

THE NEW GROUND-BASED OPTICAL TELESCOPES

The next round of advances in ground-based optical and infrared astronomy can only be made with larger telescopes or arrays of telescopes. New mirror designs make possible telescopes much larger than any in existence.

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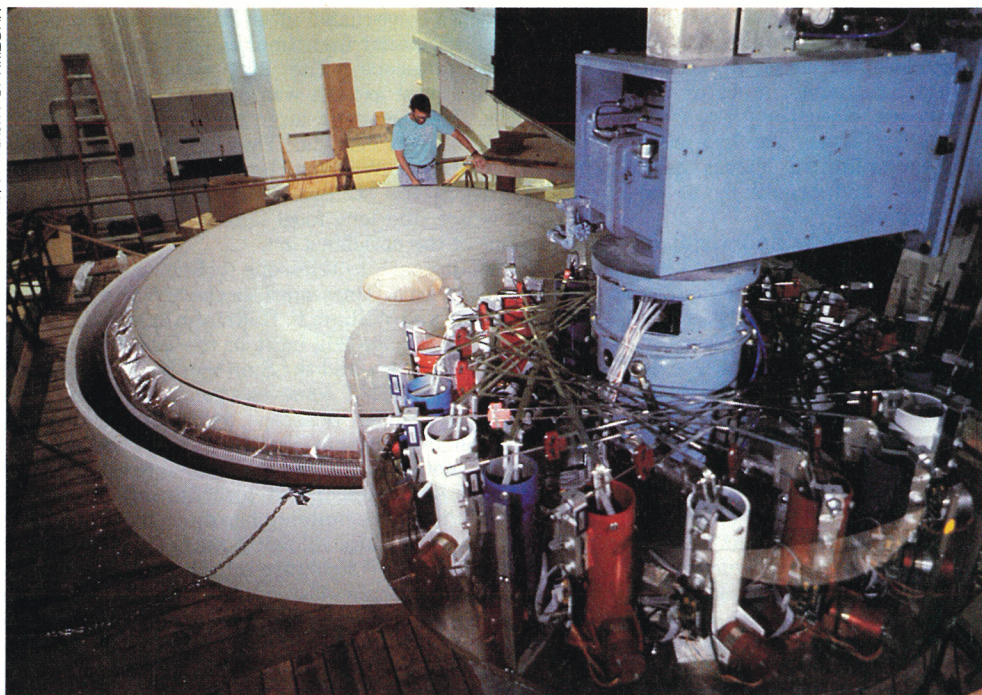
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We are in a period of rapid improvement in the capability of telescopes. Great strides are being taken to improve angular resolution, to increase sensitivity at all wavelengths and to make the most efficient use of wide-field images. The technical challenges involved in such development are great, for not only do we need mirror surfaces much larger than what we have used before, but we require higher image quality. It has recently become clear that the best mountaintop observatory sites occasionally deliver images as sharp as 0.3 arcsecond, an image quality that many existing telescopes cannot maintain.

The motivation for a new generation of much larger telescopes includes both scientific goals and new technical capabilities. Angular resolution at wavelengths longer than about $10\text{ }\mu\text{m}$ has always been limited by diffraction, so that better resolution can only be obtained with larger telescopes or arrays. This has generally not been the case in the visible or near-infrared range of the spectrum, where atmospheric distortion of the incoming wavefront limits the resolution of ground-based telescopes. The Hubble Space Telescope (see C.R. O'Dell's article in *PHYSICS TODAY*, April 1990, page 32) was designed to reach the 0.06-arcsecond diffraction limit of its 2.4-meter aperture at a wavelength of 600 nm. It now appears that practical adaptive optics will yield ground-based diffraction-limited imaging of at least some objects, even in the visible. As this hope is realized in the coming years, resolution will improve with aperture size at all wavelengths.

Over the past 40 years, increased sensitivity has come not from larger apertures but from better detectors, which also offer broader spectral range. Solid-state detectors are now 50 times more efficient than photographic plates. But the long series of advances in sensitivity in the visible spectrum is at an end, because solid-state devices now have quantum efficiencies near 100% and negligible readout noise. Infrared array detectors have not yet reached the same limits, but progress is being made toward closing the gap.

The next round of advances in both resolution and



New facility for polishing at the Steward Observatory Mirror Laboratory is the first capable of producing finished 8-m-class mirrors. This 3.5-m, $f/1.5$ honeycomb sandwich mirror is being polished with a stressed lap that was developed for large mirrors with short focal lengths.

Figure 1

sensitivity can thus be made only with larger telescopes or arrays of telescopes. This has led to an intense interest worldwide in making a new generation of larger ground-based instruments. Major programs for building single or multiple 8-m-class telescopes are under way in Europe, Japan and the United States, and other nations are developing plans. The 1990s should see a quadrupling of the total light-collecting area available to astronomers and an order-of-magnitude increase in the production rate of new collecting area compared with the past two decades.

In this article we review the concepts being developed for implementing new large ground-based telescopes. Much of our discussion will focus on the primary mirrors, for these present the greatest challenge. Major facilities, including ours at the University of Arizona (see figure 1), are being developed to supply these mirrors of unprecedented size and accuracy.

Telescope projects in advanced stages of design or construction¹⁻⁷ are listed in the table on page 24. The key technology advances are in mirror fabrication, for the size, weight, stiffness and focal ratio of the primary mirror are the dominant influences on the telescope design. It is remarkable that after three decades of only modest development, three very different primary mirror designs emerged in the 1980s. All three designs are being pursued vigorously by different groups around the world, making for a healthy competition that is likely to lead to even more powerful instruments as we move into the 21st century.

