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ASTRONOMICAL TELESCOPES: A NEW GENERATION

After a hiatus of more than a decade, astronomers are poised to build a new generation of large ground-based telescopes. With their larger areas, rigorous imaging specifications, and modern control systems, they will allow astronomers to extend traditional astronomical observations to fainter, more distant objects, and will permit fundamentally novel investigations from the ground. New technologies, such as segmented mirrors, active figure control, "spin-cast" mirrors, and multiple mirrors, are being applied to extend the size of today's largest single-mirror telescope (6 m in diameter) and to combine the light from smaller individual mirrors to create effective apertures up to 16 m in diameter. The Johns Hopkins University, in collaboration with the Carnegie Institution of Washington and the University of Arizona, is designing an 8-m telescope using a spin-cast mirror.

INTRODUCTION

A Dutch spectacle-maker, Hans Lippershey, is credited with the invention of the telescope in 1608.[1] Galileo subsequently heard of Lippershey's achievement, made several improved telescopes of his own, and used them to discover the spots on the Sun, the lunar mountains, the phases of Venus, and the moons of Jupiter. In 1611, at a banquet in his honor near Rome, his instrument was christened "telescope." Although his discoveries initially promoted Galileo's career, the last two provided support for the Copernican theory and eventually led to Galileo's trial for heresy.

Progress on telescopes was slow during the next hundred years. The presence of chromatic aberrations (imperfections in image quality caused by variation with wavelength in the index of refraction of glass) limited the usefulness of the instruments. Telescopes made of simple lenses were built with diameters up to 20 cm, but they could be as long as 46 m.

Chromatic aberration can be greatly reduced by the achromat, which combines two glasses with different dispersions into a lens to give focusing without dispersion. The two-element achromat was invented by Chester Hall in 1733 (and reinvented and patented by John Dollond in 1758)[2] and led to the development of the modern refractor. The best telescopes of the nineteenth century were refractors, but lens diameters eventually were limited to 1 m by the difficulty of preventing the glass from distorting under its own weight, by constraints on the uniformity of the glass, and by developments in the technology of reflecting telescopes.

Defeated by chromatic aberration, Newton gave up all hope of perfecting Galileo's form of telescope and turned his attention to making concave mirrors that reflected light to a focus without dispersing it. Newton's first reflecting telescope, invented 60 years after the refractor, was 15 cm long, with a mirror 2.5 cm in diameter. So successful was the performance of this pygmy that he made a larger one, now held by the Royal Society

of London. All modern large telescopes can trace their ancestry to Newton's discovery. Reflecting telescopes have several advantages when compared with refractors; unlike refractors, they do not suffer from chromatic aberration, and the mirrors are much easier to support than lenses because the entire back surface is accessible.

Reflecting telescopes increased in diameter. In 1789, Sir William Herschel built a 122-cm telescope, and by 1845, Lord Rosse had made one 183 cm in diameter. All the early reflectors had mirrors of speculum, an alloy of copper and tin. Speculum, however, is an imperfect material for a telescope because, like most metals, it is harder to figure and polish than glass and has a high thermal expansion coefficient, which distorts the mirror once installed in the telescope. It was not until 1856 that a chemical method for silvering glass was first developed. This technological advancement, a prerequisite for the big glass reflectors of the first half of the twentieth century, culminated in 1948 with the dedication of the 5-m Hale Telescope at Mt. Palomar in California.

The Hale Telescope represented a watershed in telescope construction. It weighs 450,000 kg and floats on oil bearings. The f number (focal ratio), the ratio between the focal length of the primary mirror and its diameter, is 3.3, smaller than for earlier reflectors.[3] The focal ratio establishes the length of the telescope and the size of the dome housing it. The Hale dome is 41 m in diameter and 40 m high.

Construction of the telescope, begun in 1927, was lengthy, expensive, and technically difficult. The telescope was not used regularly until 1949 (demonstrating that our frustration over the time needed to build instruments like the Hubble Space Telescope is not without precedent). The principal problem was the primary mirror: $600,000 was spent in a futile attempt to make it from fused quartz. Even after switching to borosilicate glass (Pyrex), the first attempt to cast the mirror failed. The cost was $6.5 million ($6 million came from the

Rockefeller Foundation), a considerable amount in the 1940s. Because of these difficulties, the 5-m telescope held the size record for almost three decades, until a 6-m telescope was constructed in Russia in 1974. That telescope, which also uses borosilicate glass, is affected by diurnal temperature variations; as the temperature falls at night, the mirror cools, contracts, and distorts. With such a massive piece of glass, the image quality can be degraded for the entire night.[4]

The large telescopes of the 1970s and 1980s were built with diameters of about 4 m (see Table 1). The focal ratio of the primary mirror is significant for comparison with the new generation of large telescopes. The values range from 2.5 to 5.0 (average, 3.25), which, as we will see, is considerably higher than the focal ratios planned for the new telescopes.

