

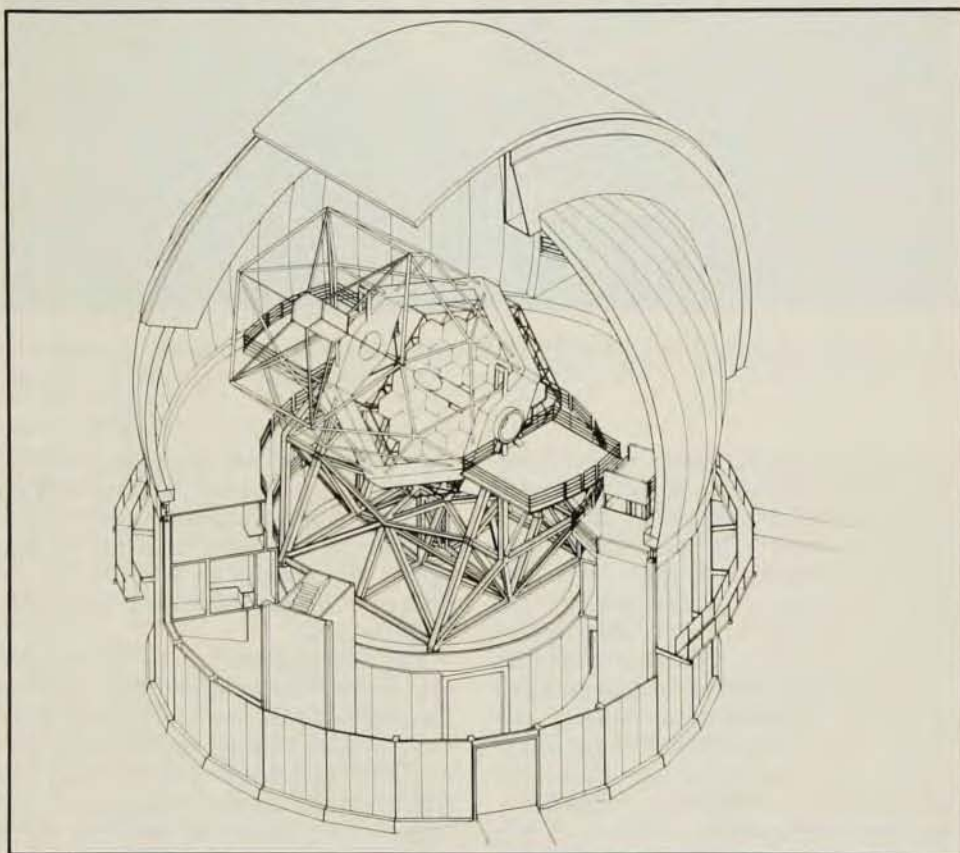
Large new-technology optical telescopes proposed

The 5-meter telescope on Mt. Palomar was designed and funded more than fifty years ago. Since its completion shortly after World War II, only one larger optical telescope has been built. And that instrument, the Soviet 6-meter reflector, begun in 1966, has been a disappointment.¹ In recent decades the emphasis in optical-astronomy instrumentation has been primarily on the improvement of light detectors. Modern photon detectors are a hundred times more sensitive than the photographic plates originally exposed at Mt. Palomar.

With quantum efficiencies of better than 50%, these detectors are now approaching the theoretical noise limit of photon sensitivity. Astronomers are therefore turning once again to the quest for larger telescope mirrors, to gather more light for their detectors. Advances in telescope technology have opened the way to construction of a generation of much larger "new-technology telescopes" within contemporary budget realities.

Three universities are at present actively working toward that end. A University of California group has recently received a \$1.1-million grant from the University's Regents for the design of a 10-meter telescope whose primary mirror would consist of 36 contiguous hexagonal segments (PHYSICS TODAY, October 1978, page 19). The University of Texas is planning an instrument with an extraordinarily thin monolithic mirror, 7.6 meters in diameter. Astronomers at the University of Arizona are experimenting with honeycombed Pyrex modules, in hopes of using this light, inexpensive material to build a larger version of the Multiple-Mirror Telescope (MMT), whose total collecting area is equivalent to a 4.5-meter single reflector (PHYSICS TODAY, September 1978, page 30). The MMT, completed in 1979, is operated jointly by the University of Arizona and the Smithsonian Astrophysical Observatory.

