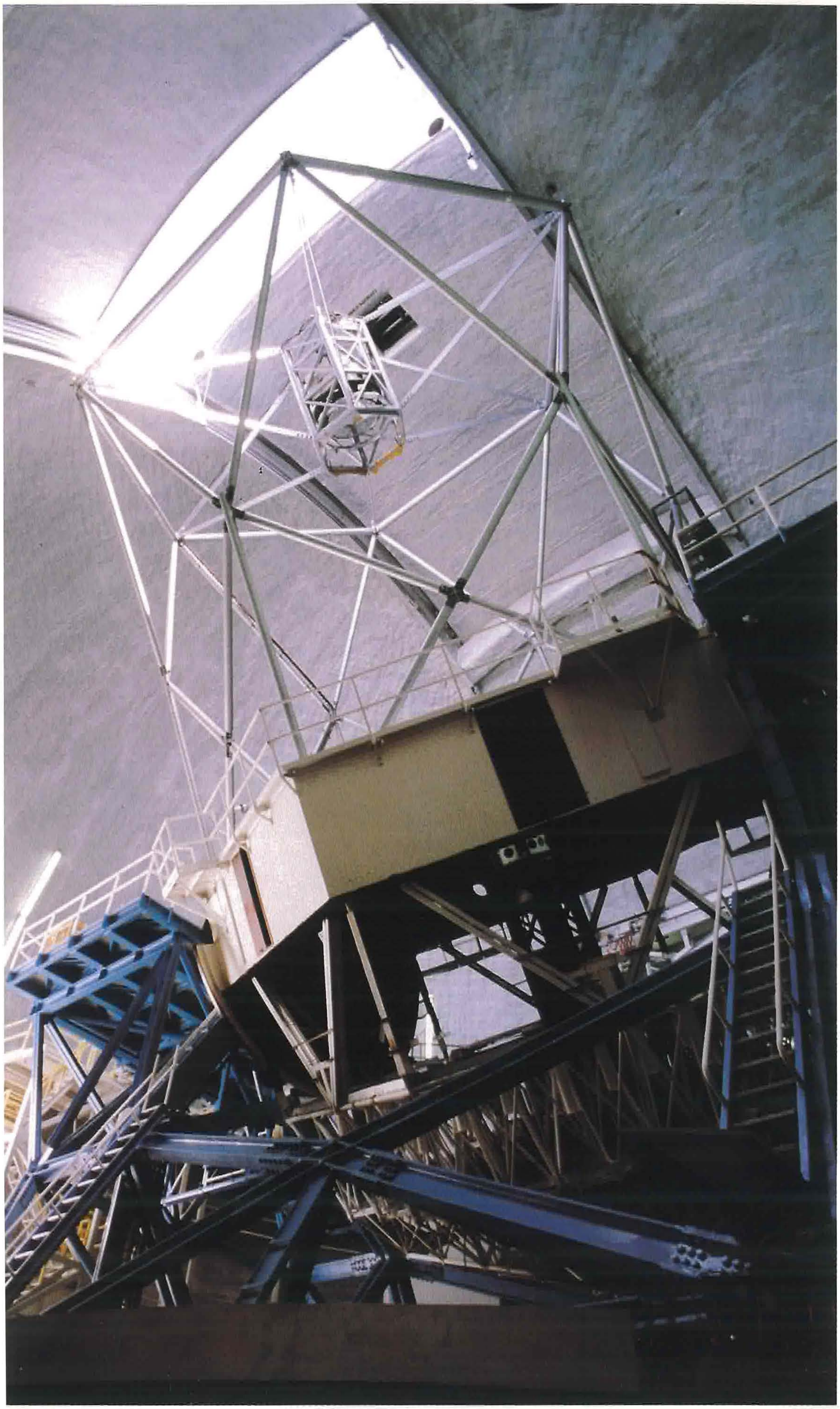


Deep Into That Darkness Peering

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.