Performance goals

Ground-based optical-infrared telescopes operate over a spectral range—defined by atmospheric transmission—of 0.3–30 μm . For the new large telescopes angular resolution over most of this range is limited by atmospheric distortion, and the resulting resolution is nearly independent of wavelength. Telescope design criteria that relate to image quality—such as mirror figure, pointing and tracking, and thermal characteristics—are therefore largely independent of wavelength, and it makes sense to

give telescopes the capability to cover the whole range. All the planned large projects will include instruments for imaging and spectroscopy at infrared as well as visible wavelengths.

Many of the performance requirements for ground-based telescopes are related to the blurring of images by the atmosphere. A good mathematical model of image degradation,⁸ based on A. N. Kolmogorov's theory of turbulence, describes the wavefront distortion in terms of a single parameter, usually chosen to be the coherence length r_0 . The coherence length is the separation between points in the aperture whose rms phase difference is nearly π . When the telescope diameter d is much larger than r_0 , the instantaneous image seen at a wavelength λ consists of many speckles of size λ/d , and the long-exposure image has a width of λ/r_0 . Measurements show that the best locations all have similar image quality, limited mostly by high-altitude turbulence. The coherence length r_0 is typically 15 cm at 500-nm wavelength, and occasionally as high as 30 cm. These values correspond to long-exposure images that have widths of 0.67–0.33 arcsecond. The coherence length scales with wavelength as $\lambda^{6/5}$, and thus image width decreases slowly (as $\lambda^{-1/5}$) with increasing wavelength. Since the diffraction-limited image size scales linearly with wavelength, diffraction dominates at sufficiently long wavelengths. One of the incentives for making telescopes as large as 8–10 m is that diffraction will not significantly degrade their resolution, relative to the atmospheric limits, in the highly transparent 10- μm window.

In principle, the atmospheric blurring suffered by ground-based telescopes can be removed by dynamic corrective optics, known as adaptive optics.⁹ This correction is difficult, especially in the visible, because the complicated wavefront distortions change on a time scale on the order of 10 msec, and few sources are bright enough to allow measurement of the wavefront error in such a short time. Both the spatial scale and time scale on which the correction must be made are relaxed toward longer wavelengths, in proportion to r_0 . Working adaptive

systems have been put into operation in the near infrared by European astronomers, and the US military has sponsored a great deal of classified work aimed at extending this technique into the visible. Part of the resurgent interest in ground-based telescopes stems from the fact that these technical challenges are becoming increasingly tractable. Diffraction-limited images have been obtained in the infrared¹⁰ and are likely to be obtained in the visible within a decade.

The criterion for optical quality can be simply stated: The optics must be good enough that the best wavefronts likely to be encountered will not be substantially further degraded. The optical specification is given most simply in terms of a structure function that specifies the wavefront distortion on all spatial scales (see figure 2). At the shortest length scales, the criterion for optical telescopes becomes the same as for radiotelescopes: The shortest wavelengths must be reflected without significant scattering.

Development of telescopes in this century

The 19th century saw the construction of many large refracting telescopes, culminating in the construction of lenses up to 1 m in diameter. The first step in modern cosmology, the discovery in 1914 that galaxies are moving apart, was made by Vesto Melvin Slipher with the Lowell 0.6-m refractor in Arizona. Further advances came almost exclusively from reflecting telescopes, particularly the 2.5-m Hooker Telescope at Mount Wilson, completed in 1918. Here Edwin Hubble first estimated the extra-Galactic distance scale from observations of Cepheid variables. (See Robert W. Smith's article in *PHYSICS TODAY*, April 1990, page 52.) The success of the first "modern" reflecting telescopes at Mount Wilson led to the construction of the 5-m Hale Telescope at Palomar in the 1930s and 1940s.

Telescopes constructed after Palomar were predominantly 4-m or smaller instruments, the largest being the Soviet 6-m telescope. The long period of relatively stagnant telescope growth was due in part to technical difficulties. Most existing large telescopes are scaled-up versions of smaller designs. They represent the largest possible scaling of William Herschel's 18th-century design, in which the stiffness of a thick slab keeps the mirror's figure, and long focal length is a consequence of limitations of the optician's art.

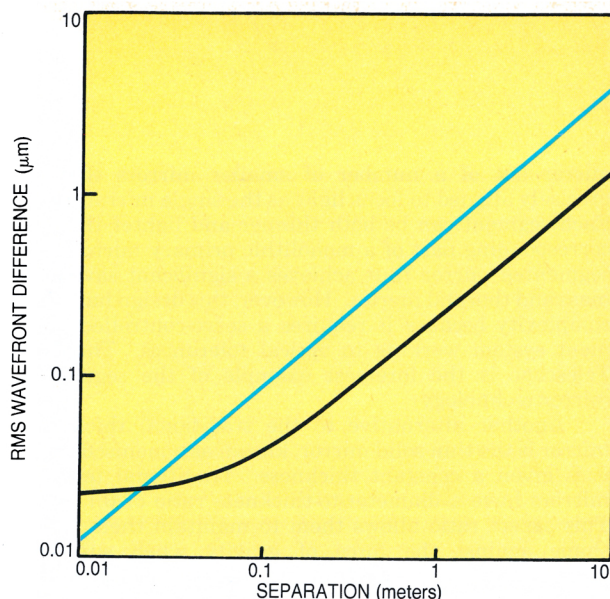
A new approach to telescope technology was used in the Multiple Mirror Telescope (see the article by Nathaniel P. Carleton and William F. Hoffmann in *PHYSICS TODAY*, September 1978, page 30), built in the late 1970s by the University of Arizona and the Smithsonian Astrophysical Observatory. The MMT achieves a collecting area equivalent to that of a 4.5-m telescope by combining the light from six 1.8-m mirrors on a common mount. The telescope structure is not only lighter and less expensive than a conventional 4-m telescope; it also fits into a compact rotating building. The building has much more open area than traditional domes, allowing natural ventilation to bring the mirrors and structure into thermal equilibrium with the nighttime air. Experience with the MMT and other 4-m-class telescopes has shown that much of the image blurring previously ascribed to the free atmosphere is in fact caused by thermal effects in the telescopes and their enclosures.