The Field Committee report, soon to be released by the National Academy of Sciences Astronomy Survey Committee, headed by George Field (Harvard-Smithsonian), is expected to recom-



A 10-meter optical-infrared telescope is proposed by a University of California group. Its segmented primary mirror would consist of 36 contiguous hexagonal elements, 1.8 meters wide and only 7.5 cm thick. With sensors and actuators maintaining the mirror's overall figure to within a micron, the total moving weight of the telescope would be only 150 tons.

mend the construction of a 15-meter optical-infrared "National Telescope" later in the decade. (The report is currently being reviewed by the NAS, prior to its release.) Studies carried out at the Kitt Peak National Observatory in the late 1970s concluded that so large a telescope could not realistically be built with a single monolithic mirror. At last year's Tucson conference on "Optical and Infrared Telescopes for the 1990s," the MMT and segmented-single-mirror configurations emerged as the front runners for a 15-meter design. NSF is funding a consortium of Kitt Peak and the three universities to investigate the scientific, technological and cost trade-offs between the two approaches.

New-technology telescopes. It is estimated that without radical technologi-

cal departures the cost of large ground-based reflecting telescopes grows as something like the 2.6th power of the mirror diameter. At that rate, a conventionally built 10-meter reflector would cost more than \$200 million—twice as much as the Field Committee is reported to regard as an acceptable cost for the 15-meter National Telescope. Clearly the new generation of large telescopes will require novel design features to keep costs within reasonable bounds.

The dominant cost factors for a large reflecting telescope are the weight and material of the primary mirror, and the size of the dome. A 10-meter mirror built in the classical style of the Soviet 6-meter or Palomar reflectors would have to be about 6 feet thick, with a weight of more than 130 tons. Simply



Honeycombed pyrex mirrors produced at the University of Arizona are being considered for the next generation Multiple Mirror Telescope. Test casting seen here without faceplate.

making the mirror much thinner presents severe problems of rigidity under the enormous gravitational stresses to which the mirror is subjected as it is tilted to observe different regions of sky. To preserve image quality, one cannot tolerate surface deformations much greater than a tenth of a micron.

To minimize deforming gravitational strains as they track the diurnal motion of the celestial objects under observation, the new-technology telescopes will have to be mounted in altitude-azimuth configuration instead of the traditional equatorial mounts. The rotation axis of an equatorially mounted telescope points at the North Star, simplifying diurnal tracking but subjecting the mirror to awkward stresses. Alt-azimuth mounting, in the manner of large artillery pieces, is more stable structurally, but it requires a more complex star-tracking program. With modern computer-driven motors this presents no problem.

There are several approaches to reducing the weight of primary mirrors. One can either produce a very thin monolithic mirror from a single blank, or one can configure an array of contiguous or separated mirror modules to function as a single mirror. All these approaches require a delicate system to sense minute deformations of the mirror's overall shape, or "figure," and make appropriate corrections. The six separate 2-meter mirrors of the MMT were originally intended to be kept in alignment by a complex of laser beams running through the system. This has not worked out in practice, primarily because it was impossible to distinguish

between mirror misalignments and the effects of atmospheric fluctuations on the laser beams traversing the dome. At present, the MMT mirrors are realigned periodically by sharpening the images of bright stars near the object under study.

The exacting tolerances on the mirror figure also require that thermal distortions be kept to a minimum. One usually does this by making the mirrors from special glasses with very low coefficients of thermal expansion. Because such glasses cost about as much per pound as silver, the University of Arizona group is examining the alternative of using honeycombed configurations of cheaper glasses to speed the approach to thermal equilibrium.