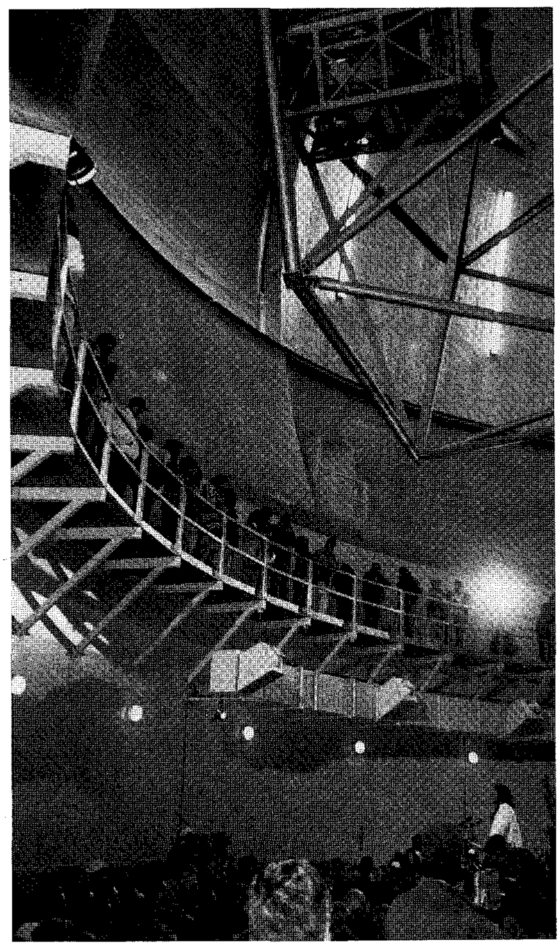
On Thursday, November 7, 1991, some 150 invited spectators from Caltech, the University of California, and the W. M. Keck Foundation joined the observatory staff to witness the dedication of the W. M. Keck Telescope and the ground blessing of the site of Keck II. The twin telescopes, collectively known 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