The principal difference between the new telescopes and the 5- and 6-m telescopes is the use of low-expansion glasses and vitreous ceramics (e.g., Cervit or Zerodur) for the main mirror. Low-expansion glass makes larger temperature gradients tolerable in the polishing process and during use. The surface of a good telescope has a figure accurate to 5% of a wavelength (25 nm), a precision very difficult to maintain if temperature gradients exist within the glass.

Although sizes did not increase, there were significant developments in telescope guidance and control, detectors and instruments, and site selection. Charge-coupled devices have enabled astronomers to use more efficiently the photons delivered to the focal plane. These devices, with quantum efficiencies of 50%, have largely replaced photographic film, which has an efficiency of 2% at most. Thus, the effective diameter of the Hale Telescope is about five times what it was in 1950.

The cost of telescopes was believed to be predictable, on the basis of an extrapolation of adjusted dollars for the instruments up to 5 m. The cost followed a power law, $S = 0.37D^{2.58}$, where D is the diameter in meters and S is the inflation-adjusted cost in millions of dollars.[5] Larger sizes could be shown to be prohibitively expensive; an 8-m telescope would cost about $80 million and a 16-m telescope would cost $473 million. Few dissented from this conclusion.

The Multiple-Mirror Telescope (MMT), begun in the early 1970s and dedicated in 1979, was an attempt to supply a large collecting area at a relatively low cost. Resulting from a collaboration between the University of Arizona and the Smithsonian Astrophysical Observatory, the MMT has six 1.8-m-diameter primaries mounted on the same structure in a hexagonal array. A central, smaller mirror is used for guidance. Computer control combines the images from all six mirrors into a single focus. The aperture is equivalent to a single 4.5-m-diameter mirror.

In the 1990s, a new generation of telescopes will be constructed. Single-mirror telescopes with diameters of 8 to 10 m and MMTs with diameters up to 16 m will be built by various consortia, including one in which The Johns Hopkins University is cooperating. The designs for these telescopes will be very different from the Hale Telescope design. The equatorial mount has already been replaced by the altitude–azimuth drive. The monolithic primary mirror, with a thickness of 15% of its diameter, is being replaced by multiple mirrors, segmented primaries, thin deformable mirrors, and light-weighted spin-cast mirrors. Focal ratios as fast as $f/1.2$ are contemplated to keep the telescopes light and the domes small, resulting in lower cost. Several new technologies are being used to construct the telescopes that will serve astronomers well into the next century. We will review these technical developments, and the major telescope projects they are making possible, in this article.

Table 1—The world's largest optical telescopes.

Location	Ownership	Altitude (m)	Diameter of primary (m)	Year
Mt. Pastoukhow, Caucasus, USSR	USSR	2050	6.05	1974
Mt. Palomar, Calif., USA	USA	1800	5.08	1949
Mt. Hopkins, Ariz., USA	USA	2600	4.60*	1979
La Palma, Canary Islands, Spain	UK	2400	4.20	1986
Kitt Peak, Ariz., USA	USA	2100	4.01	1973
Cerro Tololo, Chile	USA	2500	4.01	1974
Siding Spring, New South Wales, Australia	UK–Australia	1200	3.88	1974
Mauna Kea, Hawaii, USA	UK	4200	3.80	1979
Mauna Kea, Hawaii, USA	Canada–France–USA	4200	3.60	1979
La Silla, Chile	Europe	2450	3.57	1976
Calar Alto, Spain	FRG–Spain	2160	3.50	1979
Mt. Hamilton, Calif., USA	USA	1300	3.05	1959
Mauna Kea, Hawaii, USA	USA	4200	3.00	1979

*Multiple-mirror-telescope equivalent light-collecting area.

SCIENTIFIC RATIONALE

Several factors determine the usefulness of any telescope. The main reason to build a larger telescope is to increase the amount of light delivered to the detector. An 8-m telescope has 4 times the light-gathering power of a 4-m telescope and 11 times that of the 2.4-m Hubble Space Telescope. For ground-based telescopes alone, the increased area of an 8-m telescope compared with a 4-m telescope implies that one can observe four times as many objects on the same number of nights or see objects two to four times as faint as one could before. An 8-m telescope will deliver about 0.7 photons$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$Å^{-1} from a 22nd-magnitude star. Consequently, medium-resolution ($\lambda/\Delta\lambda = 1000$) spectroscopy of 23rd-magnitude objects should be possible, as should low-resolution ($\lambda/\Delta\lambda = 100$) spectroscopy of 25th-magnitude objects. (Stellar brightness is measured in magnitudes on a logarithmic scale in which a difference of one magnitude repsents a brightness difference of $\sqrt[5]{100}$ or 2.512. Stars visible to the naked eye range in magnitude from -1 to 5 or 6.)