For a given f ratio (focal length divided by aperture diameter), the height of the telescope dome must grow linearly as the mirror diameter—with the cost of the enclosure growing even faster. To keep dome costs down, the large new telescopes will have to have unusually "fast" (low f ratio) mirrors, or slower parabolic mirrors are difficult to shape accurately because of their greater curvature and departure from sphericity. The recent development of laser-controlled grinding and polishing techniques now makes it possible to produce accurate large mirrors as fast as $f/2$. Alternatively, one can keep the telescope enclosure small by going to the MMT configuration with slower mirrors. In such an arrangement, the overall height of the dome is determined by the focal length of a single mirror, irrespective of the total collect-

ing area of the multiple-mirror system. It is in fact a misnomer to refer to the extraordinarily compact, almost cubical, enclosure of the MMT on Mt. Hopkins (Arizona) as a "dome."

The McDonald Observatory of the University of Texas, headed by Harlan Smith, wants to build the largest feasible optical-infrared telescope that can be built quickly—with a minimum of untried technological innovation. They have therefore opted for a very thin monolithic mirror, ground from a single blank of fused silica, a low-expansion-coefficient form of quartz. We were told by Thomas Barnes, assistant director of the Observatory, that consultations with glass manufacturers, grinders, transporters and engineers had convinced them that a 300-inch (7.6-meter) monolithic mirror was feasible; anything larger would be too problematical.

The Texas mirror, ground from a meniscus-shaped blank to a focal ratio of $f/2$, would be only four inches thick at its center—an order of magnitude slimmer and lighter than a conventional mirror design for that size. So delicate a shape would surely sag under its own weight, changing its shape far beyond tolerable limits as it scanned across the sky. The mirror will therefore be buttressed by a system of actuators that can pull or push it back into proper figure. The information necessary to control the actuators would come from a laser-reference system, whose interferometric measurements will have to detect surface deformation as small as 1000 Å. Barnes told us that the Texas group is now preparing to build a prototype laser-reference system to test this scheme. The Texans are considering a variety of actuator designs, including those currently being developed at the Lawrence Berkeley Lab by George Gabor and Jerry Nelson for the University of California's segmented-mirror telescope.

Both the California 10-meter and the Texas 7.6-meter telescopes are designed to be diffraction limited at infrared wavelengths. In the visible region they would be limited, like all ground-based telescopes, to a resolution on the order of an arc-second by atmospheric fluctuation.

The 7.6-meter telescope would be located on Mt. Fowlkes in Texas, a 6600-ft. peak owned by the McDonald Observatory. The estimated cost of the telescope, its rotating enclosure building, support facilities and auxiliary instruments is \$45 million. The University of Texas is looking primarily to private contributors to fund this project, Barnes told us. Private philanthropy is a fine old tradition in astronomy. The original Yerkes telescope, a gift of 19th-century philanthropy, is still in productive use, he reminded us. If the funds

were made available tomorrow, the 7.6-meter telescope could be operational by 1986—in time for the Texas sesquicentennial, Barnes pointed out.

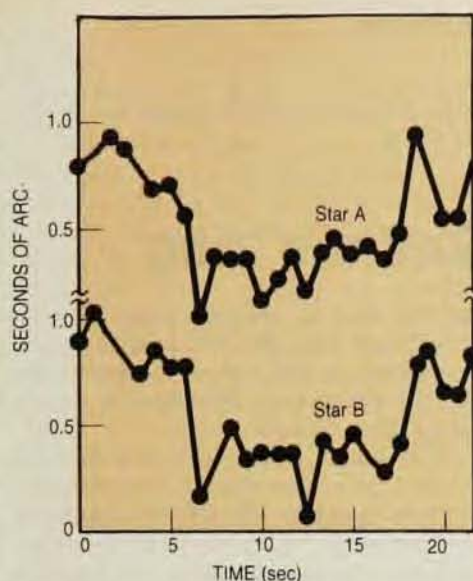
The University of California group led by Nelson (LBL) and Sandra Faber (Lick Observatory), is designing a 10-meter reflector. Because this size appears to be beyond practical bounds for a monolithic mirror, and because they want to develop techniques suitable for still larger reflectors, the group intends to construct its primary mirror of 36 hexagonal segments, each 1.8 meters wide. With a thickness of only 7.5 cm, this mirror will be extremely light.