The newest 4-m-class telescope, the European Southern Observatory's 3.5-m New Technology Telescope (see *PHYSICS TODAY*, May 1990, page 17), combines an MMT-style open building with careful control of internal temperatures to minimize local distortion of the incoming wavefront. By incorporating active control of the mirror surface and optical alignment through wavefront sensing

Major new ground-based optical telescopes

Project	Organizations	Primary area (m ²)	Type of primary	Reference
Very Large Telescope	European Southern Observatory	210	Four separate telescopes; 8.2-m glass-ceramic meniscus	1
Columbus	Italy Ohio State University University of Arizona	110	2×8.4-m borosilicate honeycomb sandwich	2
Keck Telescope	Caltech University of California	76	36×1.8-m hexagonal glass-ceramic meniscus segments	3
Magellan	Carnegie Institution John Hopkins University University of Arizona	50	8-m borosilicate honeycomb sandwich	4
NOAO (north)	National Optical Astronomy Observatories Great Britain Canada	50	8-m borosilicate honeycomb sandwich	5
NOAO (south)	National Optical Astronomy Observatories Great Britain Canada	50	8-m borosilicate honeycomb sandwich	5
Japanese National Large Telescope	National Astronomy Observatory of Japan	44	7.5-m zero-expansion meniscus	6
MMT conversion	Smithsonian Institution University of Arizona	33	6.5-m borosilicate honeycomb sandwich	7

Atmospheric wavefront distortion and telescope optics specification. The blue curve represents the wavefront distortion produced by the atmosphere under excellent seeing conditions (0.33-arcsecond FWHM at 500-nm wavelength), and the black curve is a representative wavefront specification for a large primary mirror. The quantity plotted is the rms wavefront difference between points in the aperture as a function of their separation. For a ground-based telescope, wavefront distortions produced by the optics should be less than those produced by the atmosphere on all spatial scales, so the specification becomes increasingly tight on smaller scales. On the smallest scales the atmospheric distortions become negligible, and the requirement is simply that little light be scattered by surface irregularities. **Figure 2**



and adjustable support forces, it also achieves the best image quality of all existing telescopes. The first observations with the NTT, made in excellent atmospheric conditions, produced images of remarkable quality: 0.33-arcsecond full width at half-maximum.

The capabilities of the new ground-based telescopes are inevitably compared with those of the Hubble Space Telescope. Only space telescopes can work in the ultraviolet, and they have the great advantage of avoiding the bright background of atmospheric line emission at wavelengths of 1–2 μm . The larger ground-based telescopes will provide diffraction-limited imaging at wavelengths longer than 10 μm and will be superior for observations where spectral resolution is limited by the number of photons.

At visible wavelengths, ground- and space-based observations are complementary, and will remain so even after new instruments restore diffraction-limited imaging to the HST and adaptive optics begin to bring diffraction-limited imaging to ground-based telescopes. The HST will provide sharp images over a field of 2.6 arcminutes and will have the precise and stable diffraction pattern needed for high contrast. The ground-based instruments will have at least an order of magnitude more light grasp, and with adaptive optics will have higher resolution. But it will be very difficult to make adaptive corrections over a field of more than a few arcseconds in the visible. For sky surveys and other observations that do not require diffraction-limited images, however, the ground-based telescopes will have fields of view of up to a degree, making them uniquely powerful survey instruments.

Mirror technology

Mirrors are made of glass because of its remarkable dimensional and chemical stability. Metal reflectors were used from the time of their invention by Newton through the 19th century, during which period they competed with refractive designs for prominence. They had to be repolished frequently due to figure changes and corrosion. Justus von Liebig's discovery in the 1850s of a means of chemically depositing a thin layer of silver on glass eventually made it possible to combine the reflectivity of metal with the stability and polishability of glass.

The 1.5-m and 2.5-m mirrors on Mount Wilson are made of soda-lime glass with an expansion coefficient α of roughly 10^{-5} K^{-1} . Thus they suffer significant figure

distortion when the temperature changes by 1 K or more. In seeking to reduce this problem the designers of the Palomar 5-m mirror first experimented with fused quartz (with an α of $7 \times 10^{-7} \text{ K}^{-1}$) and eventually succeeded in producing a blank with an α equal to $2.8 \times 10^{-6} \text{ K}^{-1}$ using a variant on Pyrex, the laboratory and ovenware glass developed by Corning around the turn of the century. A number of new materials for mirror blanks emerged in the 1960s and 1970s. These include glass-ceramics, such as Schott's Zerodur, which achieve negligible thermal expansion by combining a glassy or vitreous phase, which has a positive coefficient, with a ceramic or crystalline phase, which has a negative coefficient. Corning later developed ULE fused silica, used for the HST primary mirror. ULE is given an expansion coefficient near zero by doping the fused silica with titanium dioxide. Most of today's 4-m-class telescopes use one of these new materials.

