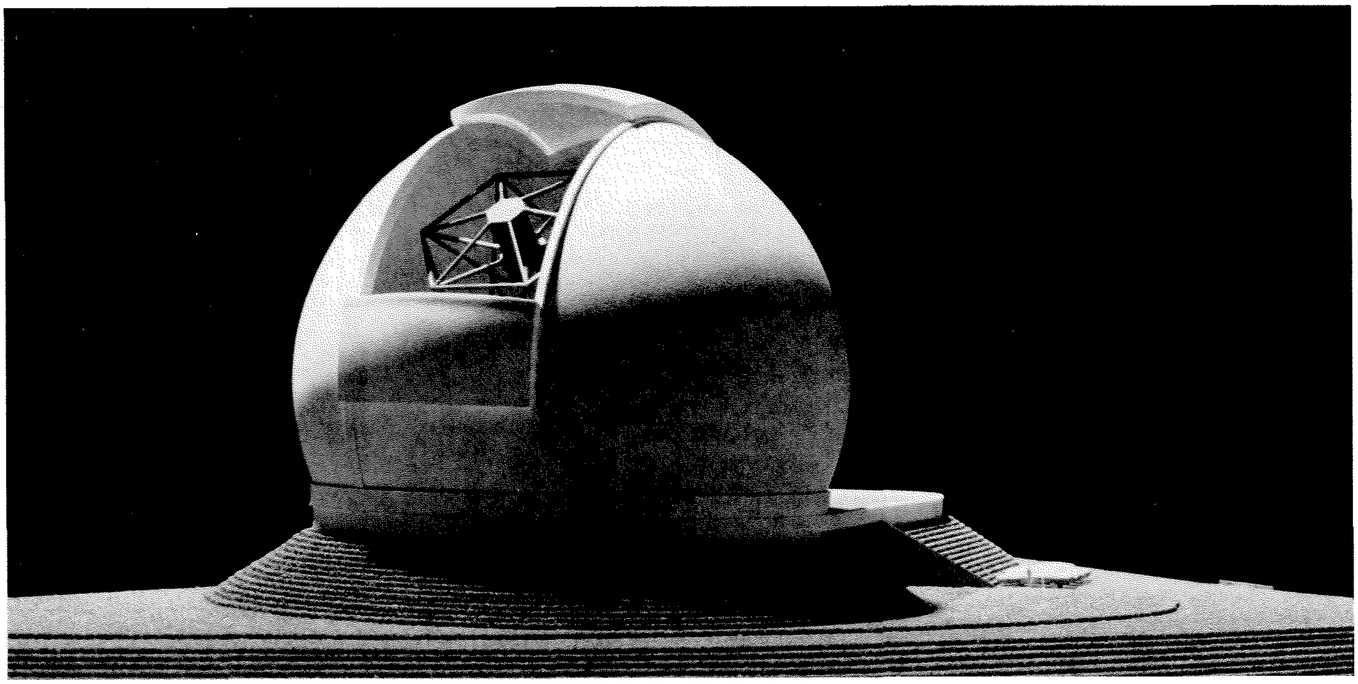


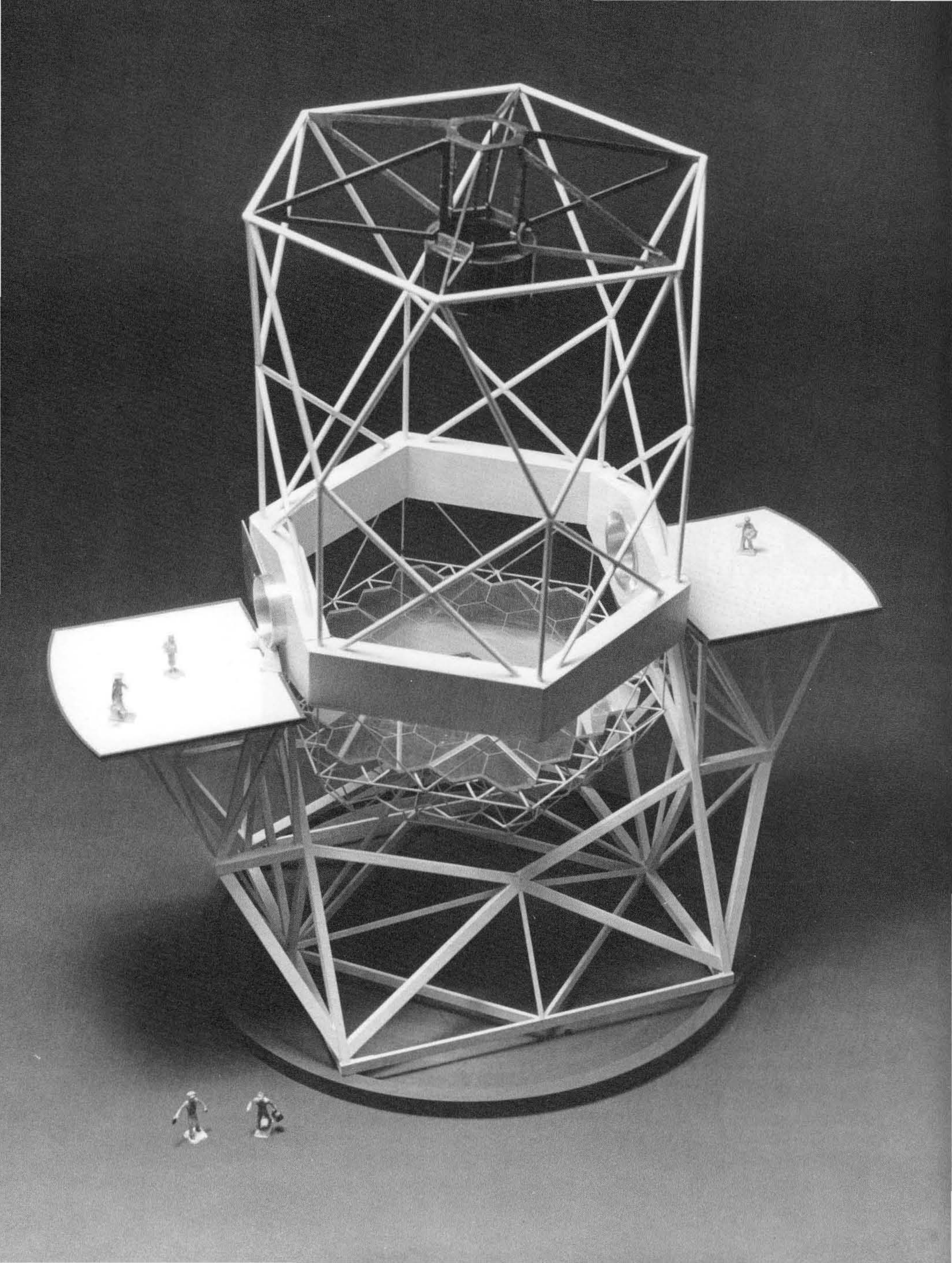
# The W. M. Keck Observatory

IT WILL BE POWERFUL enough to see a single candle at the distance of the moon. But the Keck Telescope won't be looking at anything so mundane as the moon. Its faceted eye will look at the center of the galaxy to see if there's a black hole there. It will look at the clouds of hot gas that are the birthplace of stars. It will function as a time machine, peering 12 billion years into the past, three-quarters of the way to the birth of the universe. When construction is complete in 1992, this telescope, the most powerful in the world, will be set to answer fundamental questions in the fields of optical and infrared astronomy.

And it will do so from a most unworldly landscape — the remote high ridge of an extinct volcano already dotted with the white domes of observatories. Perched at the 13,600-foot level on Hawaii's Mauna Kea (White Mountain), a site that has some of the best "seeing," astronomically speaking, in the world, the Keck Telescope will be the culmination of a 15-year, $85 million project to design and build the premier weapon in the astronomical arsenal.

With the largest private gift ever made for a single scientific enterprise — $70 million from the W.M. Keck Foundation — Caltech will provide most of the funds for the observatory's construction. The University of California, whose scientists began designing the ten-meter telescope in 1977, will provide funds for the scope's continuing operation. Observation time will be split evenly between UC and Caltech astronomers, with a fraction of the time going to astronomers from the University of Hawaii, which is providing the site.

