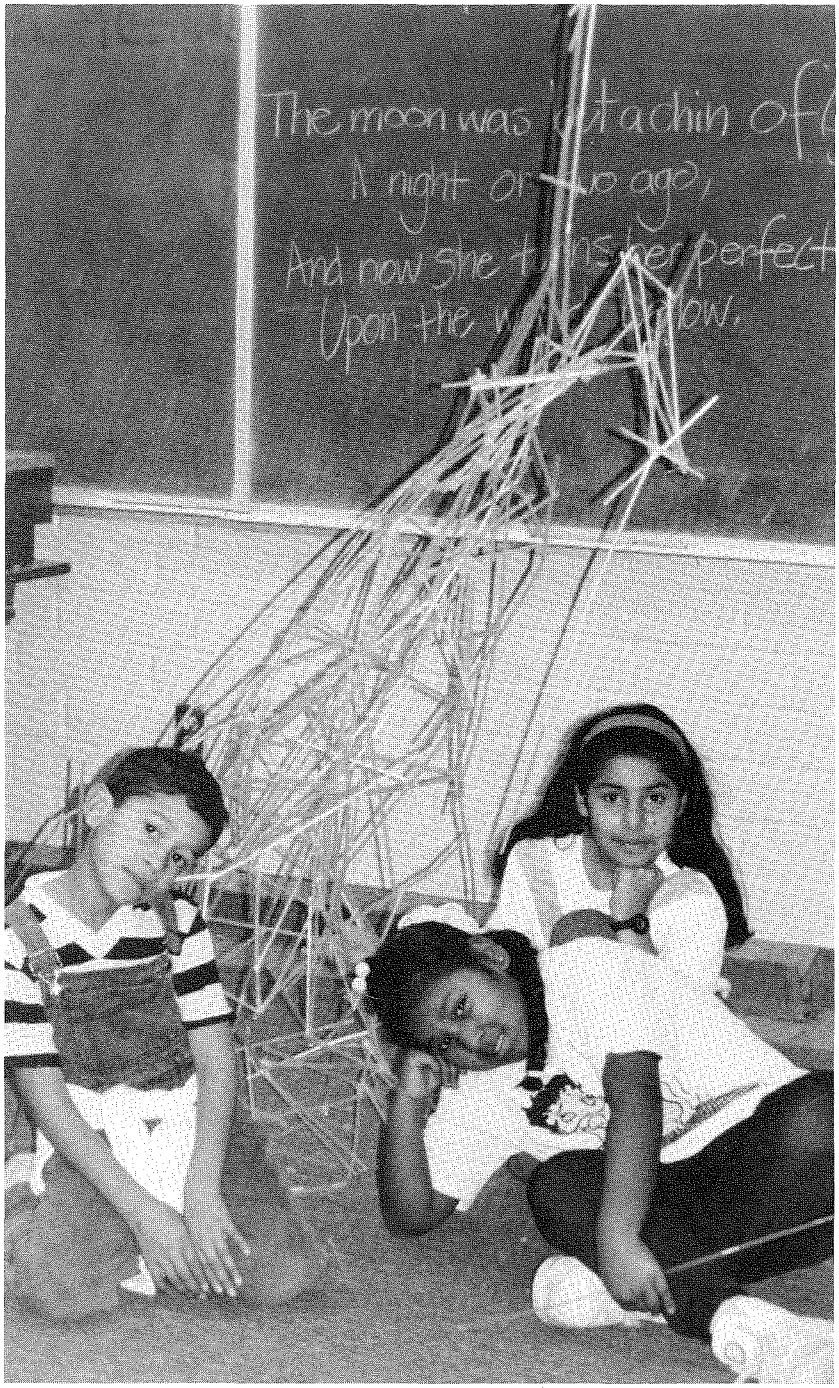
"This may be the only program in the nation where scientists work together with the teachers on the materials the teachers are already using in the classroom."

experimentation, and helping them feel more comfortable about their ability to teach science. The scientists let them know it's okay not to know the answers to a question, but to say, 'Why don't we try some things, and see what we can find out?'"

"This may be the only program in the nation where scientists work together with the teachers on the materials the teachers are already using in the classroom," says Jennifer Yuré, Project SEED coordinator for the Pasadena Unified School District.

As the project has grown, others from the community have joined the Caltech scientists in the training process—Caltech alumni, local engineers, and members of the American Association of University Women who have scientific backgrounds. "We feel it's important to involve people from the community, not just Caltech scientists," says Yuré. "If we want Project SEED to be a model for other districts, and we only use Caltech resources, then others will say, 'You have a unique situation. It won't work for us.' We want to demonstrate that any community has people who can support good science teaching." But she adds that it's important for these people to have some research background, because they must model a process where the kids have to seek an answer that isn't known.

Project SEED leaders have been pleased with the enthusiastic response of the Caltech scientists to their role in the innovative program. "Several left their phone numbers with the teachers at the end of the summer training, saying, 'Call if you need me,'" says Yuré. "And teachers have asked



"SEED is not just about science. . . . It helps children develop skills in critical thinking that are needed in every aspect of life."

The leaning tower of Pasadena? Third graders at Cleveland Elementary School (above) show off their straw structure—the tallest in the class.

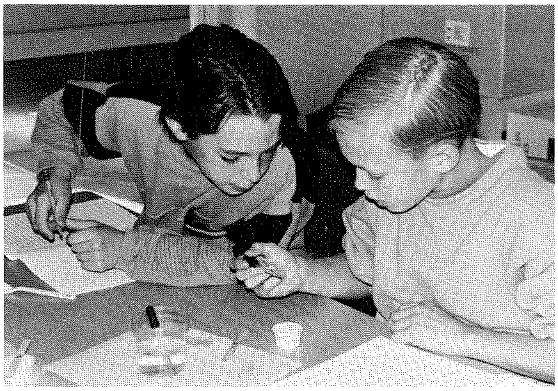
them to come help with a lesson, or talk about what they do. This has been good for the kids, because they get to see that scientists are normal people. It has helped to demystify science."

Equally pleasing was the response of principals at an introductory training session on Project SEED methodology. Originally planned for twice a year, the principals decided they wanted to work through some of the science kits themselves, and opted for monthly sessions. Pine and Bower are planning evening training sessions for parents, to show how they can do hands-on science with their children.

Teachers are gratified by the way Project SEED entices many high-risk kids with poor reading and writing skills. Fascinated by the experimental science, they find they can participate in SEED on an equal footing with their peers, offering suggestions and reaching conclusions. "One teacher told me about a kid who spent most of last year in the principal's office," says Yuré. "Now he won't leave her room when science is in progress, and he begs to stay in at recess to continue working with the experiments in the kits."

Pine points out that "SEED is not just about science. It cuts across the lines dividing scientific and mathematical disciplines, and also involves language skills and the social sciences. It helps children develop skills in critical thinking that are needed in every aspect of life."

Teachers who may originally have feared that Project SEED would take over the entire classroom have learned its value for incorporating such subjects as vocabulary and history. History



Fifth graders (above) at Sierra Madre Elementary debate the identity of a "mystery powder," while others (far right) study electricity. Below: A third grader's round, clay "boat" teaches her about water displacement, volume, and weight.

can be integrated into a unit on plants, for example, if a teacher explains how ancient civilizations planted and harvested crops. Reading and writing come into play if students are asked to write poems about their favorite plants, or to read supplemental material from books.

Although it's too early to tell how SEED will affect students' future interest in science, Yuré notes that two members of the original Field School group have gone on to win at the science fair in middle school.

Each of the five grades participating in SEED studies four units of hands-on science during the year. And seeds really do play a role. First graders, for example, grow seeds during the first quarter, learning about the parts of plants. How do you learn what's actually a seed? Well, you plant one and see if it grows. Some red hots, distributed with the kits, have failed to meet the test, despite the hopes of the children who planted them. During the second quarter, first graders study the five senses. Frogs and tadpoles are topics during the third quarter (some frog eggs get planted as students remember their seed project), and the children end the year learning about pollution.