The 4-m-class telescopes—apart from the MMT and NTT—use solid, stiff primary mirrors about half a meter thick. Two factors limit our ability to scale up these designs to diameters 8-m and larger. The first is simply the weight of the mirror. A 4-m mirror stiff enough to hold its figure on a relatively simple support weighs around 15 tons. The scaled-up 8-m mirror would weigh 120 tons and would sag four times as much under its own weight unless a more elaborate support were used.

The second factor limiting mirror size is thermal inertia. While the low-expansion materials effectively eliminate thermal distortion of the mirror figure, there remains the problem of convective air currents due to temperature differences between the glass and surrounding air. These currents, like turbulence in the free atmosphere, will distort the incoming wavefront. The magnitude of this "mirror seeing" depends on details of the convection, but is in the neighborhood of 0.3 arcsecond of image blurring for each 1-K temperature difference between glass and air. The older 4-m-class mirrors have thermal time constants of many hours and rarely come into equilibrium with ambient air. The problem would be much more severe for the massive, scaled-up 8-m mirror, and would frequently limit image quality to an arcsecond or worse.

Faced with these difficulties in scaling up the 4-m-class mirror designs, astronomers and engineers have recently developed three alternatives for making glass mirror substrates. One method is to make the primary

mirror out of a number of smaller mirrors that are precisely aligned to focus light as the single mirror would. Each segment can be both thinner and lighter than the corresponding part of a monolithic primary mirror. The segmented mirror thus achieves a significant savings in mass and thermal inertia. However, this design has added complexity because it requires a servo-controlled alignment system working to optical tolerances. The Keck Telescope is the foremost example of the segmented-mirror technology.

Another alternative to the traditional thick solid mirror is the thin solid mirror, known as a meniscus when it is given a constant thickness. Traditional telescope mirrors have a diameter-to-thickness ratio of 6:1 or 8:1. This aspect ratio allows them to maintain their precise shape against the force of gravity when supported passively at relatively few points. Meniscus designs, with aspect ratios of 40:1 or higher, sacrifice this overall stiffness in favor of weight reduction. Rigidity then depends on an actively controlled support system that has as many as several hundred actuators distributed over the back of the mirror to counter the forces of gravity and wind. The meniscus technology is being pursued for the European Southern Observatory's Very Large Telescope and for the Japanese National Large Telescope.

A third alternative is to make the mirror lighter by making it hollow. Just as I-beams provide the most efficient geometry with which to obtain stiffness in linear elements, ribbed sandwich structures give the greatest ratio of stiffness to weight for two-dimensional surfaces like mirrors. Our group at the University of Arizona has developed a method for casting large honeycomb sandwich mirrors out of borosilicate glass. Their deformation under gravity is similar to that of a solid blank of the same dimensions, but the honeycomb has less than one-quarter the mass of a solid blank. A valuable byproduct of the honeycomb structure is that its thin glass sections are able to come quickly into thermal equilibrium with the ambient air. These mirrors will be used for three collaborative projects involving US universities and private and foreign observatories, and are likely to be adopted for proposed US-British-Canadian 8-m telescopes.

The new telescope designs differ from existing telescopes in a number of ways in addition to the type of primary mirror. One of the most far-reaching changes from older designs is the evolution toward short focal lengths. In all existing telescopes, the primary mirror's focal ratio, or f -number—the ratio of focal length to diameter—is relatively large, in the range of 2.2–5. Such “slow” mirrors are used because of the difficulty of fabricating the more aspheric surfaces of “fast” paraboloids, which have small focal ratios. However, with increasing aperture diameter there is increased pressure to minimize the overall length of the telescope by using a faster primary mirror. One reason is simply economic: An enclosure 60 m in diameter would cost roughly eight times as much as a 30-m enclosure. But short telescopes also offer improved performance, particularly in terms of stable and accurate tracking of celestial sources when the telescope is buffeted by winds of 5–10 m/sec. These advantages have led the groups designing 8-m-class telescopes to choose focal ratios of 2 or less—even as fast as 1.14 for the Columbus Project.