Another element in determining the usefulness of a telescope is the quality of the images it delivers. The sky is bright compared with the faint objects one would study with an 8-m telescope. The sky background at a site uncontaminated by man-made light is equivalent to one 21.25th-magnitude star per square arc second. Therefore, for observations of stars, an 8-m telescope regularly delivering images of 0.5″ to the focal plane is equivalent to a 16-m telescope delivering images of 1″.

TELESCOPE DESIGN AND CONSTRUCTION

The telescope builder faces assorted interconnected optical, mechanical, and environmental problems. The Johns Hopkins University is involved in the design of an $f/1.4$ 8-m telescope (the Magellan Project), which we will use to illustrate the techniques being applied to overcome those design difficulties.

Optical Design

The basics of large optical telescopes are straightforward. Figure 1 shows a schematic of the simplest concept on which all ground-based and most space telescopes are founded. The large primary mirror collects light from an object at infinity and images it at the prime focus at a distance f, one-half the mirror's radius of curvature, from the mirror. The ratio f/D_p (where D_p is the diameter of the primary) is the focal ratio or f number. The radius of curvature r is an important design parameter of the telescope, because it determines the sag of the mirror δz or the depth of the bowl, given approximately by $\delta z = D_p/(16\cdot f)$ number. For an $f/1.4$ 8-m mirror, the sag will be 0.36 m, which requires the grinding away of a large amount of glass if one begins with a flat blank. The sag of the Hale Telescope was only one-quarter this value, yet it required the removal of 4500 kg of glass to get the rough blank. To simplify telescope construction, all modern techniques for manufacturing mirrors involve the generation of a blank with a shape as close as possible to the final figure of the mirror.

The shape of the primary mirror is parabolic, a shape yielding a perfect axial image at the prime focus. The departure from sphericity is a further complication in manufacturing the mirror. The separation between the rims of an $f/1.4$ 8-m spherical mirror and a parabolic mirror of identical vertex radii is only 0.29 mm, a small value, but sufficient to produce polishing difficulties. For comparison, the 5-m Hale mirror would have a separation of only 0.014 mm. Polishing spherical surfaces is relatively easy, because when two rigid bodies are rubbed against each other with an abrasive between them, a spherical boundary tends to form. For a weak parabola, such as the Hale mirror, where the departure from a sphere is only a few tens of wavelengths, localized work with small tools puts the aspheric component on an initial sphere. With a strong aspheric, however, the radii along the mirror radius and along a direction perpendic-
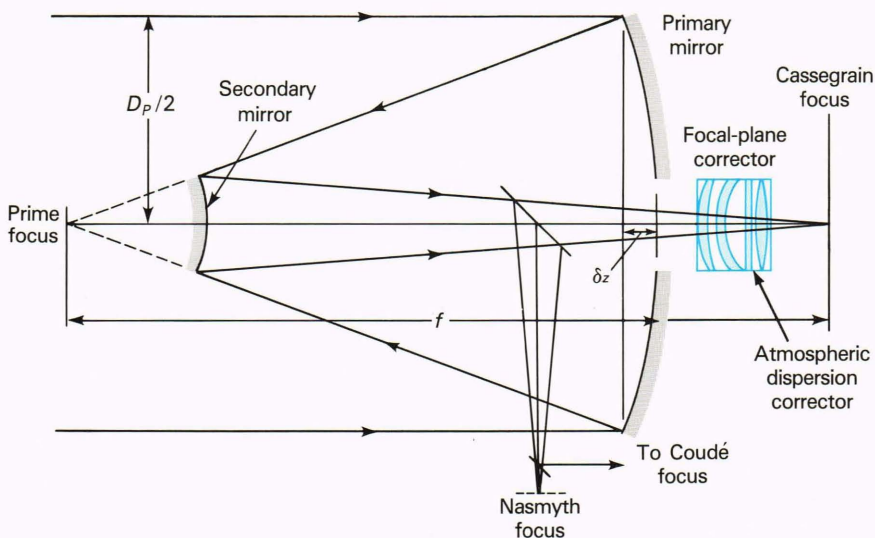

Figure 1—The basic optical telescope has two mirrors, a large concave primary and a smaller convex secondary, which produce an image at the Cassegrain focus. A multilens focal-plane corrector is used to correct the curvature of the focal plane and reduce other aberrations. It may also include thin prisms to correct for atmospheric color dispersion. Additional mirrors are used to reflect the beam to other foci, such as the Nasmyth (to the side of the telescope) or the Coudé (below the telescope). A key feature of the mirror is the sag, δz, which is the depth of the mirror dish.

ular to it differ by too much to make this approach practical. Also, the difference is variable along the radius. Although it is easier to polish mirrors with high focal ratios, the overall size of the telescope, the dome enclosing it, and therefore the cost, are also set by this primary *f* number, so there is a strong motivation toward small focal ratios.