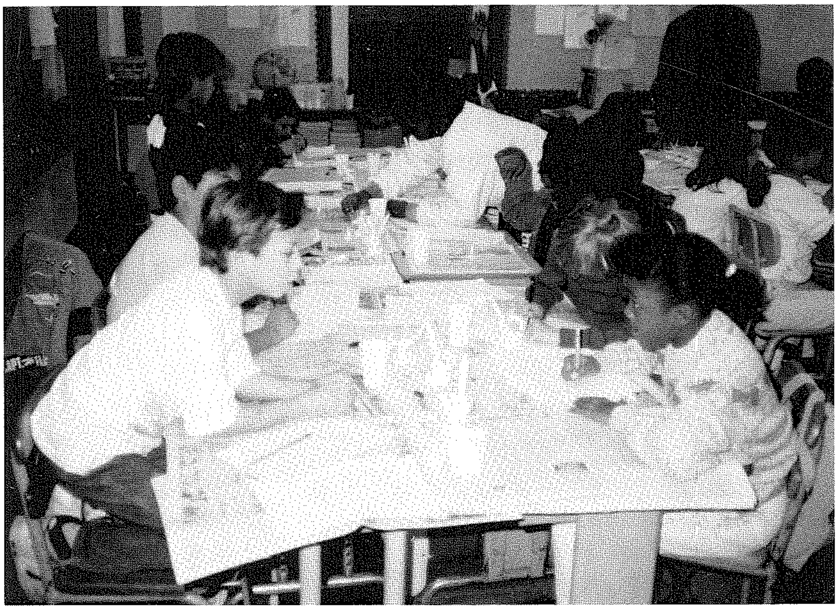
Third graders start with a lump of clay in the first quarter. Making boats from the clay, they learn about water displacement, volume, mass, and weight. After that they study brine shrimp. In the third section, they use straws to support a book and then build more and more complex structures. And during the last quarter they study scientific reasoning, observing pendulums and other mechanical devices that demonstrate engineering principles.

By the time they are fifth graders, they are studying "mystery powders." Students are given five unidentified common white household powders to identify by using their senses and various tests involving heat, iodine, and water. They go on to learn about electricity, using batteries and bulbs, making switches and fuses, and aligning poles. The third and fourth quarters bring in daytime astronomy (building sundials is included here) and the ever-popular crayfish.

Computer simulation has been a part of the Project SEED curriculum since the beginning and continues to be tested in the Field School, where SEED was launched. "We've tried to mimic the way scientists use computers in their research, but at a level appropriate for elementary school," Bower says. Working with him have been Caltech faculty, research staff, and students at Caltech, and computer scientists at TRW, Inc.

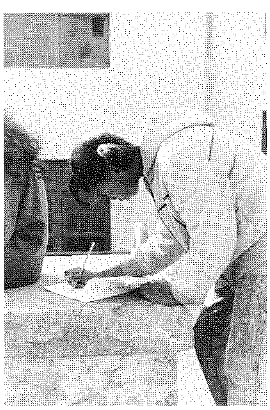
At Field School, for example, a simulation model of growing seeds enables students to use a computer to control the number of sunny days that corn will get, the number of cloudy days, and the amount of rain. They can watch the corn grow, decide when to harvest, watch a little harvester come on the screen and cut the corn stalks, and they can then measure the yield. Through a computer kids can even venture inside a cornstalk, discovering how water flows there and how photosynthesis works.

The computer programs reinforce the hands-on science offered through the kits. They allow students to increase complexity, accelerate or slow down time, expand or contract space, and



"As it's turning out, we're not only training kids, we're training scientists to train kids."

Science can be exciting with a little help from your friends, or intent on a project by yourself.



access additional data. Students can use the computer for graphing and analyzing real data obtained from the simulations. They learn concepts of data retrieval, data recording, and data abstraction.

Bower and Bill Gross (BS '81), president of Knowledge Adventure, a computer simulation firm, are collaborating on making better software for children's science education. (Gross may be remembered by many in the Caltech community for his first company, GNP—Gross National Product—famous for its Valkyrie speakers, which Gross designed.) Bower is also looking into ways to market the simulation programs he and his colleagues have developed, and plans to use any profit for further simulation research. The Apple Computer Vivarium Project supplied the computers for the pilot program. Project SEED is also supported by the Pasadena-based Community Bank, TRW Inc., the Caltech President's Fund, the Educational Foundation of America, and Rockwell International.

A new phase in SEED's expansion gained impetus in 1990 when the Alfred P. Sloan Foundation awarded a three-year $300,000 grant to develop a computerized science library. The library program, developed in collaboration with the UCLA Graduate School of Library and Information Science, uses Apple Macintosh software graphics to give students access to information in public libraries. Information from 57,000 children's science books in the Los Angeles Central Library has been converted for reading on computer.

"SEED is supposed to excite kids about science," Bower remarks. "It seemed unfair to excite them and then leave them without ways to get additional information." In creating this project, Bower and his colleagues are investigating the information-seeking behavior of children and designing software that kids can easily use and understand.

The library program also features a computerized adventure game designed to inspire students to seek out information. The game introduces a rural environment with a farm, a swamp, woods, and a small town. The kids can wander through the environment on the computer screen by manipulating controls. In each section, they meet various animals, for example, a frog in the swamp. Initially the frog dives out of sight into the swamp. But if the child learns to feed the frog a bug, the new friend takes the child with it to the bottom of the swamp where it leads the child on a tour of the frog's world.

The library system has now been introduced to the Ninth and Tenth Street schools in Los Angeles and the University Elementary School at UCLA. It's also in the children's section of the Los Angeles County public library. Through the Ninth and Tenth Street schools, says Bower, "we're gaining piles of information about how homeless kids and kids from other language and cultural backgrounds use the library to get information."

An unexpected side effect of Project SEED has been the enthusiasm it has generated in young Caltech scientists. One of these, Leila Gonzales, after graduating from Caltech with a BS in biology, earned a PhD in developmental genetics

"Doing something is a better way to learn about it than reading or hearing about it."

Right: Jim Bower discusses hands-on science with teachers, and (below) two students from Dean Cooper's class at Field Elementary School give some serious thought to their crayfish.

at Harvard and came back to Caltech as a postdoc. Investigating computational neurobiology in Bower's lab, she volunteered to become involved with Project SEED and now works with it full time. She has decided to change her career from science research to science education.

Says Bower, "One of SEED's contributions may be to set up a pipeline for people who find in Project SEED an opportunity to use their imaginations and their science training in ways more directly related to human beings than if they went into research. As it's turning out, we're not only training kids, we're training scientists to train kids."

In March scientists and engineers who are interested in becoming involved in kindergarten-through-12-grade education came to Caltech from all over the country for a working conference on precollege science education. It was sponsored by the National Science Resources Center, which is operated by the Smithsonian Institution and the National Academy of Sciences. Educators already experienced in developing innovative curricula in science explained their ideas and programs during the week-long conference. Visits to Pasadena elementary schools to see Project SEED in action demonstrated the enthusiasm that children can bring to learning science.

"Doing something is a better way to learn about it than reading or hearing about it," says Pine, pointing out that many Caltech scientists didn't become enthusiastic about the subject in the classroom. They learned in their basements, creating their own experiments. "We've tended to turn kids off to science in about the third grade," says Bower. "But if science is made exciting, kids want to know more about it. They want to learn."