For the parabolic or nearly parabolic primary mir-

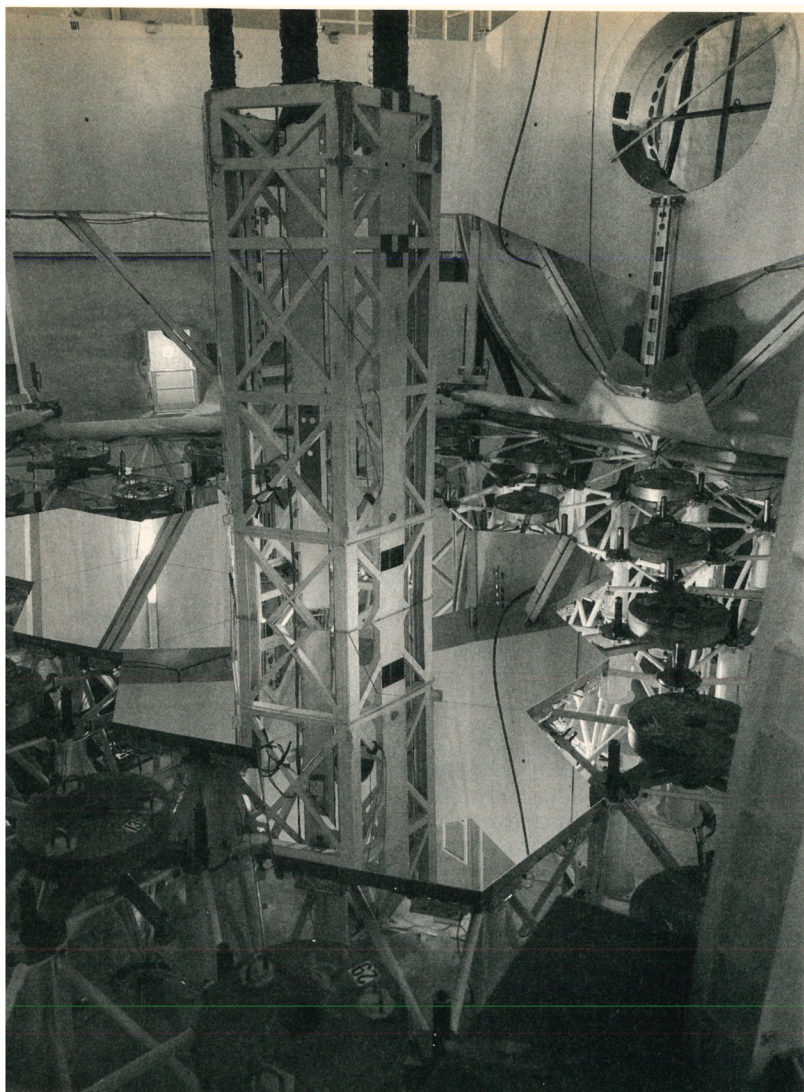
rors, the departure from the best-fitting sphere increases in proportion to diameter and the inverse cube of the focal ratio. While an 8-m $f/3$ paraboloid would depart from the best-fitting sphere by at most 72 μm , an $f/1$ mirror the same size would have almost 2 mm of asphericity, vast by optical standards. Opticians prefer to use relatively large and stiff polishing tools because of their strong smoothing action, but these tools have the strongest tendency to make spheres. Very aspheric surfaces require a different approach. Among the techniques developed are small tools, for which the asphericity of the surface is limited to a few microns over the face of the tool¹¹; flexible tools that bend to match the shape of the optical surface; active control of the shape of the tool or the glass; active control of the pressure distribution across the tool¹²; and controlled removal of glass with ion beams.¹³

The Keck Telescope

Of the new large telescope projects, only the 10-m Keck Telescope—a segmented-mirror instrument located near the summit of Mauna Kea in Hawaii (see the photo on the cover of this issue)—has moved from design into construction. One quarter of its primary mirror was in place to obtain first-light images in November 1990. The Keck Telescope mirror (see figure 3) consists of 36 hexagonal segments, which are independently supported to form the 10-m-diameter, $f/1.75$ hyperboloid. Among the telescope's many innovative and challenging aspects, the fabrication and active alignment of the 36 segments of the primary mirror and the single 1.4-m secondary mirror stand out. Each hexagonal Zerodur segment is 1.8 m across and 75 mm thick, light and stiff enough to maintain its figure with a passive support.

With the primary mirror divided into many small segments, there is no need to fabricate, support and protect a huge piece of glass. However, because the segments are not only quite aspheric (as much as 200 μm peak-to-valley) but nonaxisymmetric, their fabrication presents a challenge. Starting in the 1970s, project scientist Jerry Nelson and his colleagues developed a technique to simplify the polishing of these complex surfaces.¹⁴ Each segment, initially a circular disk, is bent elastically while it is polished so that the desired optical surface becomes spherical. This spherical surface is polished conventionally. The segment is then allowed to spring back to its relaxed state, and the polished surface takes on the desired aspheric figure. A breakthrough in the development of this stressed-mirror polishing technique was Nelson's realization that because the required bending modes have low spatial frequency, one could induce them to optical accuracy by applying moments and forces only to the edge of a circular disk (along with linearly varying pressure across the back of the disk).

The new technique, put into practice initially at Kitt Peak National Observatory and later for production at Itek Optical Systems and Tinsley Laboratories, succeeded in polishing segments rapidly to an accuracy of about 250 nm, about an order of magnitude greater than the goal. Further stressed-mirror polishing would have limited value because figure errors of similar magnitude are introduced when the circular disks are cut into hexagonal segments. This operation eliminates stresses at the cut surfaces, causing the segment to warp. Stressed-mirror polishing cannot be performed on the cut disks because the



TOM WYNN/CARA

Keck Telescope's primary mirror, with nine segments in place. The view from inside the dome shows the telescope as it was configured for first-light observations in November 1990. The mirror is designed to be a mosaic of 36 1.8-m segments, each supported independently. Together they will form a 10-m-diameter $f/1.75$ hyperboloid. As viewed from a star each segment is a regular hexagon. Sensors at the segment boundaries provide the information needed to form a continuous optical surface and to control the overall figure. **Figure 3**

principle of using edge moments and forces applies only to circular disks.

To correct these errors and the warping of the cut segments, the Keck scientists bend the segments back into the correct shape using a set of mechanical springs built into the support system of each segment. For the nine segments installed for first-light observations, the combination of stressed-mirror polishing and corrective springs produced surface accuracies of 20–40 nm rms. This level of accuracy brings the image quality of the individual segments within a factor of two of the goal of 0.24-arcsecond diameter for 80% of the incident light. One segment has been refigured at Kodak's new ion-beam figuring facility to a surface accuracy of 90 nm rms before application of corrective springs, establishing this technique as a promising means of meeting the full specifications.