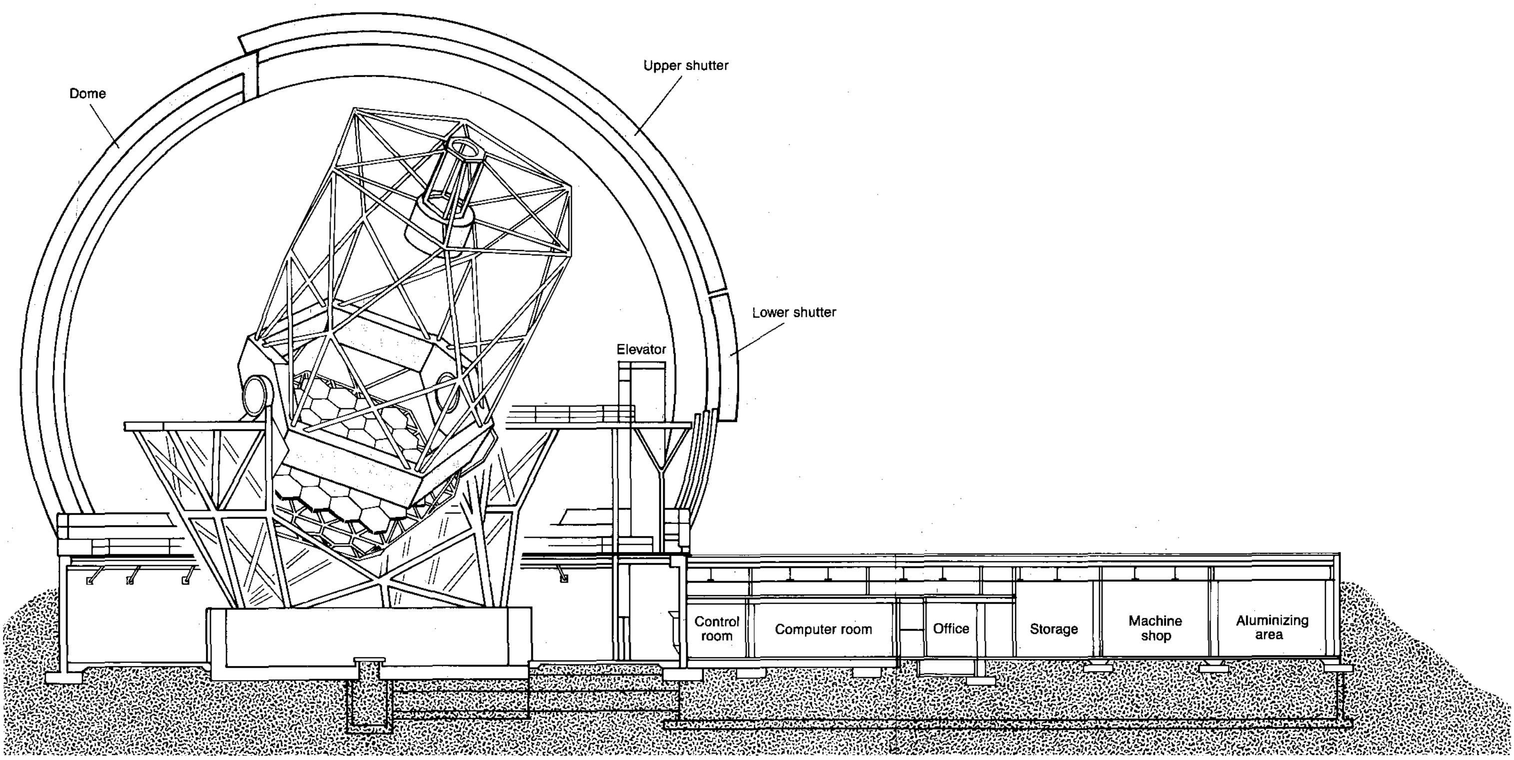


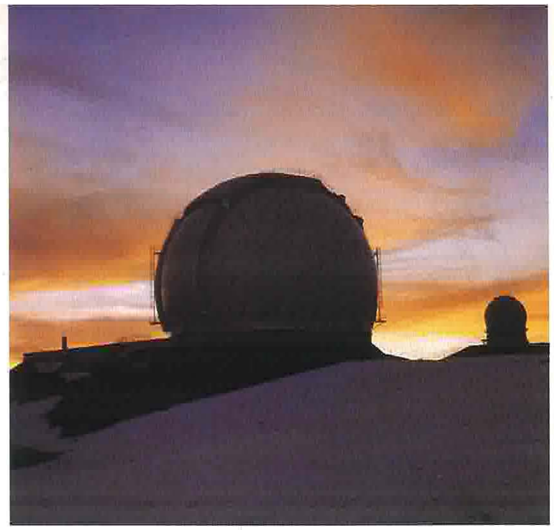
Diagram by Steven Simpson, courtesy of *Sky and Telescope*

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.)

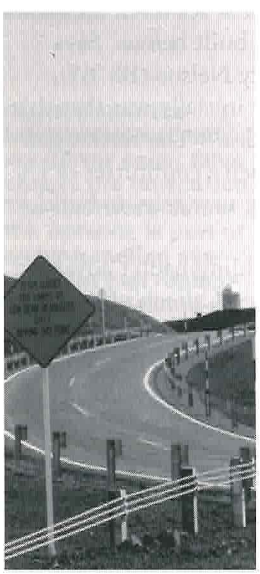
At one point in the proceedings, Cronkite remarked that "the mere fact of [Keck I's] construction on top of a mountain at 14,000 feet is nothing short of an engineering miracle." Building *anything* on a 14,000-foot mountaintop is an engineering miracle. Judgment clouds at that oxygen-poor altitude, 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).

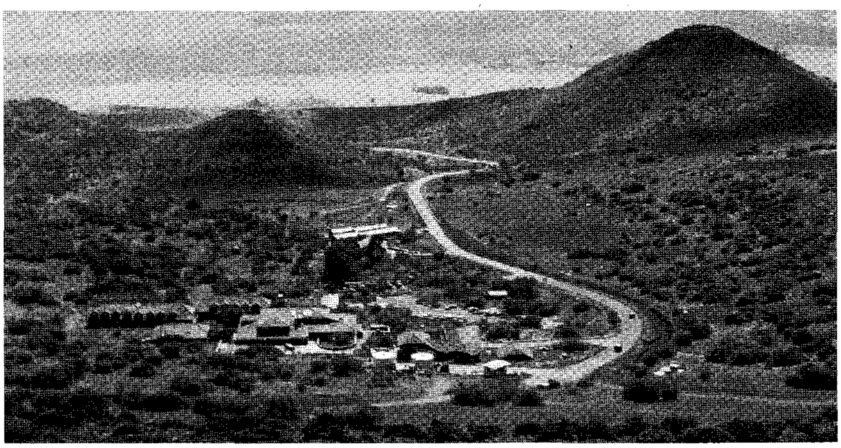
Right: Sunrise over the Keck and the Canada-France-Hawaii Telescopes.



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.