Occasionally, the prime focus is used as the location for scientific instruments. For example, the 5-m Hale Telescope has an observing cage at this focus, and the Hopkins Ultraviolet Telescope locates its spectrometer here. Because the off-axis aberrations are large and the location is not easily accessible, this configuration is not usually preferred. The most common configuration is to use a convex secondary mirror, which changes the *f* number of the beam of light and produces a magnified image at the more convenient Cassegrain focus behind the primary mirror. A secondary mirror with a hyperboloidal figure produces an abberation-free axial image. The placement and radius of curvature of the secondary mirror determine the exact position of the focus and the focal-plane scale (i.e., the ratio of the angular separation of two objects in the sky to their linear separation in the focal plane of the telescope). For wide-field applications, one desires as fast a final *f* number as possible, since even at *f*/6 a 40′ field subtends 0.6 m, making it difficult to image the entire field with modern detectors. The Magellan Project is planning an *f*/6 optical Cassegrain focus, with an *f*/1.4 8-m primary. The secondary mirror, with a diameter of 1.9 m on the Magellan telescope, is also aspheric (the Magellan secondary differs from the best-fit sphere by 0.25 mm); that, together with the convex shape, makes it challenging to manufacture and test.

Any instruments using the Cassegrain focus are attached to the telescope and move with it. Two other foci frequently used are the Nasmyth focus, in which a tertiary mirror reflects the beam out the side of the telescope along the altitude axis, and the Coudé focus, which uses additional reflections to send the beam below the telescope. Both locations are convenient, since the instrument can be fixed and does not change its orientation as the telescope tracks a star. The image plane will rotate, however. The Nasmyth focus is used on telescopes with altitude–azimuth mounts, as shown in Fig. 2a, where the beam is reflected along the altitude axis, which is always horizontal. The advantage is that the instrument can be built on a platform whose orientation with respect to gravity does not change as the telescope moves. Thus, flexure of a massive instrument is not a serious problem. Also, there are two Nasmyth foci on opposite sides of the telescope so that one can be dedicated to a permanently mounted instrument (e.g., a high-resolution spectrograph), while instruments are switched regularly at the other focus. The basic disadvantages of the Nasmyth focus are that it requires an additional reflection and that the focal ratio must be relatively large, typically greater than *f*/12.

A telescope using a parabola–hyperbola combination is free of spherical aberration, and the mirrors have no
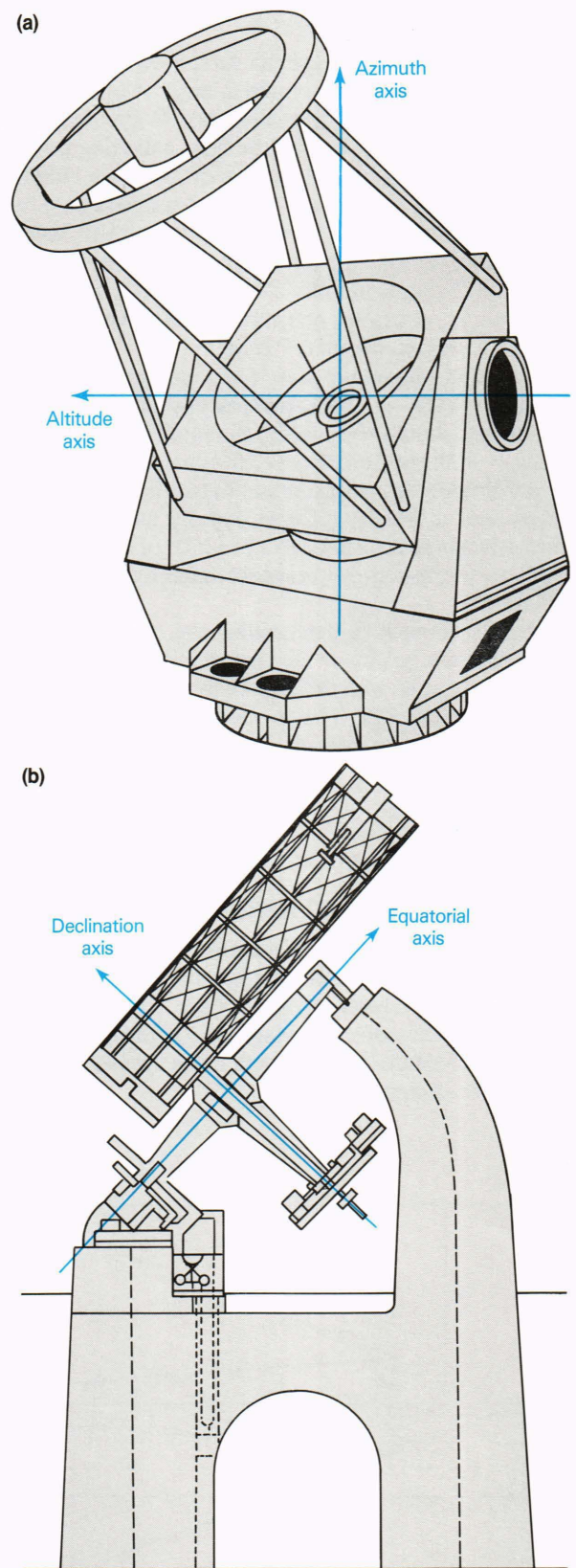
Figure 2—Modern telescopes now use the altitude–azimuth mount (a) in preference to the older equatorial mount (b). In exchange for greater drive complexity (two drive axes with non-uniform rates), the altitude–azimuth mount offers a simpler structural support for the telescope, two Nasmyth foci, and fixed axes—one horizontal and one vertical—for the bearings.