Alignment of the segments is achieved initially with starlight, and maintained with capacitive sensors that continuously measure axial displacements between each segment and its neighbors to accuracies of a few nm. A microprocessor uses these displacements, 168 in all, to adjust the positions of the three actuators supporting each segment. This edge control system acts as though there were hinges at the segment edges, and the effect of hinging rigid hexagonal segments is to fix the overall shape. This principle is applied in holding the figure of the mirror

against deformation of the steel support structure. Ultimately, then, the shape stability is determined by the resistance of the individual segments to bending.

Variants of the segmented-mirror technology are planned for use in the Spectroscopic Survey Telescope¹⁵ and the German Large Telescope Project.¹⁶ The SST, being planned by the University of Texas and Penn State, will use 85 spherical segments to form a 9-m spherical primary mirror. Fiber optics will feed light from moving focal-plane correctors to a fixed spectrograph. The concept for the German Large Telescope calls for a 12-m primary mirror made of 4 to 13 large segments.

Telescopes with thin meniscus mirrors

Two projects will use thin meniscus mirrors made of zero-expansion materials. ESO's Very Large Telescope, depicted in figure 4, will actually be an array of four 8.2-m telescopes that can be used either independently or in a combined mode with all four focused on a common detector. Interferometric capabilities are also planned, with optical path-length modulators to maintain coherence among the four beams. The VLT will be built on Cerro Paranal in the Chilean Andes. The second meniscus project is the Japanese National Large Telescope, a 7.5-m telescope to be built on Mauna Kea.

The Zerodur mirror blanks for the VLT will be cast in a concave rotating mold at a facility recently built by

Schott in Germany. The first of the four blanks is scheduled to be delivered in 1993. They will be polished by the French company REOSC. With focal ratios of 1.8, the mirrors can probably be polished without the need for fundamentally new technology.

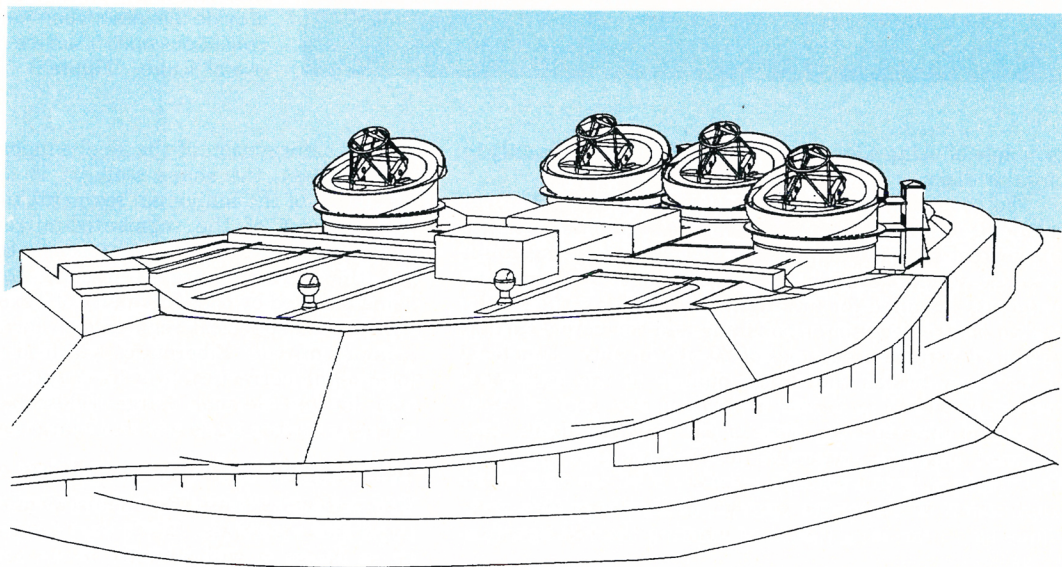
Only 175 mm thick and weighing 23 tons each, the VLT mirrors will need to be supported at several hundred points, with very accurate active control of the forces at these points. The active support system will have to compensate for slowly varying thermal expansion of the telescope structure, more rapid but predictable changes in gravitational loads as the telescope tracks, and very rapid and unpredictable changes in wind loading. To maintain the required surface accuracy of 100 nm rms, the reflected wavefront from a star will be monitored and used to adjust the support forces.

The VLT mirrors' axial support system will consist of two stages: a passive hydraulic system that distributes the weight of the mirror over some 450 points, and a set of active electromechanical actuators whose force will be added to that of the passive system at each point. The number of actuators will be reduced by spreading the force of each actuator over three support points. The lateral support system, which will apply forces roughly parallel to the mirror surface when the telescope points away from the zenith, will be a passive hydraulic system that distributes forces along the outside edge of the mirror. Were it not for the active axial supports, the flexible mirror—having

