Keck Telescope Ushers in a New Era

The first and most radical of the "new technology" telescopes is almost ready for first light—but getting there took money, perseverance, and astronomers willing to get their hands dirty

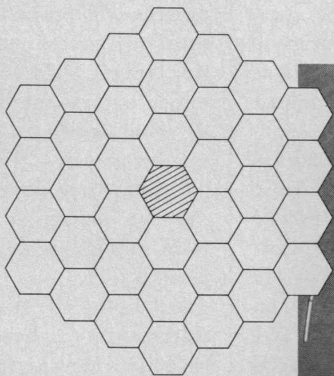
Mauna Kea, Hawaii—BACK IN 1977, when Jerry Nelson was a young astronomer at Berkeley, he tried to talk his University of California colleagues into backing his concept for building the largest telescope in the world. This wouldn't be just another clone of the venerable 5-meter telescope atop Mount Palomar, he told them. This telescope would have a primary mirror twice as wide: 10 meters. And instead of casting that mirror in the traditional form of a heavy, monolithic glass disk, he promised them he would create a radically new "segmented" reflector—a mosaic built up of thin, hexagonal glass tiles.

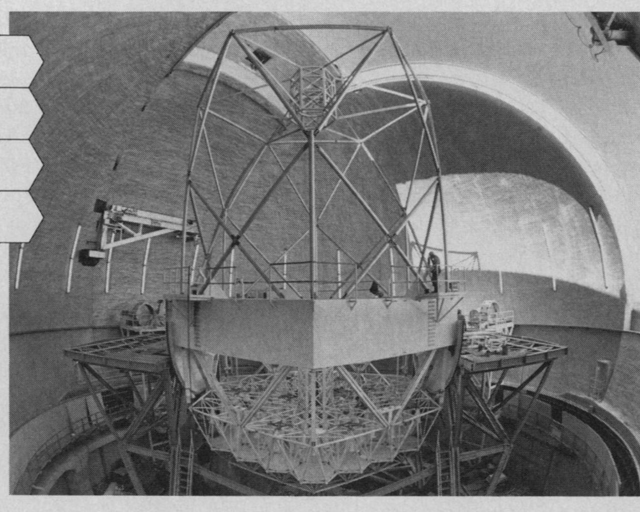
Thirteen years and $94 million later, in the chill of a Hawaiian summer morning at 14,000 feet, chief scientist Jerry Nelson of the W. M. Keck Observatory finds himself staring up at an airy metal latticework rising high into a wide, silvery vault. The framework and dome of the Keck telescope have essentially been finished for months; the hard-hatted figures roaming the telescope's platforms and stairways are now making it ready for the first mirror segments. If all goes as planned—and there are plenty of well-bitten fingernails around here—the workmen will have installed nine of the 1.8-meter-wide segments by late October, enough to take a "First Light" image of the heavens. Nelson and his colleagues will have brought to life a telescope concept that most astronomers once thought too radical to have any chance of working. They will have inaugurated an era of "new technology" telescopes: in the 1990s, at least half a dozen massive instruments are to sprout up around the world (see table p. 1245). And they may well have opened the way for funding of an identical Keck 2 right next door. *If* all goes as planned. . . .

High overhead, another test of the telescope's drive system is already under way and seems to be going well: smoothly, silently, almost imperceptibly, the immense latticework is tilting away from the vertical as if it were already tracking the stars.

So—after 13 years, how does it feel? "Wonderful!" laughs Nelson, a man with a brand new toy.

He isn't the only astronomer feeling exuberant today. The six members of the Keck Science Steering Committee—three each from the two equal partners in the project, the University of California and Caltech—have just spent the morning in hard hats climbing around the telescope like schoolchildren. "The Keck is going to be a powerful cosmology machine," declares committee cochairman Garth Illingworth of the university's Lick Observatory. For one thing, he says, the Keck is designed to have very good sensitivity at infrared wavelengths, where you expect to find the red-shifted light of the youngest and most distant galaxies. For another, the Keck's enormous size will make it very efficient at collecting photons for spectroscopy, which in turn should make it a powerful tool for analyzing the composition and dynamics of faint objects.