The observations these scientists will make should help answer some of the most perplexing of astronomical riddles. One of these involves the large-scale structure of the universe. Galaxies cluster in groups ranging



from small ones only a million light years across, to superclusters, which span nearly a billion light years. Scientists link the small and medium-sized galactic clusters to tiny density irregularities arising among fundamental particles during the Big Bang. But they find the superclusters much more difficult to explain. Some scientists believe that superclusters owe their existence to primordial fluctuations in the density of as-yet-unidentified elementary particles, so particle physicists are vitally interested in the results of these studies as well.

Often superclusters occur in enormous filaments or chains, and the details of these structures that the telescope will reveal may provide important clues to their origin. Computer simulations indicate that the clustering process continues to this day. The ten-meter telescope will be able to trace this back in time by capturing light that's been traveling our way for billions of years. Present day telescopes, like the five-meter (200-inch) Hale Telescope on Palomar Mountain, are just barely able to make out the most distant (and hence the oldest) galaxies, but they can't collect enough light from them to determine their redshifts, a measure of astronomical distance. (The further away an object is, the faster it recedes from us. The faster it recedes, the further its light is shifted to the red end of the spectrum.) Redshift information is indispensable in mapping the structure of these ancient clusters. The ten-meter telescope, with its huge light collecting area, is admirably suited for this sort of work.

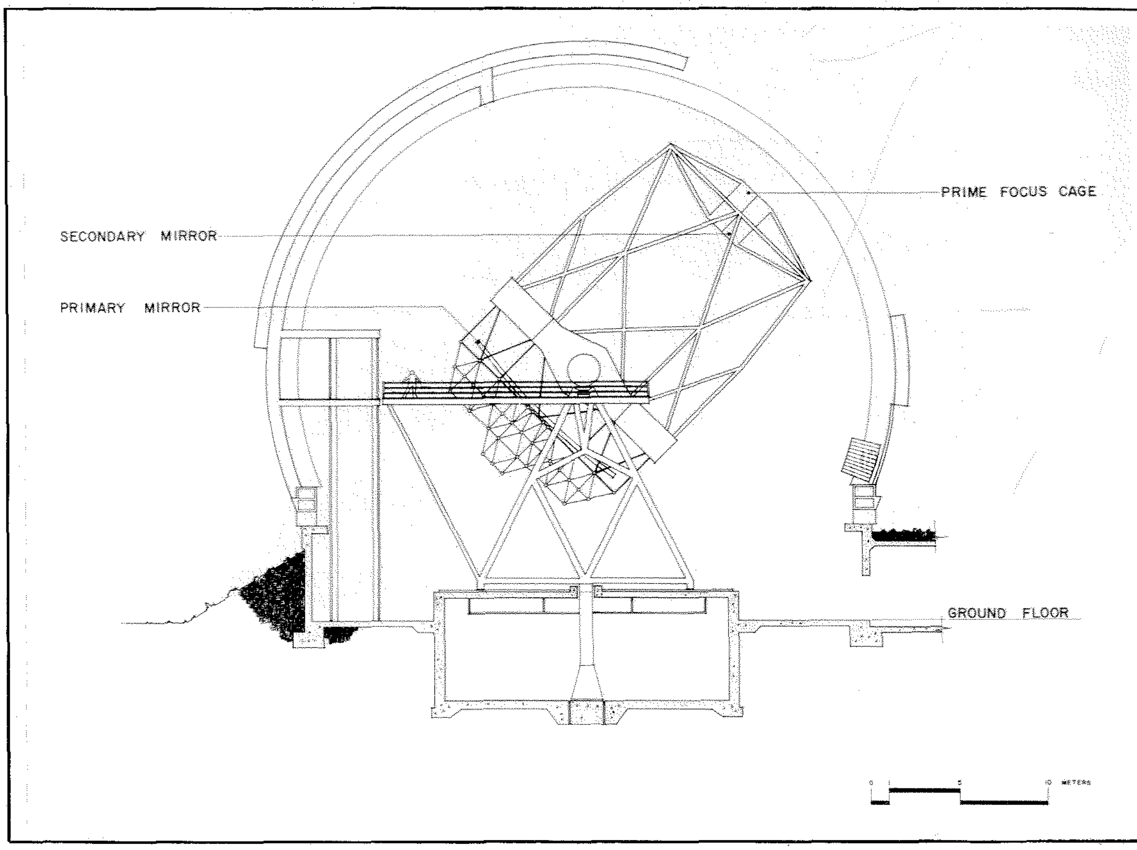
The telescope may also provide a solution to one of the major problems in astronomy — the question of why, where, and how stars form. Thick clouds of dust obscure most star-forming regions. But though the dust blocks visible light, infrared light gets through and the ten-meter telescope will be the biggest infrared instrument in the world, with a resolution three times that of its nearest competitor. The ten-meter telescope will be able to differentiate actual stars from nearby clumps of dust that scatter light and mimic stars. It will also be able to separate one nascent star from another in these densely packed areas. And the telescope may help solve the mystery within a mystery of certain small, young stars, which come into being as the result of an unknown mechanism operating outside the usual star-forming regions.