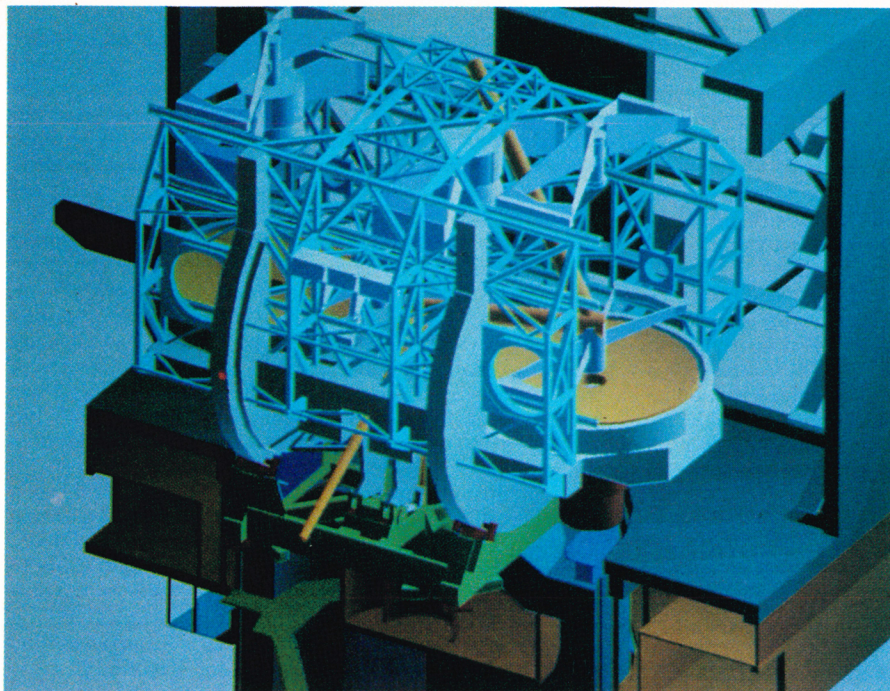
lateral supports only at its edge—would deform drastically when pointed away from the zenith. The active component of axial supports will be adjusted as a function of zenith distance to compensate for these deformations.

The astronomers at ESO intend to turn the relatively flexible mirror and elaborate support system to their advantage, and have already done so in the New Technology Telescope, which serves as a prototype for the VLT project. The actuators needed to provide dynamic balancing of the forces of wind and gravity can also induce static shape changes to compensate for polishing and testing errors. The NTT was found at first light to have a $4\text{-}\mu\text{m}$ figure error of the same form (and probably with a similar cause) as the error in the HST. The error in the NTT figure was removed to high accuracy by the active axial support actuators. An extension of this trick is to change the optical design of the telescope during operation. While the VLT optics are designed as Ritchey-Chrétien systems (with hyperbolic primary mirrors) for secondary foci at $f/15$, they will be "redesigned" as classical Cassegrains with parabolic primary mirrors for use at other foci. The $20\text{-}\mu\text{m}$ change in mirror figure required will be accomplished with the active actuators.

Compared with the VLT design, the JNLT meniscus mirror design is more conservative. With its $f/2$ primary, the JNLT will be the slowest of the new telescopes but still faster than any 4-m-class telescope built to date. The 7.5-m mirror will be 200 mm thick, making it some 30% more



Very Large Telescope, being built by the European Southern Observatory, will consist of four 8.2-m telescopes that can be used independently or in combination. In interferometric observations, the beams will be combined in phase by optical delay lines to compensate for path differences to the four telescopes. It will be possible also to combine smaller auxiliary telescopes with the main array for these interferometric observations. Retractable enclosures are planned to facilitate reaching thermal equilibrium with the surrounding air and to minimize convective turbulence. **Figure 4**



Columbus Project telescope being built by Italy, Ohio State University and the University of Arizona is shown in a computer-generated drawing. Using the two 8.4-m primary mirrors separately will provide a collecting area equivalent to that of an 11.8-m telescope; used interferometrically, they will give the angular resolution of a 23-m telescope. Since the mirrors are on a common mount, no optical delay lines are needed to phase the telescope during observation. Two large C rings provide the elevation motion and transmit forces directly from the optics support structure to the ground. The resulting stiffness makes for a stable platform for interferometry, with a lowest resonant frequency of 10 Hz. The corotating enclosure (shown here in cutaway view) has openings on all four sides to provide natural ventilation. (Drawing courtesy of A. D. S. Italia.) **Figure 5**

resistant than the VLT mirrors to deflections under its own weight, but will be supported by 264 actuators. Each of these will incorporate purely active axial forces with passive lateral forces applied at the same points. Holes drilled into the mirror will allow the forces to be applied at its midplane, with the result that the lateral forces will produce little or no deformation.

To maintain the required surface accuracy of the thin meniscus mirrors, axial forces must be controlled at a level of accuracy that cannot be measured with commercially available load cells. Both the European and Japanese groups have developed force sensors, based on measurement of the vibration frequency of a stressed member, that have relative accuracies better than 10^{-4} .

Telescopes with honeycomb mirrors

A number of large telescope projects are based on the honeycomb sandwich mirrors being cast at the University of Arizona. The largest of these, at 8.4-m diameter and $f/1.14$, will be the twin mirrors of the Columbus Project telescope. This telescope, shown in figure 5, will be the most powerful of any on a single mount: It will have the collecting area of an 11.8-m filled aperture and high angular resolution from its elongated pupil—23 m from end to end. The site for the Columbus telescope is Mount Graham—at 3200-m elevation, the highest of the mountain islands in the Arizona Sonoran desert.