"Our students," says Yuré, "are having a ball." □

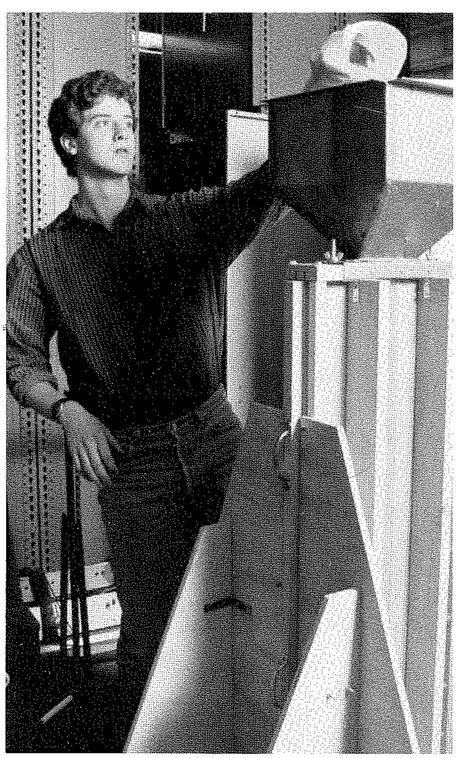
Winifred Veronda recently retired as editor of Caltech News *after 20 years at the Institute.*

SURFboard

The trickle of sand through an egg timer is anything but steady as a ticking clock when seen up close, but spurts and dribbles instead.

Chute the Works

Erik Taylor loads beads into the chute.

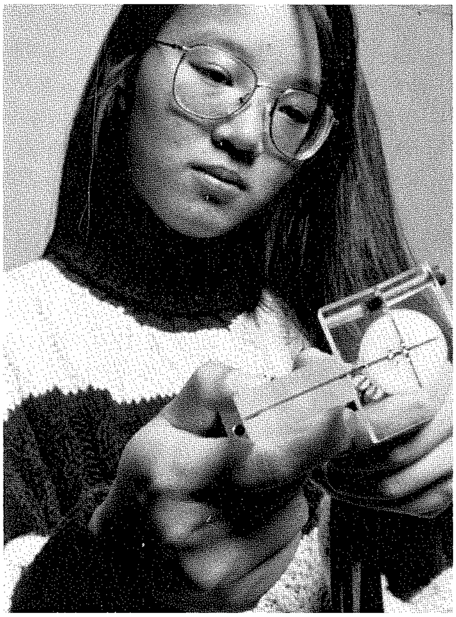


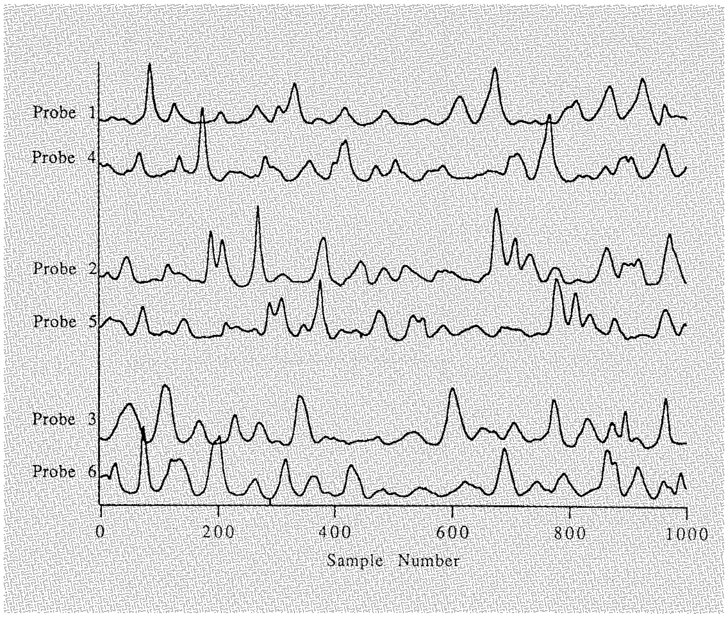
The next time you pass a gravel quarry or a grain elevator, take a look at those huge chutes. You know nearly as much about what's happening inside them as the people who designed them. Fluid flows have been studied rigorously since at least Newton's time, but "it's only recently that people have started to make any scientific measurements of flows of solid material" according to Assistant Professor of Mechanical Engineering Melany Hunt. There are elaborate mathematical treatments that assume that the coal lumps, fertilizer clods, frozen broccoli tips, or what have you are just very large gas molecules, and apply the principles of gas dynamics to them. But the models are on shaky ground without real-world observations to test their assumptions. Says Hunt, "We aren't even sure how to define the flow's properties—things like viscosity or shear stress, which we measure easily in fluids." Take flow rate, for example—the trickle of sand through an egg timer is anything but steady as a ticking clock when seen up close, but spurts and dribbles instead. And the flow varies from place to place as well as from time to time as individual sand grains tumble into each other, jostling their neighbors sideways as they flow downstream.

This past summer, Hunt and SURF (Summer Undergraduate Research Fellowships) students Garland Lee (senior, engineering and applied science) and Erik Taylor (junior, applied physics) worked on ways to measure an individual particle's motion in detail—a first step to abstracting the flow's bulk properties. Existing methods, including a fiber-optic system devised by Hojin Ahn (BS '85, MS '86, PhD '89), measure a particle's down-the-chute velocity but not its side-to-side buffeting, and tend to give average readings rather than specific data on individual particles. Lee modified Ahn's system to work in two dimensions, while Taylor wrote an image-processing program that tracks particles from a series of video images. "We wanted to try two different approaches, because we weren't sure which one would work better," Hunt explains.

Both detection systems track the flow of a column of beads down a vertical wooden chute about three feet tall, three inches wide, and three-quarters of an inch thick—thin enough to assume the beads only moved downward and side-to-side. The front and back walls are glass, and the replaceable side walls allow various flows to be set up. The beads are three millimeters—a shade less than an eighth of an inch—in diameter. A valve at the chute's bottom controls its flow rate. Graduate student Shu-San Hsiau built the chute and assisted Lee and Taylor with their projects.

Lee's detector, which mounts flush





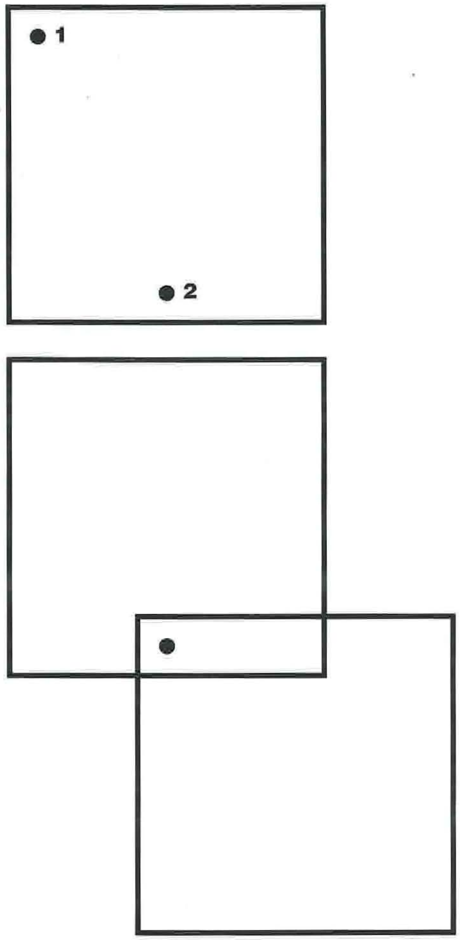
Above: Garland Lee's detector consists of six fiber-optic probes in two horizontal rows of three each.

Right: A bead falling in front of a probe registers as a spike. Probe 1 is directly above probe 4, 2 is above 5, and 3 is above 6. A distinctive set of peaks appearing first at an upper and then at a lower probe marks the passage of a group of beads.

against the glass, consists of six fiber-optic probes. Each probe is 1.6 millimeters in diameter—about half the size of a bead—and consists of two semicircular bundles of optical fibers, one to emit light and one to collect it. The probes are grouped in two horizontal rows of three. Each row is one bead wide, so a bead partially crossing the central probe will trip its neighbor as well. The lower row's probes lie, like a snowman's smile, in an arc centered on the upper row's middle probe. The two rows are a bead's width apart—far enough for a falling bead to move sideways a bit, but not enough to get clean away. A bead passing directly through a probe's line of fire will reflect most of its light back to the collector, while an off-center bead won't register as strongly. (Clear glass beads work best.) Thus each probe generates a pattern of irregular peaks. A computer compares the patterns, looking for a distinctive set of peaks from an upper probe to reappear in a lower probe. To be sure that the peaks were actually related to the beads, Lee placed a dishful of beads on a spinning turntable to carry them past the probe at a known rate. The correlation between a first-row detector and the one directly downstream from it was quite good, but sideways motion wasn't so tractable—correlations between diagonal probes weren't as strong.