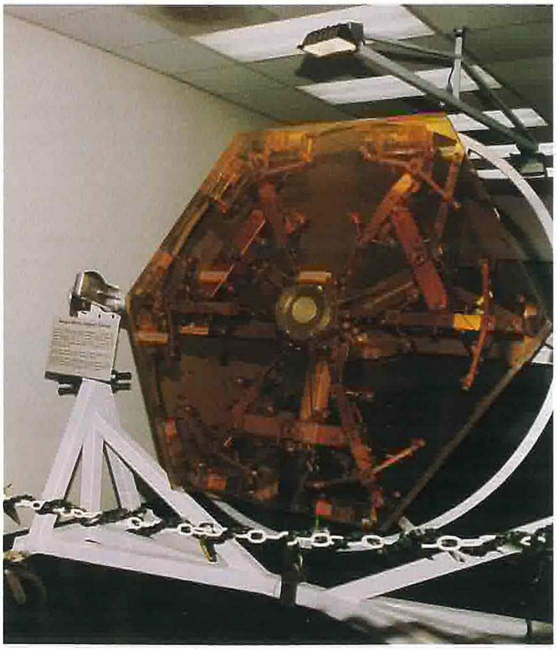
Even after the glass cools, it never really solidifies, but subtly sags and warps as the telescope tilts to follow an object across the heavens.

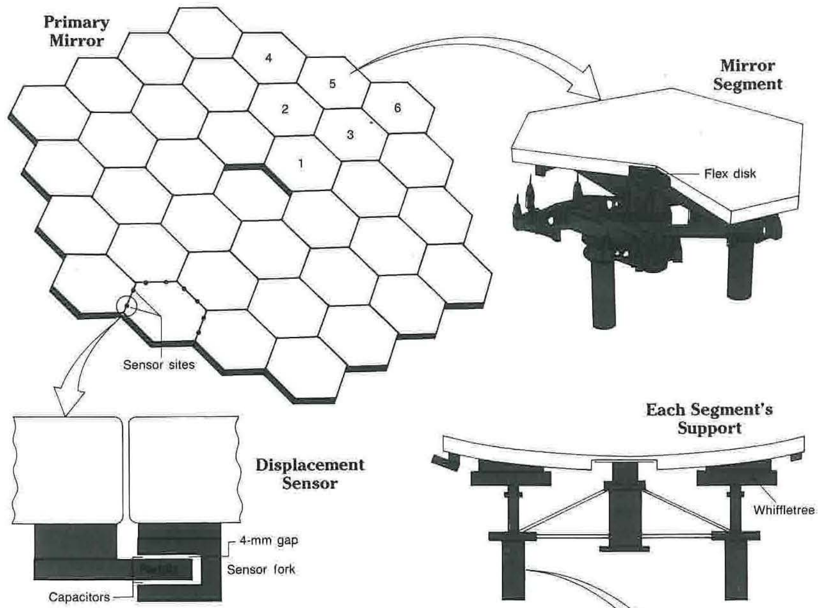
luxury." And with thinness comes flexibility—the segments would be even more vulnerable to gravitational warping and other stresses that could deform the mirror and blur its focus. Furthermore, while precisely polishing a symmetric mirror like the Hale's is easy, creating an accurate asymmetric surface 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





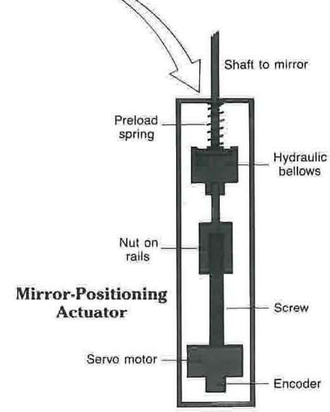


Diagram by Steven Simpson, courtesy of *Sky and Telescope*

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.

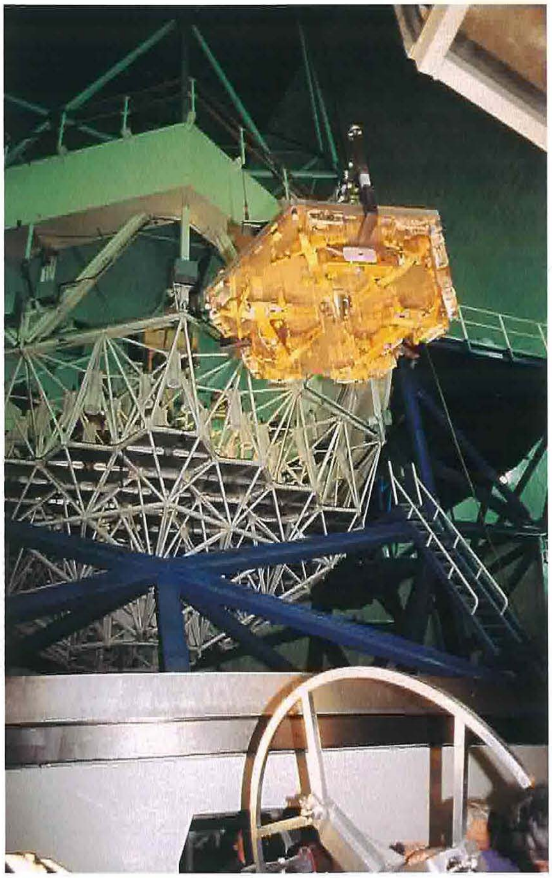
across the mirror, creating a forest of truss rods not unlike a metallic mangrove tree. At each of the 36 attachment points, the whiffletree sprouts a short metal rod, the diameter of a toothpick, that threads into a sleeve epoxied into a hole drilled in the mirror's underside.