The honeycomb mirrors are made in one piece in a complex mold that yields a hollow structure with a diameter-to-thickness ratio of 8 or 10 to 1. The mirror structure consists of a 28-mm-thick front plate and a 25-mm-thick back plate separated by 11-mm ribs in a 200-mm hexagonal pattern.¹⁷ The casting is done in a rotating oven, giving the front surface of the mirror blank the correct parabolic curve to an accuracy of about 1 mm. While the cast surface misses optical tolerances by four orders of magnitude, spin casting eliminates the need to grind out some 20 tons of glass (at \$30 000 per ton) and reduces the annealing time from more than a year to two months.

The Arizona mirrors are cast of E6 borosilicate glass (similar to Pyrex) made by Ohara in Japan. This glass melts at modest temperatures, reaching a viscosity of 10^5 poise at 1200 °C, at which point it will flow into the mold of the honeycomb sandwich. The glass-ceramics, while they have lower thermal expansion than borosilicate, can only be cast in solid shapes. Fused silica, another candidate, has no liquid state and can be formed into lightweight structures only by fusion bonding, as was used for the HST mirror, or by milling out a solid disk. Either process would be prohibitively expensive for an 8-m-class mirror.

The largest honeycomb sandwich mirrors will be 8.4 m in diameter and weigh 14 tons. They will be 850 mm thick at the edge, but the total volume of glass will be

equal to that in a 100-mm-thick meniscus. Compared with such a meniscus, deflections of the honeycomb due to wind and gravity are reduced by factors of 7–10. The improved stiffness-to-weight ratio of the primary mirror is generally transferred to the telescope structure as well, since it supports a lighter mirror.

So far three 3.5-m-diameter mirrors have been cast at the Steward Observatory Mirror Lab, and the furnace has recently been expanded to the full 8.4-m capacity. The first large casting, scheduled for the fall of 1991, will produce one 6.5-m mirror to replace the six 1.8-m mirrors of the Multiple Mirror Telescope. The conversion project will more than double the telescope's collecting area, with little impact on its structure or the enclosure. This upgrade is made possible by giving the 6.5-m mirror such a short focal length that the new telescope can fit into the rotating building that now houses the six mirrors. At $f/1.25$, the new MMT requires only a minor extension of the existing building—and a new name.

After the 6.5-m casting, a series of castings at 8–8.4 m will be made at 9-to-12-month intervals. The Magellan Project will use an 8-m, $f/1.2$ primary for a telescope to be located on Las Campanas in Chile. In addition to the Columbus and Magellan projects, the National Optical Astronomy Observatories have proposed to build two 8-m telescopes—one on Mauna Kea and one on Cerro Tololo in Chile—using $f/1.8$ honeycomb mirrors.

The choice of very fast primary mirrors for most of the honeycomb projects is based on optical and mechanical performance, as discussed above. A new method of polishing is being developed to produce the severely aspheric surfaces. An actively stressed polishing tool, known as the stressed lap (see figure 1),¹⁸ changes shape continuously as it sweeps across the mirror surface, always matching that part of the aspheric curve with which it is in contact. The stressed-lap method is based on the same mechanical principles as stressed-mirror polishing. The bending of the polishing disk is accomplished in essentially the same way used to bend the Keck segments, but the edge moments applied to the stressed lap are continuously updated by computer so that the lap can travel over the entire mirror surface. Stressed laps are currently being used to figure two mirrors, the 1.8-m, $f/1.0$ primary of the Vatican Advanced Technology Telescope and a 3.5-m, $f/1.5$ paraboloid for a US Air Force telescope. Both mirrors have been figured to a surface accuracy of better than 400 nm rms as of January 1991.

The borosilicate honeycomb mirrors will incorporate active control of the glass temperature to minimize temperature differences within the mirror and with respect to the outside air. Unlike the glass-ceramic mirrors, borosilicate's expansion coefficient— $2.9 \times 10^{-6} \text{ K}^{-1}$ —is not negligible. Internal temperature differences ΔT produce strains and consequent surface slope errors of order $\alpha \Delta T$. To keep these errors below about 0.06 arcsecond requires that ΔT be no more than 0.1 K. The open structure of the honeycomb sandwich mirrors provides a simple mechanism for achieving the necessary thermal control. Temperature-controlled air is blown into each of the hexagonal cells through holes in the back plate. A side benefit of this air conditioning system and the lightweight structure is that the mirror's thermal time constant is reduced to about 40 minutes. This assures that in most observing conditions the glass will remain within 0.2 K of ambient temperature, and convection off the mirror surface will not degrade the images appreciably.

Future directions

Beyond the implementation of the projects described in

this article, there is great interest in improving angular resolution through adaptive optics and interferometry. Adaptive optics is most advantageous when used to correct very large apertures. If the elements of a large segmented mirror were small—of order 20 cm—they would be agile enough to correct the atmospheric wavefront. One of us has proposed a 32-m telescope with a fast spherical primary of this type.¹⁹

While a fixed interferometric array of mirrors spanning a baseline B gives some information on structure down to angular size λ/B , true images require a sampling of the pupil plane that can only be obtained practically with mobile telescopes. ESO has already drawn up plans for four movable 2-m-class telescopes to enhance the interferometric power of the VLT, and has further extensions—including baselines as large as 1 km and operation wavelengths as short as $1 \mu\text{m}$ —in its long-range plan.

In addition to proposed extensions of the ground-based telescopes, there is growing interest in placing a telescope of 10-to-16-m diameter in Earth orbit or on the Moon. Such an ambitious project is likely to take 20–30 years to come to fruition and cost some \$5–10 billion in current dollars. It will, however, start on a sound technical footing with the experience of not only the HST but a generation of 8-to-16-m class ground-based telescopes behind it.

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