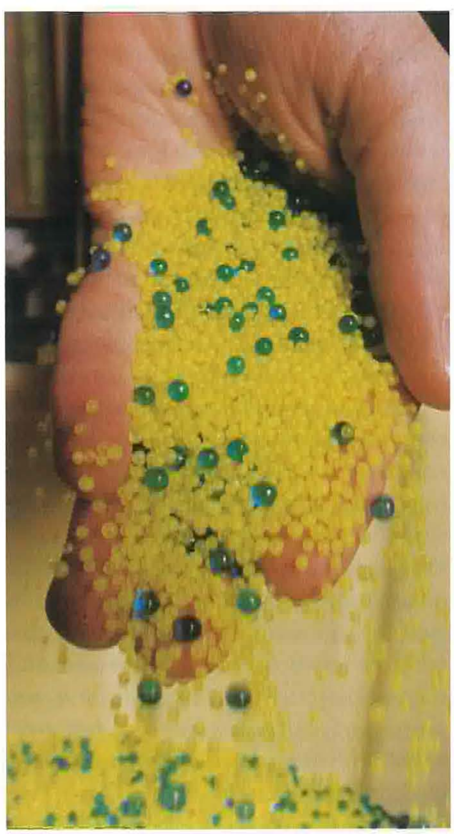
Taylor uses a video camera to follow a few individual beads in the stream. Black beads against a background flow of bilious Day-Glo yellow-green beads give the best contrast. A frame-grabber converts the video feed into a series of still pictures. After various processing steps to remove graininess and enhance contrast, each pixel in the image is given a value of 1 if it's part of a high-contrast bead or 0 if it's part of the background. Taylor's program then searches the 200-by-200-pixel image for round blobs containing 15 to 20 pixels, rejecting oblongs and other odd shapes. When the program finds a blob it likes, it draws a tall, thin rectangle from the bead down. The program then searches for the bead in the corresponding rectangle in the next image by a process called "autocorrelation," superimposing the second rectangle on the first and multiplying the corresponding pixel values. Since bead pixels are 1's and background pixels are 0's, only those pixels containing a bead in both frames will give a nonzero product. The program adds all the products to get an "autocorrelation value," which it remembers, and then shifts the second image by one pixel and repeats the process. The peak autocorrelation value happens when the bead is superimposed exactly on itself, and the amount of offset the process took gives the bead's velocity. The program stores the velocity and looks for the next bead. On

"Ask anybody who designs these chutes how they behave, and they'll say, 'We just build them. Then, when they clog up, we get out shovels and unclog them.'"



Right: How autocorrelation works. (Top): A bead (1) falls to a lower position (2) in the next video frame. (Bottom): The computer moves the two frames until the bead is superimposed upon itself, then uses that offset to calculate the bead's velocity.

Below: Lee (seated) fires up the computer as Hunt (left) and Taylor look on. Their small vertical chute stands at the right, while Patton's one-cubic-meter per minute chute awaits its turn behind Taylor.

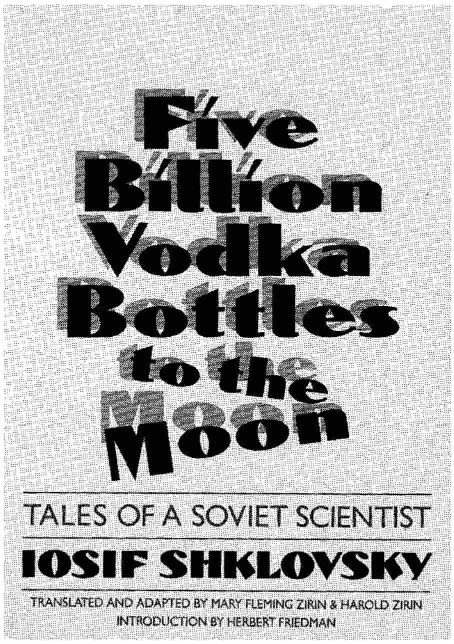


average, each bead moves three to eight pixels down and one to three pixels sideways between images. "The trick is to have few enough beads that their rectangles don't overlap, but enough to get a significant amount of data per run," notes Taylor. "I can handle about one black bead per square centimeter." The program works, but it's slow and memory-intensive. Taylor expects to speed it up considerably by making it screen the images before storage and having it store the locations of the dark pixels only.

Both methods suffer from some of the problems that have hampered progress in this field for so long. As dust and dirt builds up on the chute's walls, the accumulating gunk slows the flow. Soon, results from one run can't be repeated in the next one as the beads begin to stick together. The paint on Taylor's Day-Glo beads chips and flakes as they clatter against each other, putting more crud in the chute. The chute has to be torn apart and the plates washed with soap every few runs in order to keep the data reproducible. Life got even more interesting one dry day, when the researchers discovered that the cascading beads can generate enough charge to succumb to the curse of static cling.

The next step will be to measure flows in a more realistic setting. Behind the little vertical chute stands a huge, inclined one, built about ten years ago by J. Scott Patton (MS '80, PhD '85) for Rolf Sabersky, now professor emeritus of mechanical engineering. This baby is rated at a deafening one cubic meter per minute, enough to start taking some real-world data. "Open-channel chutes like this one are especially complex," says Hunt. "There's room at the surface for the material to expand, so the velocity varies with depth as particles ride up and over each other. Ask anybody who designs these chutes how they behave, and they'll say, 'We just build them. Then, when they clog up, we get out shovels and unclog them.' We know so little about the fundamental equations governing these flows that we can't even scale them up—half the capital cost of a plant can be in its chutes, and a lot of that money gets spent on building larger and larger prototypes. We're hoping to begin to change that." □—*DS*

Books



Translated and adapted by Mary Fleming Zirin and Hal Zirin
W. W. Norton & Co., 1991
268 pages

An informal, humorous autobiography of a leading Soviet astrophysicist (1916-85), this is also a bitter and revealing account of what it felt like to be a scientist in what was the Soviet Union. With daily newspaper accounts of internal weaknesses revealed, with the crumbling of the "Union," it may be difficult to recapture the oppressive atmosphere of his scientific life. Translated by Shklovsky's friends, Mary and Hal Zirin (Hal is professor of astrophysics at Caltech and director of the Big Bear Solar Observatory and his wife is a translator of Russian literature), the book has a long and personal introduction by the pioneering rocket scientist, Herbert Friedman, also a good friend of Shklovsky's. The Zirins have added many footnotes, explanations of historical background, personalities mentioned, and corrections. The title derives from Shklovsky's order of magnitude estimate of Soviet annual vodka consumption, which he found to be a "classified" number; but the distance to the Moon was available. Our amusement at the number may be tempered by the picture of 5×10^9 bottles in orbit between Moscow and Mare Stupefactionis, with drunkenness a plague of galactic proportions.

The title suits the book, a mixture of scientific discovery after personal struggle, of bitter experiences with inept and corrupt leadership, of the good and bad in a society that we only now see through a crumbled facade. It is not a depressing account, since Shklovsky was truly irrepressible. He was good company and a good scientist. For decades he was denied travel permission, but in only a few trips to the West he made warm friends.

Quite seriously, this book is like one I wish I could have written; not only do I lack the courage and time, however, but our country is full of lawyers. Truth is seldom a defense against the expenses of libel suits. I also have had irritating, fascinating bosses and colleagues (mostly competent); I also have served on committees to advise the government, which were mostly voices blown away in unheeding winds. Here, too, there are missed or unrecognized discoveries; the successful are not always worthy; planners and administrators make mistakes. Being a senior scientist in the US has a rich, complex reality. Alas, my autobiography on that topic will not be publishable.