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chromatic aberration. Off-axis, however, it suffers from coma, astigmatism, and field curvature. These are reduced by changing the primary mirror to a hyperbola, resulting in a configuration called a Ritchey–Chretien, and by using a focal-plane corrector, which is an optical system comprising three or more lenses located some distance ahead of the telescope's focal plane. Correctors have been designed for use with Ritchey–Chretien telescopes, and they yield good imagery up to 20' off axis.

Mechanical Design

The mechanical and structural design of a large telescope is subject to extremely tight tolerances and severe requirements. The structure must hold the relative positions of the primary and secondary mirrors to within a fraction of a millimeter to avoid excessive aberrations. Typically, for an 8-m telescope, the separation must be controlled to within 0.05 mm, and the angle must not change by more than 0.2'. These tolerances are maintained by a combination of basic structural stiffness and active control. In an 8-m telescope, the mirrors are separated by 8 to 9 m and are supported in a structure that moves, is subjected to thermal changes, and may not be protected from wind loading. Various materials have been used for the telescope structure, but steel, despite its significant thermal deformations, is normally used.

Dynamically, the telescope must be driven so that it can point to a location in the sky with an accuracy of 1″ and then track that point with an accuracy an order of magnitude greater. The mass that must be moved with such precision weighs up to several hundred metric tons. All large telescopes of the early twentieth century used the equatorial mount (as shown in Fig. 2b), which is relatively simple because uniform rotation about one axis (the polar axis aligned along the rotation axis of Earth) allows the telescope to follow an object as it moves across the sky. The other axis allows the telescope to move in declination (latitude).

One difficulty with the equatorial mount is that changes in the direction of the gravity vector are complex. In the last decade, most large telescopes (e.g., the Herschel 4-m telescope just commissioned at La Palma in the Canary Islands) have been built with altitude–azimuth mounts in which one axis, the altitude axis, points toward the local vertical, while the other rotates horizontally with the telescope. To track an object, the telescope must be driven along both the altitude and azimuth axes at rates that are not uniform. Improvements in servomechanisms, including the use of autoguiders and the availability of inexpensive and powerful microprocessors, have now made that possible. Another disadvantage of the altitude–azimuth mount is that the image of an extended object such as a galaxy rotates in the focal plane as the telescope tracks, necessitating some compensating rotation. The altitude–azimuth mount has one great advantage, however: the gravity vector is confined to a plane with respect to the telescope. Thus, because there is no change in the orientation of the axes of the drive bearings, and the telescope tube and mirrors rotate about a horizontal axis only, the structural design and the support of the mirror in its cell are considerably simplified.

Another advantage is the provision of two Nasmyth foci at the sides of the telescope, where instruments can be mounted in an environment in which gravity is constant.

Supporting the primary mirror has always been a problem. The primary can be made so thick and stiff that it cannot distort under its own weight, since its orientation changes from the horizontal to close to the vertical, or it can be supported so that the forces on its rear surface vary with orientation. In the past, a combination of these techniques has been used. With the new, lighter, thin mirrors, however, the figure of the mirror may have to be variable, as is planned for some of the new telescopes.

The dome housing the telescope has two conflicting requirements: it must protect the telescope from the environment, particularly wind, but it must allow the telescope to reach thermal equilibrium with the outside temperature. The traditional approach has been to bury the telescope inside a dome with a slit to allow it to view the sky. This produces "dome seeing" from the internal temperature variations, creating air movements that degrade image quality. Forced-air ventilation can equalize the internal and external temperatures, but not as effectively as an open dome. Protecting the telescope requires a large dome, with its consequent effect on cost. An alternative is the use of more open domes. The dome of the MMT leaves the telescope well exposed when it is open. With other telescopes, the dome may be eliminated entirely when the telescope is in use. Exposed telescopes are subject to greater wind loading and therefore require stiffer structures.