California Association for Research in Astronomy

Lacework giant. *The frame of the Keck telescope almost fills its dome on Mauna Kea. Its 10-meter mirror will be a mosaic of hexagons (inset).*

A prime example is the work of Illingworth's fellow cochairman, Wallace Sargent of Caltech. For two decades now, Sargent has been exploiting the fact that the distant, brilliantly luminous quasars can serve as cosmic searchlights: a careful analysis of their spectra shows myriads of telltale absorption lines from galaxies and gas clouds lying along the line of sight. Indeed, says Sargent, this is the only way to study these intervening objects, many of which may be galaxies caught in the act of formation; otherwise they would be much too far away and too faint to be seen.

Unfortunately, says Sargent, with conventional 4-meter class telescopes "it takes 10 hours to get this sort of information on just *one* quasar." But with the Keck you will pick up a factor of 6 in speed simply because its mirror will have six times more collecting area. And when you add in the superb quality of its Mauna Kea site, plus the fact that it will have state-of-the art instrumentation, the Keck could be as much as 20 times faster. "So even a single individual with a modest amount of telescope time can get an enormous quantity of data," says Sargent. And that, in turn, could lead to new insights into the evolution and clustering of galaxies in the early universe—still one of the least understood phenomena in astronomy.

Illingworth, meanwhile, sees the Keck as a natural partner for the Hubble Space Telescope. If and when Hubble's fuzzy vision is corrected with a new camera, he says, it should excel at finding extremely faint objects that the Keck would never notice through the shimmer of the atmosphere. Whereas the Keck, sweeping up photons with 17 times Hubble's collecting area, should be able to do the kind of spectroscopy on those objects that Hubble just won't have time for.

Of course, with the Hubble fiasco as a gruesome reminder, no one around here is taking anything for granted. Yet for now, at least, optimism is running high—in no small measure because of the faith the scientists place in two people. One is project manager Jerry Smith, on loan from the Jet Propulsion Laboratory and widely regarded as one of the most effective managers NASA has. The other is Nelson—an astronomer with the rare trait of liking to get his hands dirty.

"I was originally trained as an elementary particle physicist," he explains. "And whereas astronomers are generally trained to *use* gadgets, physicists make their living by building new experiments all the time."

In fact, he says, it was this love of building things that got him involved with telescope-making in the first place. In 1977, he recalls, he was serving on a committee to look at the university's future in ground-based astronomy, and the committee was kicking around the idea of building a "big" telescope—"big" meaning some undefined step up from the 6-meter Soviet telescope that was then the world's champion. "I thought to myself, 'Oh, that's hard. Maybe it's interesting.' "

His fellow committee member Joseph Wampler, now at the European Southern Observatory, had much the same reaction. So, with the committee's support, Nelson and Wampler went off separately to think about how to build such a large mirror—and, in particular, how to build it cheaply.

The central dilemma was obvious from the beginning. On the one hand, the thinner the better: not only would a thin mirror use less of the expensive, ultra-low thermal expansion glass that a telescope requires, but it would be lighter. And that, in turn, would make for a lighter, cheaper superstructure to support it. On the other hand, a large, thin mirror would be exceedingly flimsy, with a tendency to sag under its own weight and distort the images. Tolerances would be measured in nanometers.

Wampler was convinced that this dilemma could be resolved by a careful scale-up of the one-piece "monolithic" mirrors used in standard telescopes. He was not alone in that conviction. At the University of Arizona, Roger Angel was already starting to think about how to make very large versions of the 5-meter Palomar mirror. And in Europe, astronomers at ESO were starting to consider a variation on the single-mirror theme: sheet-like "thin meniscus" mirrors that would be supported on the back and be kept in shape by a forest of movable pistons. Indeed, both of these approaches now seem capable of producing 8-meter mirrors. And since most astronomers find the monolith designs more familiar and comfortable, they are the basis for all the other big telescopes that are currently being planned.

The New Behemoths

Project	Mirror diameter (in meters)	Location	Completion date
Keck (UC—CALTECH)	10	Mauna Kea	1991
Multiple Mirror Telescope Upgrade (ARIZONA—SMITHSONIAN)	6.5	Mount Hopkins, Arizona	1991
Magellan (CARNEGIE INSTITUTION—JOHNS HOPKINS—ARIZONA)	8	Las Campanas, Chile	1995
Columbus (ARIZONA—OHIO STATE—ITALY)	2x8 *	Mount Graham, Arizona	1996
Very Large Telescope (EUROPEAN SOUTHERN OBSERVATORY)	4x8 *	La Silla, Chile	2000
NOAO—North (NATIONAL OPTICAL ASTRONOMY OBSERVATORIES)	8	Mauna Kea	*proposed*
NOAO—South	8	Cerro Tololo, Chile	*proposed*
Japan National Large Telescope	7.5	Mauna Kea	*proposed*

* *Multiple mirrors*

But Nelson didn't like it. Monolithic mirrors would be hard to make, hard to transport, and hard to handle inside the telescope, he argued. Worse, they were a technological dead end. You might be able to make an 8-meter monolith, or even a 10-meter one. But how could you ever go larger? "I decided it was time to do what the radio astronomers did years ago," he says: build a reflecting surface out of segments. Not only would the individual mirror pieces be far easier to handle, he reasoned, but once the segmented mirror technology was mastered, it could in principle be used to build mirrors of arbitrary size, just by adding segments.