Shklovsky's was also unpublishable in Russia. The Zirins translated a smuggled typewritten copy, but Shklovsky died before his ironic sketches reached even that stage. I miss him as a colleague and as a charming, lively human being, even if his anecdote about me describes me as "thick-set," makes me director of Palomar and places Caltech in Berkeley. He ascribes magic powers to me in arranging a trip around the US, providing money for Novikov and himself (apparently through my nonexistent, high-level government influence). He tells Ed Teller that in the USSR he is given the epithet "cannibal." To my wife he says, "The Moscow Art Theater, it stinks, but today I have seen your Disneyland." An amazing personality destined to be out of place almost anywhere, he might have fitted Caltech.

He writes of many of his contemporaries in Soviet physics. A charming anecdote about Sakharov tells how they met on a train evacuating intellectuals from Moscow to Siberia in 1941. Shklovsky lent him Heitler's *Quantum Theory of Radiation* overnight. When asked if he had finished it, Sakharov replied, "Yes, why not?"

As a scientist, Shklovsky was expert in applying new ideas in physics to unusual situations in astronomy. His single most influential contribution was his 1953 explanation of the continuum radiation of the Crab Nebula (a supernova remnant) as the synchrotron radiation from high-energy electrons (1 to 100 GeV) spiraling in a magnetic field. He extrapolated its radio frequency spectrum to the optical region; he required in the Crab both that such electrons exist and that, since they lose energy rapidly, they must be replenished. (Protons at cosmic-ray energies are poor radiators.) The existence of an electron component at cosmic-ray energies had many important results; presumably they arise from the spinning pulsar in the Crab. From 1936 to 1955 I had vainly tried to explain radio frequency noise as thermal in origin; the revolution started by Shklovsky began the rush of high-energy physics into astrophysics. Magnetized plasmas, hot gases in rapid motion, seem now omnipresent.

He also became a force in the space program. Another novel contribution lent respectability to the search for extraterrestrial life and intelligence. For a symposium he organized in 1961 he wrote an imaginative account of the problem, although he admits weakness in molecular biology. He was the only participant to submit a manuscript on time, which he published in 1962 as a book that "sold out a printing of 50,000 copies in a few hours. . . five editions. . . many foreign languages. . . and in Braille." Its American translation as *Intelligent Life in the Universe,* with extensive additions by Carl Sagan, became a phenomenal success. Shklovsky's mind was fertile, freely roving; lacking the self-critical facility of the less gifted, he also made many mistakes. Herb Friedman's introduction is a warm picture of his personality and scientific contribution. Please read the book.

Jesse L. Greenstein
Lee A. DuBridge Professor of Astrophysics, Emeritus

Letters

Editor: In your fall edition on page 39 at the top you show a photograph which includes Dr. Millikan with Mrs. Balch on his right. During those years Mrs. Balch was a trustee of Scripps College. I was a junior there and in the spring of 1934 I was involved in a student protest which turned out to be both serious and important in the growth of the college. Mrs. Balch came out to interview us. For two hours she sat opposite me in probably the same dress as in the photograph and certainly the same hat. I feel you have identified her correctly.

Carlotta Welles
Member, The Caltech Associates

Editor: Not being a man of science, I very rarely am capable of enjoying articles in *Engineering & Science*. However the fall issue did contain two articles which I enjoyed reading, one on Shakespeare and the other on Sidney Weinbaum.

The latter article made me even prouder to be associated with Caltech. I think printing the article about Weinbaum and the difficult times of the late forties and early fifties, which I remember so well and need to be reminded of from time to time, in such an objective manner without editorializing about his guilt or innocence of an inconsequential "crime" peculiar to that era, speaks very well about an institution of science.

Arthur Rock
Caltech Board of Trustees

Editor: Your oral history excerpt from Sidney Weinbaum was both sobering and inspiring. Whatever his political affiliations during the Depression, three years in prison was an extraordinary price. It is hard for someone my age to fully understand the climate of that era, but I found the yellowed clippings from our local papers chilling.

Thanks for illuminating a dark chapter of our history. Perhaps with the cold war over at last, we can dismantle the vast security apparatus that has been so costly to our economy, our liberties, and our sense of decency.

Rick Cole
Vice Mayor, City of Pasadena

Editor: Your account of the Sidney Weinbaum trial includes a reference to

Highest Court May Rule on Refusal To Testify

Whether Communists, ex-Reds or suspected Communists can get special treatment from the courts by refusing to testify regarding their present or past affiliations appeared today to be headed for a ruling by the highest courts of the country.

An appeal was being framed today from the decision of District Judge Ben Harrison to send Dr. Eugene Brunner, research chemist, to jail for six months for contempt in refusing to answer questions in the federal court perjury trial of Dr. Sidney Weinbaum.

Brunner, 39, formerly a graduate student at Caltech, was called as a prosecution witness in the trial of Dr. Weinbaum, former physicist in the jet propulsion laboratory at the institute, and refused flatly to answer these two questions:

"Between 1937 and 1939 were you a member of the Communist Party in Pasadena? During the period, did you ever see Dr. Weinbaum at Communist meetings?"

BAIL IS DENIED

Judge Harrison then denied a motion by Brunner's lawyer, William Esterman, that Harrison disqualify himself. He also denied the attorney's request to fix bail pending appeal "because I find that this contempt was deliberate and wilful."

Earlier Dr. Jacob Dubnoff, senior research assistant at Caltech, admitted on the witness stand that he had been treasurer of the "Caltech branch" of the Communist party prior to 1940. He said that his "party name" was "John Kelly," and that he had collected dues from other Pasadena Reds, but he "couldn't remember" whether Weinbaum had been one of them.

Eugene Brunner in the reproduced news clipping on page 37. The combination of partial truths and omissions here can produce some bad implications. I hope I can contribute a little to help balance the history of our fellow alumnus (BS '33, PhD '38) and my fellow classmate.

I remember Eugene from our first day of freshman classes in 1929. Professor Luther Wear was laying out the plan of his mathematics course to our mixed section of the brilliant and not-so-brilliant, still to be sorted out. In his practiced way, he abruptly broke off the review to toss out a question about an equation. I had barely started to think when we heard a quick, conclusive answer. A trout had snatched the fly. I looked around to the source, a round-faced young man with thick glasses, who till this moment had looked half asleep: Eugene Brunner.

A little later in our freshman English section, Professor George MacMinn was fingering our first themes. He had been looking for some gleam of imagination out of the pile. He was largely disappointed except for one jewel, which he lifted out to read to us. It was "The Laboratory" by Eugene Brunner, a prose poem celebrating the scientist's career. We were beginning to get acquainted with our gifted classmate, who eventually went on through the difficult theoretical physics option to graduate with honors.

I left Caltech after graduating, but years after, a little before World War II, I encountered Eugene once more. He had just been hired as a hydrodynamics physicist by the Shell Development Company in Emeryville, where I was already working. He was given office space in the room I occupied. For a time we were also both members of a technical and professional employees' union. Like other unions of that time, this one had its share of Stalinists, but I never saw anything that identified Eugene with the Stalinist faction.

It was a different story with another union local member, George Eltenton. George was later alleged to be an intermediary for contacts between Robert Oppenheimer and Soviet agents. He was an English physicist who had been imported to Shell to help Otto Beeck by building one of America's first mass spectrometers. I rode in a car pool with George and had many opportunities to talk with him. Scarcely the stealthy conspirator imagined by some people, he was tirelessly forthright in advocating the Soviet system and criticizing America for withholding technical information from its glorious ally. The point is that in those times of the United Front, Communist influences had penetrated significantly into areas of American life. They had brushed closely against some of us.

In 1948 I left Shell and had no further contact with Eugene for about 30 years. Then one year I made a routine solicitation call to him on behalf of the Alumni Fund. He was living in Oregon and urged me to visit him and Mrs. Brunner whenever convenient. My wife and I were able to make this visit while touring Oregon in 1985. We spent the afternoon at the Brunner home and inevitably we talked about the court hearings. Eugene filled in my knowledge of the later history.