The telescope's infrared capabilities make it an ideal source of information about our galactic center, which is also obscured by layer upon layer of dust. Studies to date indicate that this is a most peculiar region, containing remnants of supernovae as well as chaotically moving clouds of ionized gas. Many astronomers believe that these constitute the gravitational signature of a black hole located precisely at the center of the Milky Way galaxy. The Keck Telescope will peer through the dust, searching for the high velocity regions that will distinguish a black hole from a compact star cluster, the other major candidate for the structure at the galactic center.

One technique that will be applied to the telescope is known as Multiple Object Spectroscopy (MOS), a process in which the spectra of as many as 100 objects from a single field of view are obtained simultaneously. One of the advantages of MOS is a lengthening of the maximum tolerable exposure. An astronomer may be willing to invest 10 or even 20 hours in a single exposure if 100 good-quality spectra will result. In other words MOS, coupled with the great light-gathering power of the ten-meter telescope, will mean a 600-fold increase in productivity over present telescopes.

Despite the Keck Telescope's high resolution, when construction is completed in 1992 it will not be the highest resolution instrument in use. The Hubble Space Telescope, scheduled for launch by the Space Shuttle in 1986, will have a resolution ten times better than any ground-based instrument because of its freedom from atmospheric blurring. The Space Telescope will also have advantages in ultraviolet spectroscopy (since most ultraviolet light is filtered by the ozone layer) and in certain parts of the infrared region that are attenuated by atmospheric water vapor. But the Space Telescope's primary mirror is only 2.4 meters in diameter. At more than 4 times the diameter and 17.4 times the area, the ten-meter mirror will be better able to provide the large amounts of light demanded by the exacting requirements of spectroscopy. Spectroscopy is needed in quantitative astrophysical studies to determine abundances of the constituents of stars and galaxies, as well as to determine redshifts. The two telescopes will therefore complement each other. The ten-meter telescope will often be used to conduct detailed spectrographic studies of objects first discovered or imaged by the Space Telescope.

Designing a ten-meter telescope, which




*The latest design of the telescope and its dome is fairly traditional. The one-story building will be located immediately to the right at ground level.*

must have a virtually perfect 76-square-meter optical surface, requires much more than merely scaling up a five-meter mirror like the one at the Palomar Observatory. According to University of California astronomer Jerry Nelson (Caltech BS 1965), who headed the design team, scaling these designs up by a factor of two introduces a number of formidable problems, most of them associated with the primary mirror itself. A ten-meter mirror blank has never been made, and even if it were possible, its cost would be enormous. Polishing such a blank would take a very long time and require extremely large and expensive machinery.

Perhaps even more difficult is the problem of properly supporting the mirror against the force of gravity, since the deflections of a ten-meter mirror are 16 times those of a five-meter mirror. These deflections must be limited to about a thousandfold less than the thickness of a human hair, says Nelson. Such a large mirror would require a massive telescope structure and a dome of enormous proportions, leading, again, to unacceptable costs.

To avoid these difficulties, the telescope's designers have developed a primary mirror design composed of a mosaic of 36 hexagonal mirror segments only 1.8 meters in diameter. Many of the problems are thus reduced to those of a 1.8-meter telescope. This allows a much lighter mirror, and modern computer-aided structural design tools have also made an extremely lightweight telescope structure possible. In fact, at 158 tons, the Keck Telescope will weigh less than one-third as much as the Hale Telescope.