ATMOSPHERIC PROBLEMS

The major telescopes of the world are concentrated in a few areas. Within the United States, California and the Southwest have been the locations of choice for observatories. Hawaii is now a more popular location. The mountaintops in Chile, along the western coast of South America, are the sites for observatories of many nations and will be the site for the Magellan Project telescope. The single parameter having the greatest influence on site selection is the size of the image of a star at the telescope's focal plane. The angular diameter of a star is always too small to be resolved by any telescope, since its diameter is always well below the diffraction disk of the telescope. For a large telescope, this disk is much smaller than the image diameter caused by atmospheric "seeing" (i.e., a broadening of the stellar image caused by atmospheric turbulence).

Seeing results from changes in the refractive index of the air, produced by atmospheric turbulence. The two main causes of the turbulence are convection (the heating of air by the warmer surface, followed by the rising and expansion of the warm air and its replacement by cold air) and high winds that cause turbulence by wind shear. At the best sites, the stellar image diameter is as small as 0.5″ for 50% of the nights. This image diameter decreases into the infrared, so that the diffraction limit of the telescope optics, rather than the atmosphere, dominates above a wavelength of a few microns. The

seeing pattern is continuously changing, with a turbulence–coherence time of 40 to 50 ms.

Considerable effort has been applied to finding sites where the seeing is good. The best sites have permanent temperature inversions for most of the year, which prevent the convective mixing, and laminar airflow in the prevailing wind. They also must have a dark sky and little precipitable water above. California and Chile meet those requirements. The prevailing wind is from the west, so no mountains intervene to perturb the laminar flow after its passage across the Pacific. The cold coastal waters also maintain the low humidity and the temperature inversion. Chile also has a sky that is not polluted by light from human activities. Consequently, the very best telescopes in the world today, at optimum sites and under optimum weather conditions, can deliver images to the focal plane with stellar image diameters of 0.5″.

NEW TELESCOPES,
NEW TECHNOLOGIES

Several technical approaches are being considered in the race to produce telescopes of larger diameter. Each approach has advantages and disadvantages, advocates and detractors, and it is not apparent what the future holds. In the following discussion, we outline the three basic approaches being actively followed today, and present some potential advantages and technical challenges of each. Briefly, the three approaches are as follows:

1. To use a new type of casting process to build large, light-weighted borosilicate glass mirrors, with conventional diameter-to-thickness ratios.
2. To assemble a large mirror from smaller segments and actively control the position of the segments.
3. To cast a thin meniscus mirror and actively control the surface figure on the telescope.

Spin-Cast Telescopes

Conventional primary mirrors on large telescopes are solid blocks of glass with diameter-to-thickness ratios of 7 to 10. Such mirrors, once built, are sturdy and relatively easy to support because they are stiff. They must be made of expensive ultralow-expansion glass because they have extremely long thermal time constants, and thermal distortions would prevent them from delivering 0.25″ images to the focal plane. As this type of technology is applied to larger and larger mirrors, it becomes increasingly difficult to manufacture the blank, and the moving weight scales as D^3. Using light weighting, a matrix of cavities on the mirror's rear surface reduces the weight but retains the rigidity without the expense and challenge of an active figure control system. Light weighting has been used on several telescopes, including the 5-m Hale mirror, which has 8- to 13-cm-thick ribs,[3] and the Hubble Space Telescope. Light weighting with 1.5- to 2.5-cm-thick ribs was the motivation behind the development of the spin casting of blanks, an activity centered at the University of Arizona's Mirror Laboratory under the leadership of Roger Angel.

The physics behind a spin-cast mirror blank is straightforward. Robert W. Wood[6] used the principle as early as 1909 (see the boxed insert). In the Mirror Laboratory, pieces of borosilicate glass are loaded into a mushroom-shaped furnace perched on a large rotating bearing, as shown in Fig. 3. The floor of the furnace is studded with a matrix of refractory material occupying the space that will shape the ribbed structure on the rear surface. The temperature is raised to almost 1200°C to melt the glass, and spinning begins. The combination of gravitational and centrifugal forces shapes the surface of the molten mass of glass into a paraboloid. The revolution rate determines the focal length of the blank; for an *f*/1.4 8-m primary, the oven is spun at 6.3 revolutions per minute, similar to the rate of a carousel. Once the glass has melted completely, the temperature of the furnace is lowered until the glass solidifies, and spinning can stop. After the mirror has cooled (a process taking about one month), the refractory material, which has the consistency of cardboard, is removed with a high-pressure stream of water. The resulting surface should be within 1 mm of the desired parabola. Grinding will reduce this to a few micrometers, followed by polishing to complete the figuring process. The finished mirror will weigh 13,600 kg. For comparison, the Hale 5-m mirror required 10 months for cooling, and 4500 kg of glass had to be ground away to produce the rough dish.[7]