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.

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.



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.

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

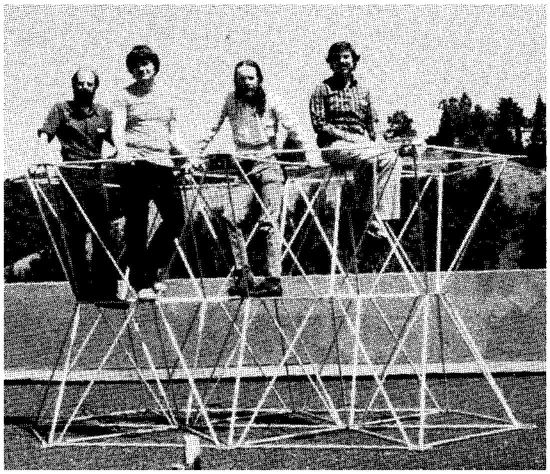
In the end, stressed-mirror polishing proved rapid and efficient, although there were some scares along the way. When the polished disks are trimmed into hexagons, their shape changes ever so slightly in an unpredictable way. Apparently, cutting the edges off of the disk alters the internal balance of 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.

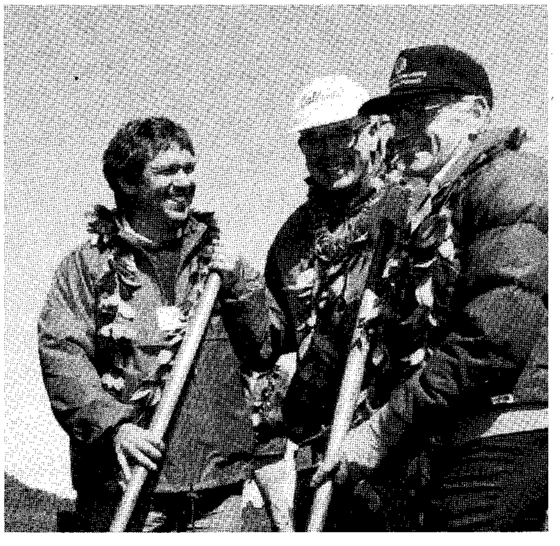
Below: Nelson and Gabor standing in the prototype built to demonstrate the active-control system. This telescope contains one full-sized mirror segment and the edge of another, adjoining one (visible on the left, in front of Nelson).



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.

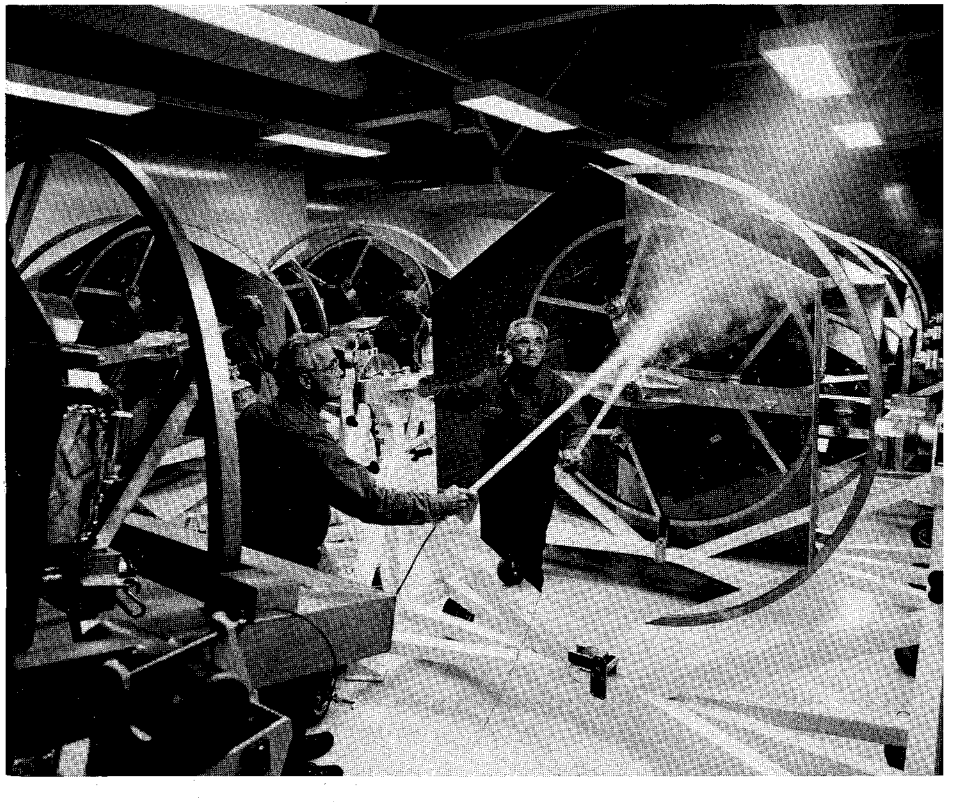
The first order of business was to find someone capable of building the thing. Back in 1983, UC had "borrowed" Gerald Smith from Caltech's Jet Propulsion Laboratory to prepare a cost estimate and plan the observatory's construction. At JPL, Smith had been project manager for the Infrared Astronomy Satellite (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.'"