The threatening tone of his interrogation had affronted Eugene, and he had steadily refused to answer. (It is useful to recall that membership in the Communist Party broke no law. And the implied acts or associations dated from more than 10 years before the hearings.) But the threat was real; his refusal to answer devastated his career. He quickly became both unemployed and unemployable in industry. Cut off from his profession, he made a living for the next 10 years as a television repairman.

The history did take one further twist, and even brightened a little bit. During his banishment, Eugene was gradually teaching himself to read Russian, not with any career plans but simply for personal interest. In some way the American Physical Society took notice of him and asked him to translate some papers from the Russian journals. His submissions were welcomed; he received more commissions and eventually found a new career of translating, abstracting, and reviewing the extensive literature of Russian physics.

I had to wonder how he could recover a mastery of contemporary physics after the long layoff. But Eugene disparaged the difficulty. Anyway, monitoring other people's achievements was less demanding than creative research of his own. The thought did cross my mind that he would have preferred the latter. But of course it was no longer an option.

Lee Carleton, BS '33

Editor: I read with much interest the interview with Sidney Weinbaum in the fall issue of *Engineering & Science*. My recollection of the events is somewhat different, and while I was not close to Dr. Weinbaum—I was not an ardent chess player—I knew Malina and Tsien very well indeed, and in particular Clark Millikan. The one statement in the interview that is plainly incorrect and unfair is the quotation about Clark Millikan "gleefully" relating the story about the Communist cell at Caltech. There was certainly no hard feeling between Millikan and Malina, and, more than that, Clark was one of the most decent, honest, and straightforward men I have known. Indeed, the only remark Clark made to me about the Weinbaum case—for which I can vouch—expressed his complete mystification as to the reason for Weinbaum's insistence on a clearance, which to him was akin to a Freudian death urge.

That Weinbaum's problems began in 1949 or so, which is much later than the date for his original clearance, may well be related to the discovery at about that time of the very real spy ring in the atomic research projects in Canada and the US. To bring in anti-Semitism as one reason for his troubles is definitely uncalled for.

I remember Dr. Weinbaum as someone even a little more nutty than the rest of us on the faculty at Caltech. We both lived close to the campus—he, I believe, on Steuben Street and I on the corner of Del Mar and Wilson—and I enjoyed walking at some distance behind him to campus because at random intervals Weinbaum performed something like a jump followed by a few dancelike steps, waving his arms like a bird. I always thought he was a Communist, and I don't think he made any pretense otherwise. One has, of course, to remember that in the Depression of the thirties many liberals looked toward communism and Russia as possible alternate solutions. The purges later in the same decade and finally the Hitler–Stalin pact turned most everybody off, but there remained a rather lunatic fringe trying to explain these terrible facts with an often bizarre logic. In any case, Weinbaum was considered odd but hardly dangerous. Indeed, Bill Sears tells me that von Kármán once introduced Weinbaum at a party as his friend dealing in chemistry and communism.

Hans W. Liepmann
Theodore von Kármán Professor of Aeronautics, Emeritus

Editor: Congratulations on an exceedingly interesting issue of your magazine for fall 1991, encompassing as it did the end of an unfortunate political era in the United States, the possible end of William Shakespeare, the end of man's last vestige of privacy (his genetic structure), and the end of the universe.

I can add some fragments of information to the Sidney Weinbaum sidebar to the article on Shakespeare.

Dr. Clyde Wolfe did indeed work for a man named Arensberg, who had previously done some writing on the Shakespeare controversy and was involved in a book considering, among other things, codes and ciphers and concealed meanings of all kinds. Wolfe's job was to assess the probability of random associations in previously discovered codes (perhaps it would be better to say purported codes) and to look for strange new combinations that would lead to Bacon's signature of authorship. Or any other signature.

Among the courses conducted at Caltech by Dr. Wolfe was one called, I believe, "Probability Theory and Combinatorial Analysis." While awaiting the arrival of the instructor on opening day, I and five or six others in the class occupied our time by writing in large letters on the board, "This is the class in uncertainty, doubt, and indecision." Wolfe called it an excellent description of his subject, unaware that it might be peculiarly apt when working on the identity of dramatists.

Wolfe became a good friend of mine, and I recall him, as I do half a dozen other professors at Caltech, with a good deal of affection. Among them was Professor George R. MacMinn, whose course on Shakespeare I took, and whose inscribed book, *The Theater of the Golden Era in California,* honors my bookshelf.

Congratulations on an exceedingly interesting issue of your magazine for fall 1991, encompassing as it did the end of an unfortunate polticial era in the United States, the possible end of William Shakespeare, the end of man's last vestige of privacy (his genetic structure), and the end of the universe.

One summer Wolfe had to be in Berkeley on some important private business and asked me if I would fill in for him on the Shakespeare job for a couple of weeks. Of course I would. He briefed me, gave me two or three days to bone up on the great controversy, and left.

The first thing I saw when I walked into Arensberg's house in the Hollywood Hills was Brancusi's famous "Bird in Flight" sculpture perched on a hall table. I had barely turned away from it before I encountered Duchamp's "Nude Descending a Staircase." It was flanked by a half dozen Picassos from one of his more incomprehensible periods.

Arensberg, as you have probably guessed, was, of course, the Walter Arensberg whose magnificent collection is now in the Philadelphia Art Museum. He had become very interested in the Shakespeare authorship and had obtained photocopies of the First Folio for Wolfe's work on codes, some of which, it was thought, might be positional, which meant, obviously, that the printer had to be in on the game.

I think it a little cavalier to sweep Arensberg into the Looney bin to which Professor La Belle discards all those who dare to question the discontinuities and contradictions in the Shakespeare of Stratford record. Also in that Looney bin one finds a good many scholarly experts, an army of lawyers who are accustomed to weighing evidence, and an amazing array of individuals of various trades, such as Mark Twain, Charles Dickens, Walt Whitman, Henry James, John Galsworthy, Sigmund Freud, and Charles Chaplin. Some of this sampling are obtained from the writing of that dreadful Charlton O. Ogburn, whom Professor La Belle stabs to death with a telephone pole. I think a fair approach would be for concerned readers to obtain a copy of Ogburn's 1974 article in *Harvard* magazine. It is mercifully short and presents the case against Stratford rather logically, I thought.

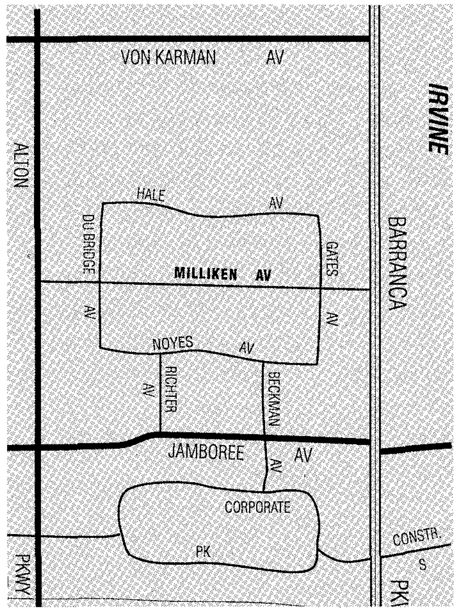
During my short stay in Clyde Wolfe's job I contributed absolutely nothing. I did not even become an expert on Shakespeare. I started out as and continue to be an impartial observer. Much of the hogwash Professor La Belle refers to is just that. So is much of the material adduced by the Stratfordites, who sometimes seem short on logic and long on emotion.

Nobody has proved Shakespeare didn't write Shakespeare. Nobody has proved beyond question that Shakespeare did write Shakespeare. Nobody has proved anyone else wrote Shakespeare.

Linton von Beroldingen, BS '29

Random Walk

Millikan's Proper Vowel Restored After 20 Years



Richter, Beckman, von Kármán, and DuBridge all have streets named after them in an industrial tract in Irvine, California. And parallel to each other in the same complex lie three streets honoring Caltech's founding fathers—Hale Avenue, Noyes Avenue, and Milliken Avenue. Milliken?