"I decided on a diameter of 10 meters because it was twice the size of the 5-meter Palomar mirror," says Nelson. "That was big enough to get into a qualitatively new regime of science but small enough to be doable."

However, it was also clear that a segmented mirror would pose at least two severe challenges of its own. First, it would need an elaborate, computer-controlled support system to keep the segments aligned to nanometer precision as the telescope moved to track the stars. And second, it would require a whole new approach to mirror-making to produce the segments. The overall surface of the 10-meter mirror would be very close to a paraboloid, the surface that will reflect starlight to a precise focus. But the individual segments would be pieces of a paraboloid—subtle shapes that are extraordinarily difficult to make with any accuracy.

Trading a constant barrage of more or less friendly potshots with Wampler's group, Nelson spent the next year and a half working at the Lawrence Berkeley Laboratory with fellow physicists Terry Mast and George Gabor to find solutions to these problems. One major innovation, developed by Berkeley engineer Jacob Lubliner, was the use of "stressed mirror polishing" to solve the problem of segment production. Instead of taking a disk of glass and trying to produce a complex surface in one step, explains Nelson, you start out by bending the disk ever so slightly in a precisely calculated way. Then you just polish the mirror face to a spherical surface, which is easy. And when the stress is released, the mirror will relax into exactly the oddball shape that you want.

"We did a quarter-scale mirror to test the idea," says Nelson. "It worked great, just like it was supposed to! That never happens in experimental science."

In the end, says Nelson, both his group and Wampler's came back to the university saying: Yes, we can do it. So the question of which approach to take was handed over to a new committee of senior astronomers, dubbed "the Graybeards Committee." And in November 1979 their verdict came down: Go with the segmented mirror.

It was a sweet moment for Nelson and his team. But of course, a commitment from a committee is not the same thing as a telescope on a mountaintop. In between came 11 long years.

A few of the steps along the way were actually rather easy. The selection of Mauna Kea as a site, for example: the mountain is a long way from California, with extended supply lines that make it an expensive place to build. But it is also the highest major observatory site in the world, with the clearest view of the stars this side of space.

Other steps, such as financing, were considerably tougher. The Californians had always intended to build the telescope entirely with private money, explains Nelson, since federal funding would have meant sharing it with every other astronomer in the country. But as he and his team refined the technology and fleshed out the observatory designs, the estimated \$50-million cost rose inexorably toward the current figure, \$94 million. And the university's fund-raising efforts were not going well at all. Years of casting about the state for an astronomically minded philanthropist had turned up precisely one potential donor—Mrs. Max Hoffman, widow of a New York auto importer. And her bequest had fallen into limbo when she tragically died less than 24 hours after shaking hands on the deal—and before signing the papers.

The project's money worries were not resolved until January 1985, when Caltech bought itself an equal partnership with a $70-million donation from the Keck Foundation, administered by the sons of the late oilman W. M. Keck. This also solved the problem of what to name the telescope. And of course, it enriched the project with Caltech's own powerful cadre of astronomers—who would now have to get half the observing time. "At the UC, everybody was disappointed to lose half the telescope," says Nelson. "But half of a real telescope is a lot better than all of an imaginary one." (Ten percent of the observing time will actually go to the University of Hawaii, which controls access to Mauna Kea.)

Then, however, came the truly difficult challenge: mass-producing the mirror segments. Forty-two would be needed in all, 36 for the full 10-meter mirror and 6 spares. "We always knew it would be hard," says Nelson. "But we had no idea it would be as hard as it turned out to be."

The difficulties became apparent almost as soon as work on the segments began in 1985 at Itek Optical Systems in Lexington, Massachusetts. The stress polishing worked well enough. But when the edges of the polished disks were trimmed to make them into hexagons, they warped. The warping was not entirely unexpected, says Nelson, but it was certainly more than the opticians could handle with touch-up polishing. So he and the Keck team had to redesign the mirror support structure, adding a "warping harness" behind each segment to bend it back into shape.