But construction of the ten-meter telescope is not without problems of its own. Polishing the mirror is complicated by the fact that each segment is neither flat nor symmetrical, but rather is one of six off-axis sections of a shallow paraboloid. The design team developed a method called "stressed mirror polishing" to arrive at each of the six shapes. This technique takes advantage of the ease with which opticians can polish a spherical surface. It involves first applying precisely calculated forces to a circular mirror blank, intentionally warping it. The mirror blank is then polished to a concave, spherical surface. Once the applied force is released, the mirror blank springs into the desired final shape. Its edges are then cut off to form the hexagonal outline.

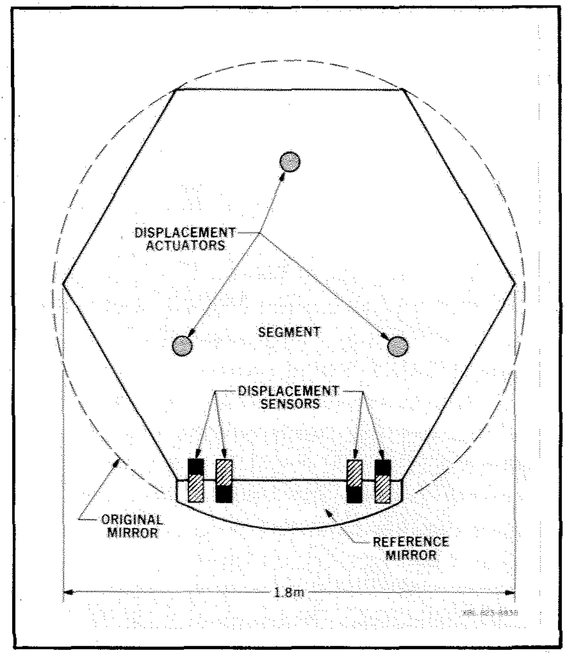
During the cutting of an initial test blank, larger than desired warping occurred. This led to the idea of putting a "stressing" jig on each segment to remove the warp. This dewarping method, whose feasibility has been demonstrated, may also lead to a faster mirror production by allowing more relaxed tolerances during the polishing phase.

These difficulties in polishing the hexagonal segments are minor compared to the problem of polishing a single large mirror. But the multi-segment approach introduces other problems. A single mirror could be held steady in a rigid but passive support. But a system of multiple mirrors must be continually realigned, since the forces that tend to disrupt the aim (gravity, wind, and heat are the most important of these) act differently at each mirror location and change over time. Each segment, therefore, has edge displacement sensors on its back surface that bridge the gaps between one segment and its neighbors. If one segment should move relative to another, these sensors will send a signal to the computer control system. The computer will then make the necessary corrections by adjusting the three actuator pistons that support each segment. In order to maintain a sufficiently stable image, the computer will make such corrections 300 times a second to a tolerance of 3.75 nanometers. In this way the 36 segments, each individually controlled, will constitute, for all intents and purposes, a single mirror.

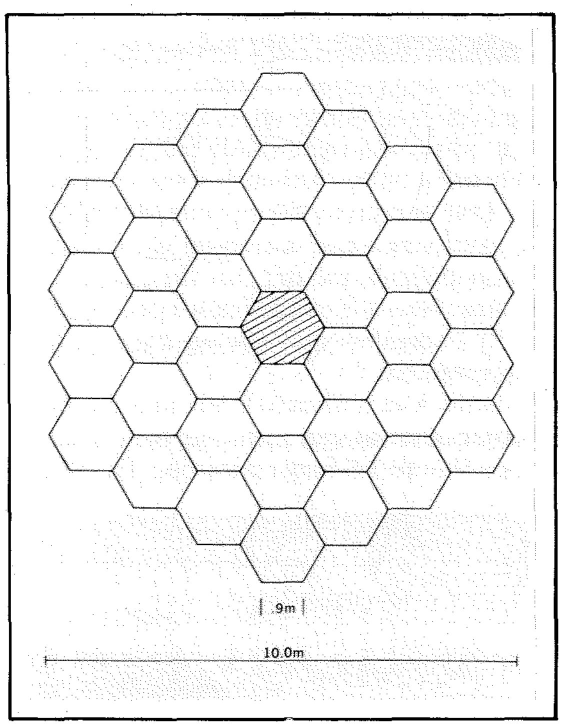
Light falling on this mirror will be directed to the telescope's six focal points, where various instruments such as cameras, spectrographs, photometers, and polarimeters will be housed. The designers have deferred decisions on the exact specifications of many of these instruments because of the rapid pace of technological advance. Light detectors in particular are currently undergoing dramatic improvements in sensitivity coupled with decreases in size, and these characteristics are fundamental starting points in some instrument designs. This flexibility to take advantage of the latest advances in instrument and detector technology is a further advantage ground-based telescopes have over space platforms.