Technological demonstrations of spin casting culminated in 1985 with the casting of two 1.8-m mirrors in a smaller furnace. One mirror is for the Vatican observatory to be built on Mt. Graham in Arizona. More recently, an oven large enough to cast 8-m-diameter mirrors was constructed in the Mirror Laboratory. In April 1988, the first *f*/1.8 3.5-m mirror blank was cast in the Mirror Laboratory. Another 3.5-m mirror was cast in the fall of 1988. This will be followed by an *f*/1 6.5-m mirror that will replace the six mirrors in the MMT (at the same time doubling its collecting area), and then the first 8-m mirror by the end of the decade.

Thermal Control of Spin-Cast Mirrors. Low-expansion vitreous ceramics, such as Cervit and Zerodur, cannot be used for spin casting, because of the way they must be annealed. Therefore, the mirrors being constructed in the Mirror Laboratory use borosilicate glass (Pyrex), which was used successfully on the 5-m Hale, the 3-m Lick, and the 2.2-m Kitt Peak telescopes (and with less success on the 6-m Russian telescope). The significant difference between the American and the Russian telescopes is that the former were constructed as ribbed plates with no section thicker than 10 cm, and the latter is a 60-cm-thick disk with huge thermal inertia.[8] Borosilicate glass has the advantages of low melting point and low cost, but its thermal expansion coefficient is 6 times that of fused silica and 30 times that of ultralow-expansion fused silica and the vitreous ceramics. (Borosilicate glass was abandoned for large-telescope use years ago because of this problem.) It is desirable to keep temperature variations in the blank during polishing below 1°C and to maintain the operating temperature of the mirror's reflecting surface to within 0.2°C of the ambient air temperature. The thin ribs and faceplates of the University of Arizona mirrors will reduce their time

THE FIRST SPINNING-MIRROR TELESCOPE

The accompanying illustration shows the observatory and telescope from which was made the first astronomical observation using a mirror whose figure was formed by a spinning liquid. The work was performed by a famous physicist from The Johns Hopkins University, Robert W. Wood, as a diversion while spending the summer of 1908 on his Long Island farm. The idea that a liquid rotating under the action of gravity would form a paraboloid surface was well known, but it had not been used to make a telescope. A telescope needs a perfect surface, and, as Wood found, considerable effort and ingenuity are required if the rotating liquid is to be ripple-free. (His research was instigated by his search for an effective method of driving a ruling engine for making diffraction gratings, which also requires a perfectly smooth drive.) Wood's mirror consisted of a 51-cm-diameter dish of mercury rotated by a motor from which it was isolated to minimize vibrations. He went to considerable lengths to prevent jarring from the drive mechanism, irregularities in the bearing, and rotational velocity variations. The spinning mirror was placed at the bottom of an old brick well 76 cm in diameter and 4.3 m deep, and a separate shaft was made for access. The "dome" was the cow barn above the well, with a hole knocked in the roof to give a view of the sky. The rotational speed was chosen to give a focal point at the location of the plate holder above ground level. The focus could be held constant to 1 mm. The total cost of the telescope was $200.

Some astronomical observations were made with the device, and Wood was able to separate the components of a double star 5″ apart. Unfortunately, the telescope could not be pointed and could observe only a small strip of sky as Earth's rotation swept it through the small field of view. Although it was never developed for astronomy, the work Wood did in devising a vibration-free drive system was later very significant in his development of ruling engines for the manufacture of diffraction gratings. The idea has recently been revived.* Some Canadians have built and spun mercury mirrors up to 1.65 m in diameter. They show architectural plans for an observatory using a 6-m liquid mirror and argue that it is scientifically useful and technically feasible to build mirrors over 15 m in diameter.