City officials don't know how Robert Andrews Millikan's name came to be misspelled back in 1972, but it has stood uncorrected for 20 years. Lee Carleton, BS '33, noticed the error a few years ago and recently, with the backing of the Orange County chapter of the Alumni Association, came right out and asked the Irvine City Council to correct the faulty vowel.

At its February 11 meeting, the city council agreed to spend $350 to patch an "a" over the "e" on each of 12 signs on the 2,607-foot-long street. Not everyone is pleased. The *Los Angeles Times* reports that a printer complained that "customers who come by and see the street name 'Millikan' on signs and notice 'Milliken' on the shop's delivery van, price lists, calendars and other promotional material might question the company's professional standards."

But Caltech's professional standards are satisfied, and Carleton is happy that Caltech's first chief executive is finally receiving his due. The city's letter, however, informing him of passage of the spelling-change resolution began "Dear Mr. Carlton . . ."

Honors and Awards

Lew Allen, senior faculty associate and former director of JPL, has been elected a Fellow of the American Physical Society.

James Bailey, the Chevron Professor of Chemical Engineering, received the 1991 Food, Pharmaceutical, and Bioengineering Award, presented by the American Institute of Chemical Engineers.

Diana Barkan, assistant professor of history, has received a $10,000 Arnold L. and Lois S. Graves Award for young faculty in the humanities. She also won the 1992 Marc-Auguste Pictet Prize presented by the Société de Physique et d'Histoire naturelle de Genève.

Nine members of the Caltech faculty have been elected Fellows of the American Academy of Arts and Sciences: Jacqueline Barton, professor of chemistry; John Bercaw, professor of chemistry; Lance Davis, the Mary Stillman Harkness Professor of Social Science; George Housner, the Carl F Braun Professor of Engineering, Emeritus; Steven Koonin, professor of theoretical physics; Carver Mead, the Gordon and Betty Moore Professor of Computer Science; Elliot Meyerowitz, professor of biology; John Seinfeld, the Louis E. Nohl Professor and professor of chemical engineering, and chairman of the Division of Engineering and Applied Science; and Edward Stolper, the William E. Leonhard Professor of Geology.

Pamela Bjorkman, assistant professor of biology and assistnat investigator with the Howard Hughes Medical Institute, has been selected as a recipient of the Cancer Research Institute's 1991 William B. Coley Award for Distinguished Research in Fundamental Immunology.

Ronald Bush, professor of literature, has been awarded a National Endowment for the Humanities grant for the academic year 1992-93 to study Ezra Pound's *Pisan Cantos*.

Sunney Chan was named the George Grant Hoag Professor of Biophysical Chemistry, a new professorship made possible by a $1.5 million gift from the George Hoag Family Foundation of Los Angeles.

David Goodstein, professor of physics and applied physics and vice provost, has been elected a Fellow of the American Association for the Advancement of Science.

Michael Hoffmann, professor of environmental chemistry, has received a Senior Scientist Award from the Alexander von Humboldt Foundation of Bonn, Germany. The award offers the opportunity for an extended research period in Germany.

Hiroo Kanamori, the John E. and Hazel S. Smits Professor of Geophysics and director of the Seismological Laboratory, will be honored with the Medal of the Seismological Society of America at their annual meeting in April.

Mary Kennedy, associate professor of biology, and Mary Lidstrom, professor of applied microbiology, are among 100 recipients nationwide of the Faculty Award for Women Scientists and Engineers, presented by the National Science Foundation.

James Knowles, professor of applied mechanics, has been named the William R. Kenan, Jr., Professor.

Rudolph Marcus, the Arthur Amos Noyes Professor of Chemistry, has been elected an honorary Fellow of the Royal Society of Chemistry and has also received two awards from the American Chemical Society.

Charles Seitz, professor of computer science, was elected to the National Academy of Engineering.

Edward Stone, professor of physics, vice president, and director of JPL, has been elected a Fellow of the American Institute of Aeronautics and Astronautics.

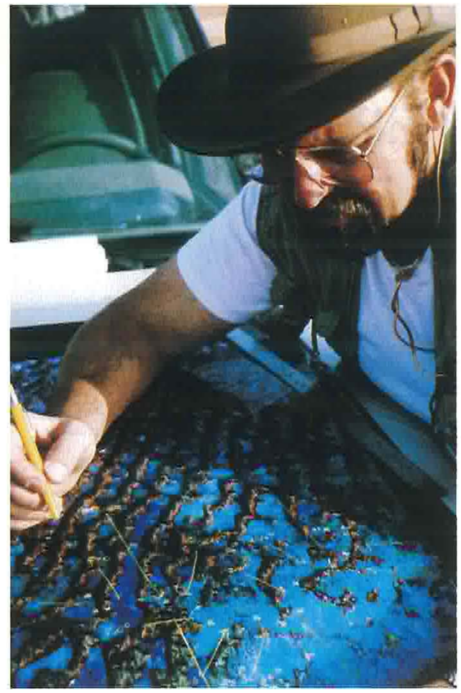
Mark Wise was named the first John A. McCone Professor of High Energy Physics; the chair is part of a $2.5 million gift from the estate of John McCone, a Caltech trustee, and the McCone Foundation.

Peter Wyllie, professor of geology, has been elected vice president of the International Union of Geodesy and Geophysics.

Ahmed Zewail, the Linus Pauling Professor of Chemical Physics, has received the 1992 Carl Zeiss Research Award.

Correction

The VLBI image of radio quasar 3C345 on the cover of the Fall 1991 issue of *E&S* should have had shared attribution; it was produced by astronomers Stephen C. Unwin (Caltech) and Ann E. Wehrle (Infrared Processing and Analysis Center/JPL/Caltech).

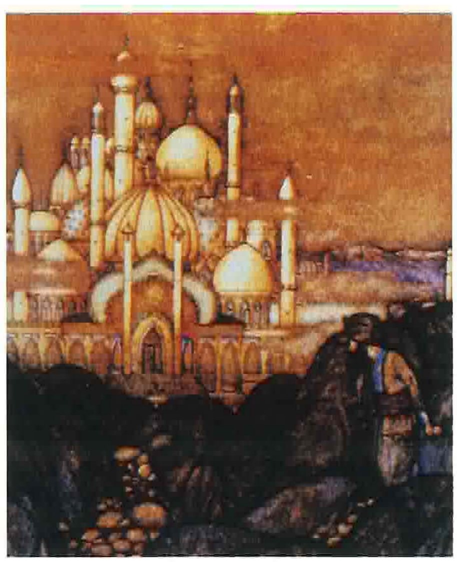


In the field JPL geologist Ron Blom plots satellite data on a Landsat image of the Oman Empty Quarter.

Space Technology Helps Find Fabled City

Led by space images of ancient trade routes, a group of amateur archeologists and Jet Propulsion Laboratory scientists has discovered the fabled city of Ubar in the Empty Quarter of Oman. Ubar, center of the Arabian frankincense trade in Biblical times, was one of the "enchanted cites" of *The Thousand and One Nights* and "the City of Towers" in the Koran.

A number of expeditions had failed to unearth the legendary site before Nicholas Clapp, a Los Angeles filmmaker, armed with clues to Ubar's whereabouts from Huntington Library manuscripts, got in touch with Charles Elachi (MS '69, PhD '71), assistant laboratory director at JPL. Using Shuttle Imaging Radar (SIR-A), which could penetrate arid sands, Elachi, who is also a Caltech lecturer in electrical engineering and planetary science, had discovered ancient channels under the Sahara (*E&S* September 1983). Elachi agreed to have SIR-B, which flew on the shuttle Challenger in 1984, scout the southern Arabian peninsula for evidence of abandoned caravan routes. JPL geologists Ronald Blom and Robert Crippen then combined long-wavelength data from the Landsat Thematic Mapper and high-resolution images from the French SPOT satellite to zero in on promising tracks in the Empty Quarter.



Ubar was one of the "enchanted cities" in the *Arabian Nights*.