But even a telescope in the best location in the world can have its seeing degraded by thermal inhomogeneities causing local atmospheric turbulence. Experience has shown astronomers that, ironically, the most damaging source of such turbulence is often the observatory itself. Ideally, all parts of the telescope would maintain the same temperature as the surroundings, but in practice this is not possible. To minimize damaging temperature gradients the designers will take a number of steps. These include painting the dome with a special, heat-reflective paint; actively controlling the temperature of the dome floor so that this massive structure will be neither a source nor a sink of heat; and locating much of the heat-producing electronic equipment in the heavily insulated observatory building.

This one-story building will contain the control room, offices, a library, and mechanical and electrical shops, including an aluminizing facility where the mirrors will be




*Each hexagonal mirror will be cut from a circular mirror blank. Displacement sensors will bridge the gap between adjacent mirrors, will detect any motion of one mirror relative to its neighbors, and will compensate for this motion by adjusting displacement actuators 300 times a second to a tolerance of one one-thousandth the diameter of a human hair.*




*The segmented primary mirror as it would appear to a star. Up close one would see that the segments are neither flat nor regular hexagons, but rather are off-axis sections of a shallow paraboloid. The central hexagon contains no mirror.*

cleaned and resurfaced. Some of these rooms will be supplemented with oxygen, since the atmosphere at 13,600 feet contains only 60 percent of the oxygen present at sea level. This low oxygen level significantly degrades a person's mental and physical performance, but often people don't notice this reduction in performance soon enough. Several of the other observatories on Mauna Kea provide masks and bottled oxygen to their personnel, but although this is a much less costly option than oxygenating whole rooms, studies show that these aids are underused. The supplemental oxygen will not provide a sea-level environment, which would be prohibitively expensive. Instead, the oxygen levels will simulate conditions at the Hale Pohaku base camp at 9,200 feet, where the astronomers and support staff will study, eat, and sleep.

Although there's a strong tradition of astronomers making their observations while in residence at a telescope, full remote control of the Keck Telescope will be possible. This will allow astronomers to make their observations from their home offices around the world, which will significantly reduce travel and housing costs. Although some astronomers may be secretly disappointed by this, since justifying a trip to tropical Hawaii will be more difficult, the fact that the temperature atop Mauna Kea is usually between 30° and 50° Fahrenheit may assuage their disappointment.

Mauna Kea is already home to a number of major observatories including the Canada-France-Hawaii 3.6-meter telescope, the NASA 3.0-meter Infrared Telescope Facility, the United Kingdom 3.8-meter Infrared Telescope and the University of Hawaii 2.2-meter telescope. In addition, the Caltech 10.4-meter telescope for submillimeter wavelengths and a United Kingdom-Netherlands 15-meter telescope for millimeter-wave observations are under construction. Caltech scientists anticipate that the Keck Telescope will be linked to the 10.4-meter telescope to form a 400-meter-baseline interferometer at submillimeter wavelengths. This will allow them to examine sites of star formation, for example, in unprecedented spatial detail.

Future hopes for the site call for the construction of a second, identical ten-meter telescope that may be used in conjunction with the first to perform optical interferometry. The effective resolving power of such tandem observations, with both telescopes trained on the same area of the sky, would be equivalent to that of a telescope having a single mirror with a diameter equal to the distance between the two scopes. No funds have yet been raised for the second telescope, which could cost an additional $60 million.

Even without its twin, the Keck ten-meter telescope will be the source of significant advances in astronomical knowledge for decades to come. Considered together with the Hubble Space Telescope and a number of other observatories that may come on line within the next decade, the Keck Observatory will set the stage for possibly the fastest increase in our understanding of the cosmos since the time of Galileo. □ — *RF*

*The Keck Telescope (foreground) will share Mauna Kea's fine "seeing" with several other observatories. Someday a second, identical ten-meter telescope may be built in the cleared space at left. Astronomers could then perform optical interferometry, an extremely powerful technique that requires tandem observations of a single point in space.*