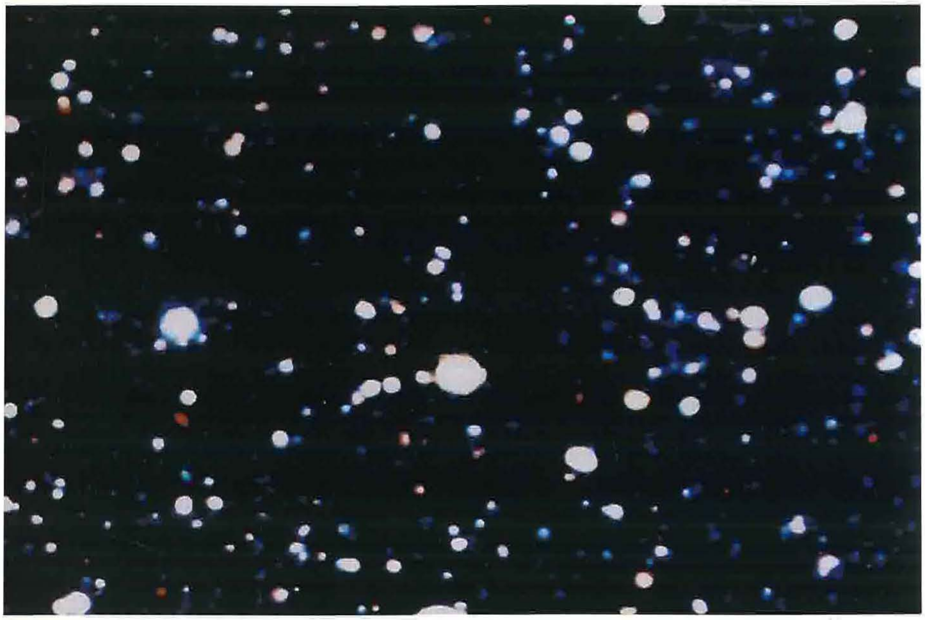
The dinner's keynote speaker was Ed Stone, Caltech vice president and professor of physics, director of JPL, and chairman of CARA. Stone prefaced his remarks by noting, "There are as many interesting questions [about the universe] as there are astronomers—in fact, there are probably more. In the interests 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?"