The enhanced images revealed a network of tracks that converged on Shisr, a remote waterhole in a region of 600-foot-high dunes that had been dismissed as a site in 1930. The expedition, which also included Clapp's partner and fellow Ubar-aficionado, George Hedges, a Los Angeles attorney, as well as a couple of "real" archeologists, and JPLer Kristine Blom, who supervised the ground geophysical surveys, used radar to scan the ruins under the sand and then began to dig. This past January they were rewarded with the remains of a castle with several tall towers and artifacts dating back to 2000 B.C.

While the expedition members don't expect to find a sign stating "City of Ubar," they are quite sure that their goal has been reached. The April issue of *Caltech News* will carry a more extensive story of the Ubar expedition.

At the former Kaiser Wilhelm Institute for Brain Research, Erhardt Geissler shows Manny Delbrück and Jonathon (left) and Toby Delbrück the laboratory where Timoféeff used to work.

Germany Names Center for Max Delbrück

In January the Max Delbrück Center for Molecular Medicine was officially opened in Berlin-Buch, a suburb in what used to be East Germany. The first ambitious attempt to combine and restructure the scientific institutions of the formerly divided nation, the new center will provide an innovative interdisciplinary setting for cooperation between basic research and clinical medicine, with emphasis on the molecular and cell-biological basis of cancer and of heart and neurological diseases. The expected staff of about 600 scientists will be drawn from groups organized around a particular project for a few years' time—a flexibility that represents a departure from traditional German research institutions.

Why would the Germans name their new institution after Max Delbrück, who left Berlin for Pasadena in 1937? He remained at Caltech as professor of biology for most of the next 45 years, winning the Nobel Prize for Physiology/Medicine in 1969 for his work on bacteriophage, considered the basis for modern molecular biology.

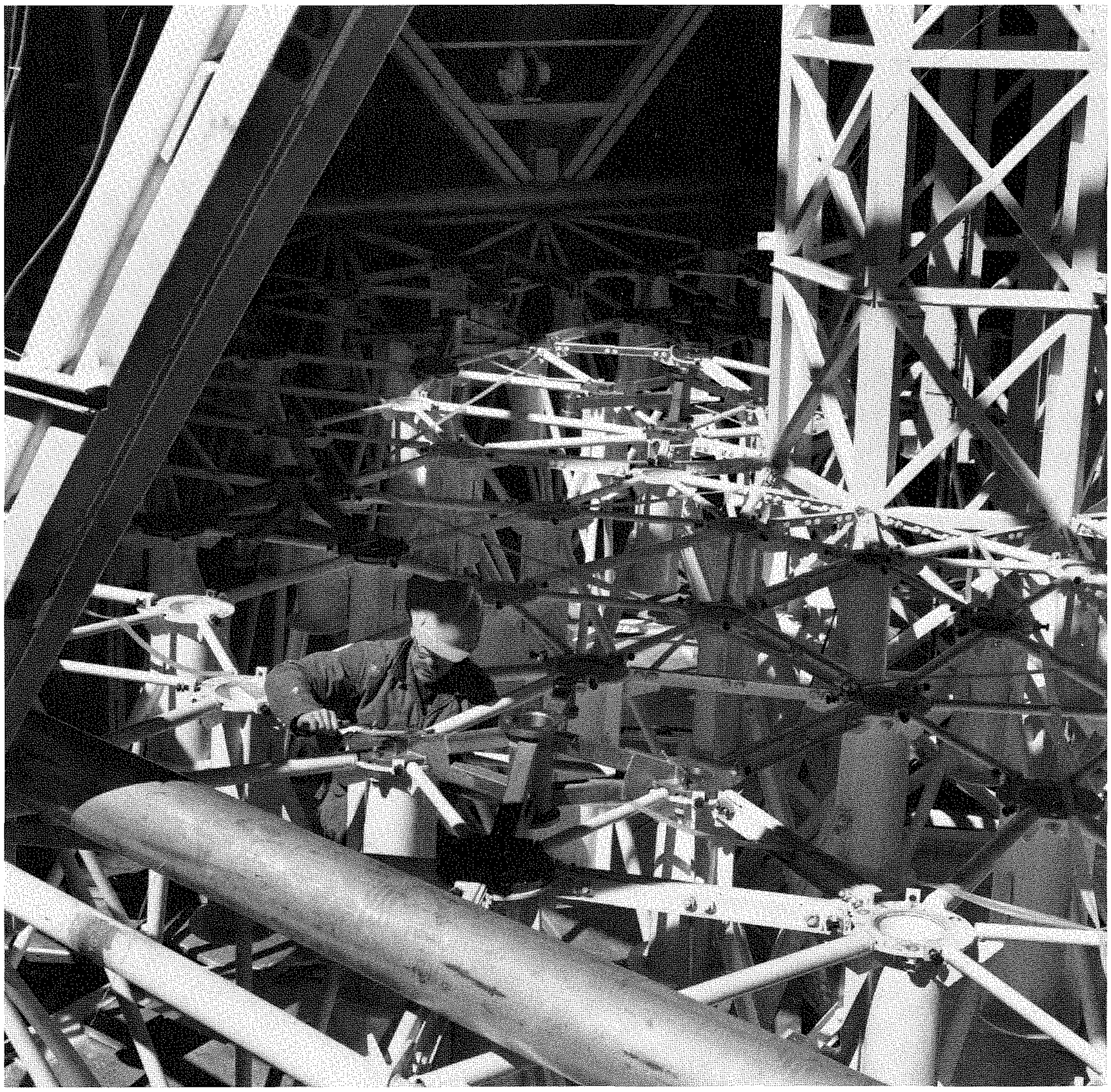
The roots of this work, however, go back to Berlin where Delbrück, then a physicist, arrived in 1932 to be the theoretical physics consultant to Lise Meitner. Delbrück's interest in biology had already been awakened by Niels Bohr's complementarity argument, which posed a complementary relationship between biology and physics analogous to the particle/wave phenomenon, and Delbrück chose Berlin primarily to be near the Kaiser Wilhelm Institutes of Biology.

At one of these, the Kaiser Wilhelm Institute for Brain Research in Berlin-Buch, a young Russian biologist, Nikolai Timoféeff-Ressovsky, was working in radiation genetics. Delbrück and Timoféeff became acquainted at an informal group of physicists and biologists (which Delbrück described as "internal exiles") that met regularly at Delbrück's mother's house in Berlin-Grunewald. Out of their collaboration, along with K. W. Zimmer, came a paper, "On the Nature of Gene Mutation and Gene Structure," in which the three men interpreted the x-ray-induced rate of mutation to arrive at a quantum mechanical description of the gene as a stable macromolecule. The paper received what Delbrück described as a "funeral first class" through publication in an obscure journal, but when it was quoted later by Erwin Schrödinger in his famous book *What is Life?*, it had a powerful influence on a generation of biologists who would eventually unravel the structure and mechanisms of the gene. Delbrück admitted later that he thought "the argument really wasn't that good," and he himself abandoned this approach because "it was clear that this was not an optimal way to get closer to the nature of the gene." Nevertheless, the revolutionary fusion of physics and biology established a new field of science.

While Delbrück left for America, Timoféeff remained in Berlin-Buch through the Nazi period, was arrested after the war and taken back to the Soviet Union, where he spent some years in labor camps before being allowed to continue his biological research. But he was forbidden to travel and still suffered under the shadow of Lysenkoism and of his "tainted" past. When Delbrück accepted his Nobel Prize in 1969, he traveled on to Moscow to try to make things a bit more comfortable for Timoféeff. He was never sure if he had accomplished much on that trip, says Delbrück's widow, Manny, but Max did give the Russian his down jacket.

Both men died in 1981. Timoféeff's old laboratory still exists in the hospital complex in Berlin-Buch that now will house the Max Delbrück Center for Molecular Medicine. In January Manny Delbrück and their two sons visited the lab as guests of honor at the opening of the new center, which is dedicated to breaking down walls of several kinds. "I could imagine Max doing something like this," says Manny, "It's the sort of pioneering thing he might have done himself."

The support structure for Keck I's primary mirror was assembled in Tarragona, Spain.



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