Capacitive edge sensors will bridge the 3-mm gaps between adjacent hexagons. These, together with a system of laser tilt sensors, will keep the actuator system informed of any changes in the mirror's figure. The computer-controlled servomechanism system would be constantly active, eliminating the need for a massive, rigid support structure.

Shaping the off-axis segments of this $f/1.75$ parabolic mirror is especially tricky, because they lack the axial symmetry that simplifies most optical grinding. To this end, Nelson, Jacob Lubliner and their LBL colleagues have developed a novel "stressed mirror polishing" technique. One holds the blank bent in a particular shape while grinding and polishing a spherical surface. When the glass is let go after polishing, it relaxes into the desired off-axis parabolic shape. It turns out that one can produce any desired fourth-order surface one likes by twisting the glass appropriately before grinding. Nelson told us that he was encouraged to use this approach by Luis Alvarez (Berkeley), who had used a similar trick to make ellipsoidal mirrors.

Two full-scale prototype segments for the 10-meter mirror are now being constructed at Kitt Peak Observatory, as part of the consortium effort looking toward the 15-meter National Telescope. The capacitive sensors are currently being developed and tested at LBL by Nelson and Gabor. Testing of a prototype module of mirror segments, sensors and actuators by laser interferometry will be completed next year. To assure coherent infrared images, the segments will have to remain aligned to sub-micron accuracy, Faber told us.

With the aid of modern computerized structural analysis, Nelson and a group of Berkeley engineers have designed an extraordinarily light supporting structure for the 10-meter mirror. The moving weight of the telescope is expected to be only 150 tons, less than one-third that of the Mt. Palomar 5-meter instrument. Cost estimates have not been completed. The University of California is also looking for



Atmospheric jitter of two star images 50 arc-seconds apart shows good correlation when viewed by a single MMT mirror. One hopes to reduce atmospheric blurring in the MMT by continually adjusting mirror orientations in response to jitter of nearby field stars.

private benefactors. A possible site for the segmented-mirror telescope is Mauna Kea, a 14 000-ft peak on the island of Hawaii.

University of Arizona. Roger Angel and his colleagues at Arizona's Steward Observatory advocate that the 15-meter National Telescope ought to be a scaled-up version of the 4.5-meter MMT. The six individual mirrors of such an instrument would be 5 to 7 meters in diameter. The mirrors of the present MMT are honeycombed, to make them light while preserving rigidity. But they are made of fused silica, which costs about \$50 a pound.

In an attempt to reduce drastically the cost of such a National Telescope, Angel's group has already produced a prototype honeycombed Pyrex mirror two feet in diameter, and NSF is funding the fabrication of a 2-meter mirror. Pyrex costs only \$1.50 per pound, but its thermal expansion coefficient is significantly larger than those of the expensive optical glasses. A ventilated, honeycombed structure should however get around this problem, Angel argues, reducing the thermal inertia of the mirror sufficiently to allow it to come quickly into equilibrium with the air around it. The Soviet 6-meter mirror is made of Pyrex. But the high thermal inertia resulting from its great thickness prevents it from coming to thermal equilibrium during the diurnal temperature cycle. In a recent paper in *Soviet Astronomy*,¹ L. I. Snezhko of the 6-meter group points this out as the main source of the difficulties that have plagued the Soviet telescope.

Angel claims that because of their low thermal inertia, honeycombed Py-

rex mirrors would perform even better than solid mirrors of zero expansion coefficient. Studies by Nick Woolf at the Steward Observatory have shown that, under favorable atmospheric conditions, resolution at visible wavelengths is limited not by atmospheric turbulence far away, but by convection currents at the mirror's surface when its temperature differs by as little as 1°C from the surrounding air.

Two years of experience with the MMT has suggested to the Arizona group a technique for significantly reducing the blurring effects of atmospheric fluctuations when one has the flexibility inherent in a multiple-mirror instrument. It occurred to Woolf and Angel that one could correct for much of the atmosphere-induced jiggling observed by each of the six primary mirrors before combining their images at the final focus. Large-scale atmospheric turbulence produces jiggles with a typical frequency of about 1 Hz—slow enough to let a feedback mechanism make compensatory adjustments of the individual mirror orientations. Information about the relative distortions of the six preliminary images would come from field stars in the image. With modern electronic detectors, Angel told us, 16th magnitude stars are bright enough to do the trick. Such faint stars are so abundant that one would almost always be found sufficiently close to the object under observation. Angel and Woolf expect to have such a system functioning at the MMT by the end of this year, reducing atmospheric blurring by more than 20%.