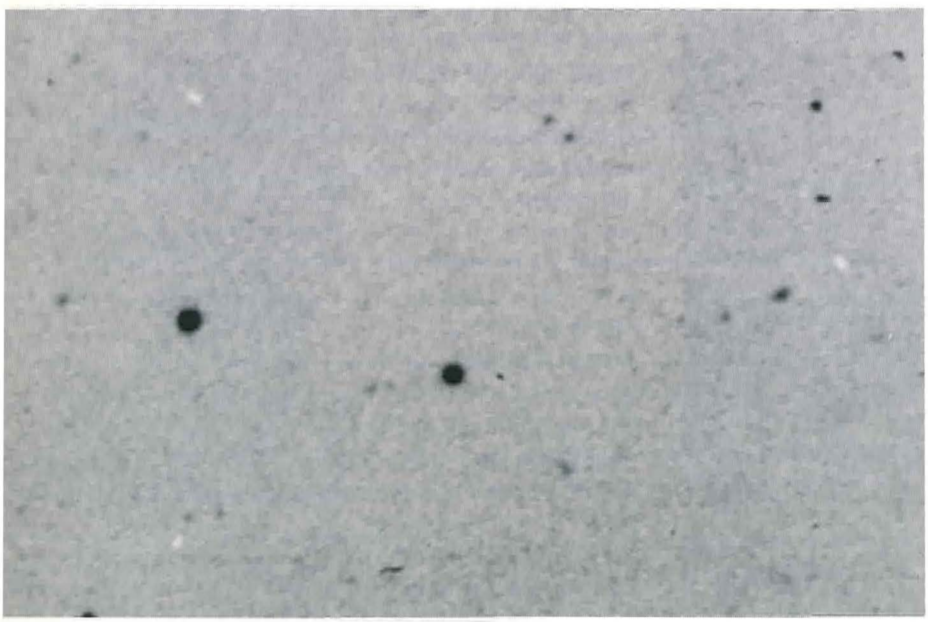
A telescope is really a time machine, although its physical being remains as solidly fixed in the present as any other object within our ken. The universe is so vast that even light, traveling at 186,000 miles per second—5,878,000,000,000 miles per year—takes a long, long time to get anywhere. The Andromeda 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.



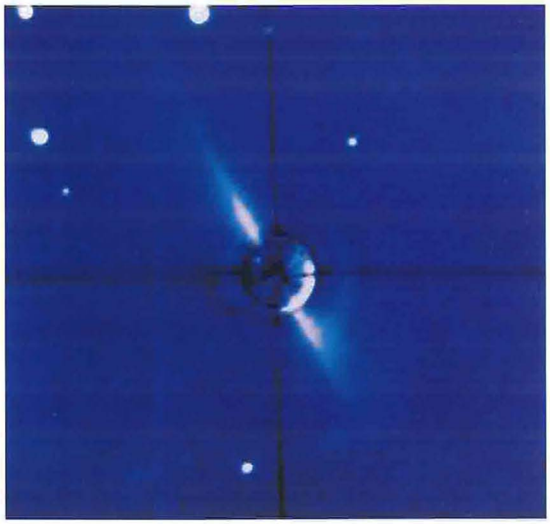


These might even be the primordial galaxies, caught in the act of formation some 13–14 billion years ago—an invaluable source of knowledge about the early universe.

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.

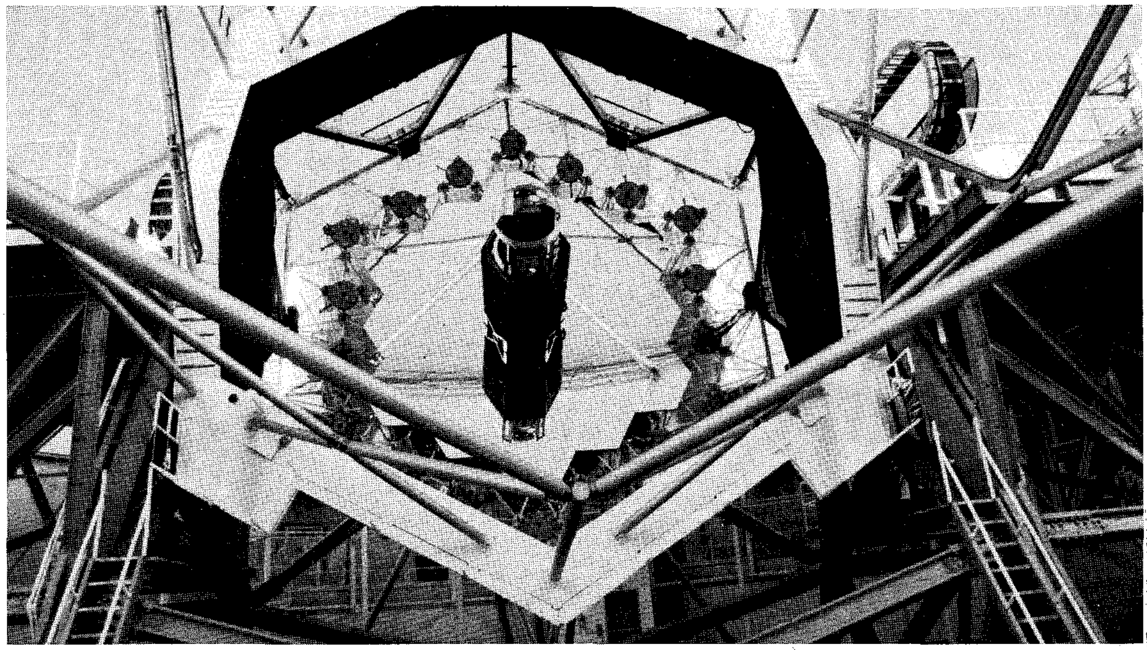
Top: T Tau as seen by the Hale.