Next, the apparatus that Itek was using to measure the accuracy of the mirror surfaces turned out to have serious optical flaws of its own. After a loud and extensive debate, Smith overruled Nelson and decreed that rebuilding the apparatus would take too long and cost too much. So instead, the final test results are now obtained by taking the raw data and running them through a computer program that supposedly eliminates the effects of the flaw. Nelson is keeping his fingers crossed.

In fact, manufacturing the segments has proved so tough that the scientists have been forced to compromise slightly on their goals for optical quality. Presumably the telescope's users will never notice except on the most crystalline nights. But the images will be just a bit fuzzier than they ought to be.

Fortunately, however, as a slow but steady stream of finished segments has begun to arrive on Mauna Kea, things seem to be going more smoothly. The project passed a major milestone in early August when the team temporarily put three of the segments into the telescope and, for the first time, activated the computer-controlled alignment system. It worked beautifully.

The next, and most important, milestone will be the first light images later this autumn. Not only will these images tell the Keck team how good their segments really are, says Nelson, but if all goes well they will be Exhibit A in the project's fund-raising efforts for a second, identical telescope. No commitments have been made yet. But Caltech physicist Edward Stone, who is serving as chairman of the partnership, has gotten expressions of interest from the Keck Foundation and is deep in negotiations with other possible partners.

The possibility of a Keck 2 has actually been in people's minds for a long time, says Nelson. The site has already been laid out with space for a second dome. And the control room building adjacent to the existing dome has even been built with a tunnel running underneath, so that the two telescopes could combine their light into ultra-high-resolution images using a technique known as optical interferometry.

"Building a second telescope just like this one doesn't need me," says Nelson, who says he hopes to go back to being an astronomer when the first one is done. And yet—nobody actually knows how to do optical interferometry. And then there's the challenge of developing "active optics" for the telescopes to eliminate the distortion of the atmosphere and give their images space-like clarity. That sounds hard, says Nelson. "And *that*'s what might interest me."

■ M. MITCHELL WALDROP

The Climate System as a Ticking Clock

The discovery of a 2-year "ticking" in the record of El Niño is fueling a growing awareness of biennial climate variations

THE COOLNESS OF NIGHT follows the heat of the day; winter follows summer: these are the obvious short-term cycles of climate change. Now, climate researchers are detecting a periodicity that extends beyond these familiar rhythms of the day and of the seasons. They are picking up a more or less regular 2-year beat to the global climate system—one that seems to be heard from every quarter.

The Amazon tends to surge every other year, as does the Mindanao Current east of the Philippines. Winds over New Zealand tend to pick up and abate on a biennial schedule, as does the pace of the bimonthly cycle of cloudiness in the tropical Pacific. And the most recently discovered example of this climatic ticking—and perhaps the most intriguing—comes from the very core of El Niño. Researchers have found that some aspects of this cycle of alternating warm and relatively cold waters along the equatorial Pacific have a tendency to repeat every 2 years. The overlying winds pulsate at the same pace, as do the globe-girdling effects of the El Niño cycle, from winter warmth in Alaska to heavy rains in Peru and drought in Australia.

The climatic ticking in the tropical Pacific is hardly as reliable as the changing of the seasons. Sometimes it is muted, and occasionally it skips a beat. But some researchers nevertheless see hope of using it in the prediction of El Niño and its global effects. In any case, climate researchers are eager to determine what makes El Niño tick. The answer could be an underlying pacemaker of this crucial atmospheric cycle.

The biennial aspect of the El Niño cycle has been glimpsed now and again for more than a decade, but conventional wisdom has always maintained that El Niño displays an irregular rhythm. The intervals between strong tropical Pacific warmings range from 2 to 7 years and average 3 to 4 years, so how can it have a 2-year cycle? The answer, according to two recent studies, is that El Niño is paced by two different clocks—one with a 2-year beat and the other with a less well defined beat of 4 to 5 years. It is the combination of these two cycles that produces the appearance of a highly irregular rhythm.

In a recent paper, Eugene Rasmusson and Xueliang Wang of the University of Maryland and Chester Ropelewski of the National Oceanic and Atmospheric Administration's Climate Analysis Center of Washington, D.C., report the detection of a 2-year oscillation in the strength of the winds blowing over the surface of the western Pacific Ocean and eastern Indian Ocean.