The Space Telescope, scheduled for launch in 1985 (PHYSICS TODAY, March 1981, page 59), must of course also be counted among the new technology telescopes, despite its modest aperture size (2.4 meters). Unhindered by atmosphere, it will offer two orders of magnitude better spatial resolution at visible wavelengths than ground-based instruments, and it will extend much farther into the ultraviolet. But Harlan Smith, chairman of Associated Universities for Research in Astronomy, and a longtime advocate of the Space Telescope, stresses that the Space Telescope will not render large ground-based telescopes obsolete. The new discoveries expected from the Space Telescope will, he argues, lengthen the already overlong queues waiting for observing time on the earthbound instruments.

Despite its higher spatial resolution, the limited collecting area of the Space Telescope will make it 10 to 40 times slower than the proposed ground-based giants at gathering light from all but the faintest sources. The data-taking rate is particularly important for spectroscopy. Because the Space Telescope

will also cost an order of magnitude more, Smith points out that each photon collected in space will cost a hundred times more than those gathered on the ground.

—BMS

Reference

1. L. I. Snezhko, *Soviet Astronomy* **24**, 498 (1981).

Cornell plans 100-GeV e^+e^- ring

Cornell University is hoping to build an electron-positron storage ring with 50 GeV in each beam. With superconducting rf cavities, for a given energy the diameter of the ring can be substantially reduced as can the power bill. If the research and development continues to go well, Cornell plans to submit a proposal to the National Science Foundation next year. The estimated cost is \$200 million in 1981 dollars. NSF has supported Cornell's previous accelerators, the 12-GeV electron synchrotron and its successor, the Cornell Electron Storage Ring, CESR, with 8-GeV electrons colliding with 8-GeV positrons.

Meanwhile, last year SLAC submitted a proposal to the Department of Energy to build a new type of collider—the SLAC Linear Collider (PHYSICS TODAY, January 1980, page 19) for electrons and positrons; the SLC would also have a center-of-mass energy of 100 GeV.

This June, at its meeting, the CERN Council decided to go ahead with the procedure for approval of Phase I of the LEP Electron/Positron Collider Project, which would also have 50-GeV electrons colliding with 50-GeV positrons. In its final phase, the LEP project would have 130 GeV per beam (PHYSICS TODAY, July 1980, page 19).

The Japanese government has ap-

proved an e^+e^- storage ring, Tristan, which will have 30 GeV in each beam; construction has already begun at the KEK laboratory in Tsukuba, an hour's drive from Tokyo.

These new e^+e^- devices would all exceed the center-of-mass energy available at PETRA (at the DESY laboratory in Hamburg), which has 37 GeV center-of-mass. However, PETRA will have its center-of-mass energy raised to 45 GeV two years from now. At present, the PEP e^+e^- storage ring has 29 GeV center-of-mass energy but may run at 35 GeV this fall.

Cornell design. Last year Cornell produced a paper design for an e^+e^- storage ring, CESR II, and presented the idea to a HEPAP subpanel (headed by Sam Trieman) that met at Woods Hole June 1980. The subpanel encouraged Cornell to continue its research and development program for superconducting cavities and to develop an accelerator design.

The basic problem with circular electron devices is synchrotron radiation. The energy loss per revolution varies as the fourth power of beam energy divided by radius. In the past, storage rings were designed to make the accelerating voltage economically and to make the radius big. If Cornell did not use superconducting cavities in CESR II, the

radius of the ring would have to be twice as large.

The cost of the storage ring is the sum of the fixed cost (experimental halls, injector with beam transport and site preparation) and the cost of making magnets, controls, vacuum and supports (which is fairly constant per running foot and hence the bigger the radius, the higher the cost) plus the cost for the required accelerating voltage. As Maury Tigner of Cornell explains, "cheap volts give less magnets and tunnels"; so superconducting cavities are desirable to minimize cost.