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?

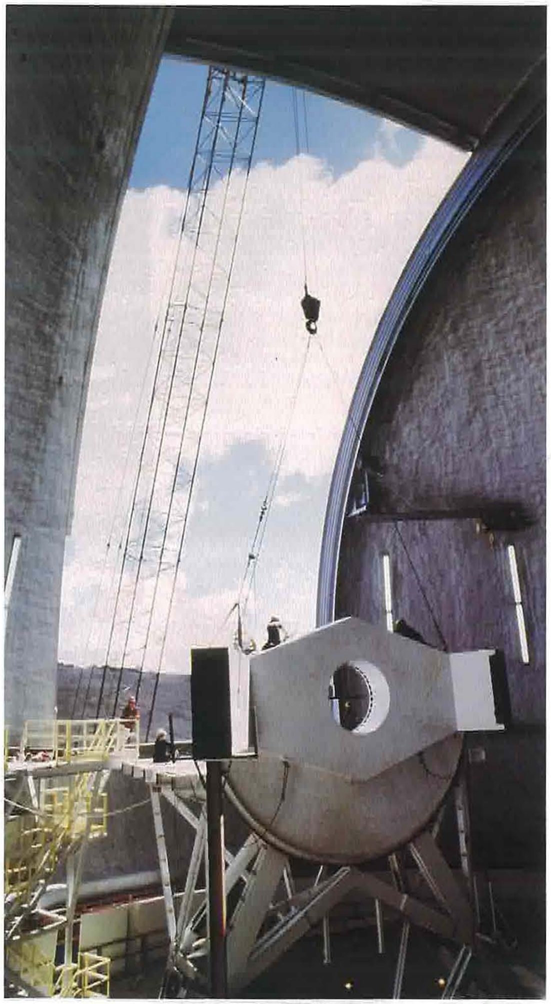
Even the twin Kecks won't be able to photograph planets on other solar systems directly, according to Stone. A star and its planet are right on top of each other by celestial standards, and the one is an awful lot brighter than the other. To a distant observer, the sun would appear a billionfold brighter 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.

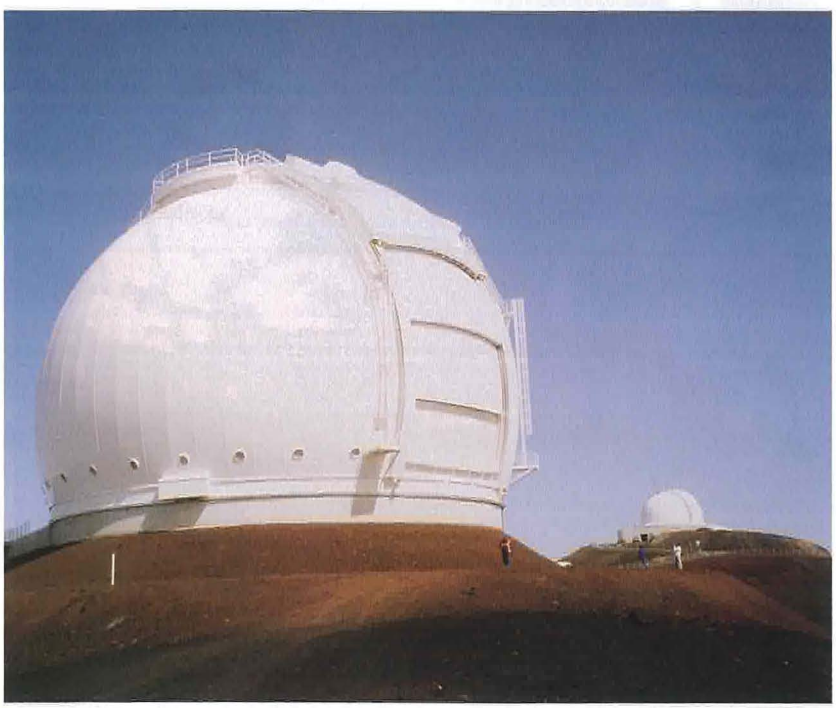
The first candidate for intensive scrutiny has already been identified this very way. In 1983, the IRAS mission found that one of the thousand or so stars closest to us—Beta Pictoris, a mere 50 light-years away, practically looming over our back fence—sits in the middle of a disk of gas and dust just 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.

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. □



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.