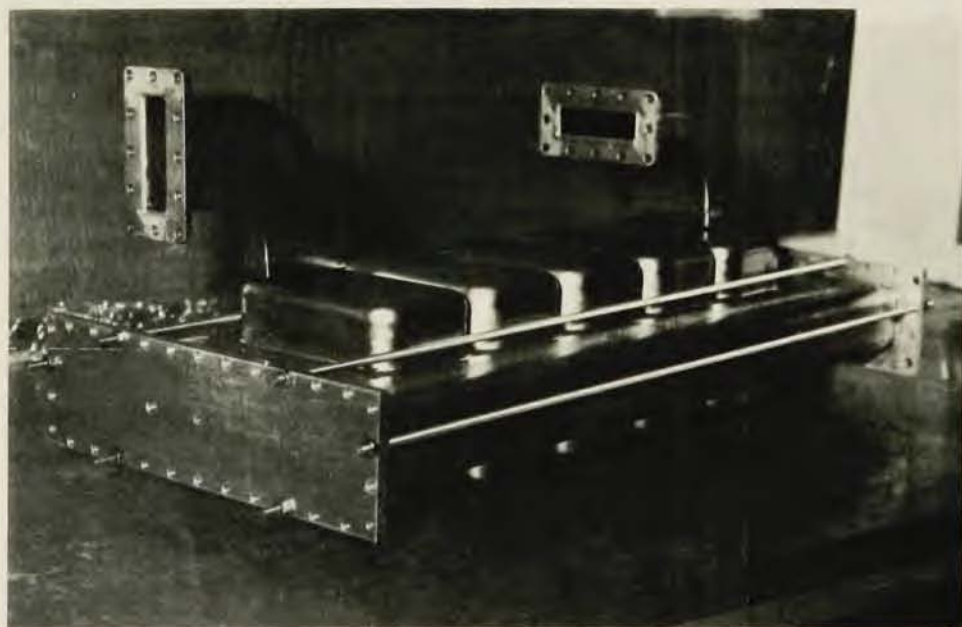
Cornell has had a small experimental program on superconducting cavities for about ten years. Originally the group expected to use them in a synchrotron. They developed a mass-production technology for producing niobium superconducting cavities and fittings (waveguides, elbows, directional couplers and vacuum windows). A two-foot section was tested at the old 12-GeV electron synchrotron in 1976. By that time, Maury Tigner told us, electron synchrotrons had "become a drug on the market," and Cornell was converting its synchrotron into CESR.

The superconducting cavities developed for synchrotron use were S band, 10-cm wavelength, and were not suitable for the 500-MHz frequency of CESR.

CESR II would operate at 1500 MHz, L band; so the superconducting cavities need to be larger in all dimensions—10-cm long and 15 cm transverse to the beam. The niobium cavities are shaped like two muffin tins, one above and one below the median plane, along which the beam passes.

The current CESR design calls for a tunnel 5485 meters in circumference with a 10-foot inside diameter and eight straight sections. Four of the straight sections would have accelerating stations and four would be interaction regions. Within each of the accelerating stations would be 45 or 50 10-cm superconducting chambers, then a 1-meter focusing quadrupole (at room temperature), then more superconducting chambers.

One of the problems in the use of such cavities in storage rings is caused by what is known as higher-mode loss. As Boyce McDaniel, director, explained, when the short (compared to the rf wavelength), intense bunch in the storage ring passes through the superconducting cavity, the effect is like striking a gong, and higher frequency modes are excited in the cavity. If this energy is absorbed in the cavities, they would go normal, unless the refrigerator were huge. The energy from higher-order modes is removed by cutting longitudinal and transverse slots in some of the cups, thus transferring the higher-order-mode energy to



Prototype superconducting rf cavity for CESR II electron-positron storage ring. Beam traverses five-cell muffin-tin cavity longitudinally between top and bottom muffin-tins. Cavity is shown closed off with end plates. Horns at top are wave guides that couple to the higher-harmonic-mode excitations, conducting the energy away from the cryostat.