Robert Wood[6] predicted that " ... we may be able to discover some substance which can be fused, rotated, and allowed to solidify while revolving with a constant velocity. Refiguring of the surface would probably be necessary .... If a suitable material can be found, ... I see no rea-
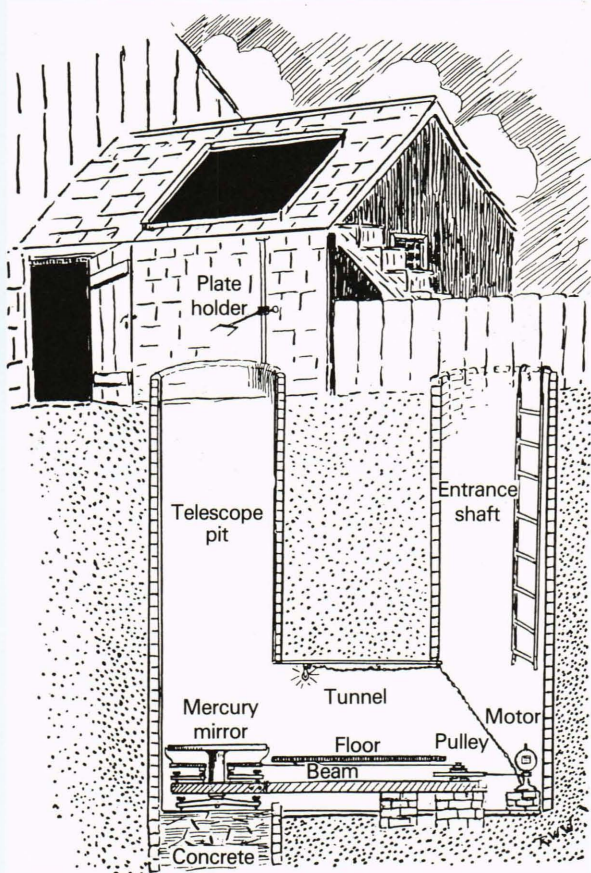
The "observatory" and telescope of Robert W. Wood of The Johns Hopkins University that used a spinning dish of mercury to produce a paraboloidal mirror for astronomical observations.

son why large mirrors cannot be made in this way at very small expense. At all events the method seems well worth trying." Almost 80 years later, Roger Angel of the University of Arizona's Mirror Laboratory is bringing Wood's prediction to life, and the future of American astronomy may well depend on the spin casting of telescope mirrors.

*E. F. Borra, R. Beauchemin, R. Arsenault, and R. Lalande, "Optical Shop Testing of Liquid Mirrors," in *Proc. IAU, Very Large Telescopes, Their Instrumentation and Programs*, Colloquium 79, p. 147 (1984).

constant to only 20 minutes.[9] Also, temperature stability may be achieved by blowing isothermal air, controlled to be at precisely the ambient air temperature, into the honeycomb structure. The final verification of this approach under observing conditions awaits the use of a spin-cast telescope on an operating telescope.

Active Lap Polishing. Another challenge is to polish the mirror and give it the correct curvature. In the final stages of manufacture, material is removed from the surface of the mirror with a rotating polishing tool, known as a lap, that must have almost the same shape as the section of the mirror being polished. With a parabola, however, the radius of curvature of a surface changes depending on the distance from the vertex of the mirror, and it is different in the radial and azimuthal directions. This mismatch between the two directions limits the size of the lap used. The smaller the lap, the longer the time it takes to polish the primary. (Difficulties in polishing

Figure 3—This dramatic sequence of photographs, taken in April 1988, shows the stages in the manufacture of a spin-cast 3.5-m mirror. The furnace (1) in which the mirror is made resembles a carousel. In the sequence, we see the chunks of borosilicate glass being loaded into the furnace (2) and the glass before closing the lid (3). Note the capacity of the furnace to make mirrors with diameters up to 8 m. As the furnace temperature increases from 829°C (4) through 907°C (5) to 960°C (6), the glass melts into a liquid mass. Spinning begins at 1170°C (7), and the glass forms the paraboloidal shape. Note the increased height of the central shape as the dish forms and the rib structure visible through the mirror surface. After cooling has allowed the glass to harden (8), the furnace lid is cracked (9) to show the still red-hot mirror. (Photographs courtesy of Roger Angel, University of Arizona Mirror Laboratory.)

are not specifically associated with spin casting, but rather result from the high curvatures of the new, fast primary mirrors.)

One approach proposed by Roger Angel[10] to solve this problem is to construct a computer-controlled polisher that continuously changes the lap surface to conform to the desired surface curvature. The lap itself consists of a plate that is deformed by wires tensioned around the back of the lap, 24 tensioning cables, and the controlling computer that updates the force pattern every millisecond. For an 8-m mirror, the lap will have a 2-m diameter. The first lap of this type is now being constructed and will be used to polish one of the 1.8-m blanks produced in the Mirror Laboratory's smaller oven, an $f/1$ primary for the Vatican telescope.

Telescopes Based on Spin Casting. A number of telescopes are being planned in anticipation of the successful generation of spin-cast mirrors. Much of the incentive for mirror development in the United States came from the ambitious National New Technology Telescope Project, a square array of four 8-m mirrors on a common mount. Unfortunately, this project is not funded, so the future of a full-size array is uncertain. We present below some continuing projects.

The Magellan Project is a collaboration between the Carnegie Institution of Washington, the University of Arizona, and The Johns Hopkins University and is in the definition/design phase. This will be a single-mirror telescope, 8-m in diameter, using one of the light-weighted spin-cast primaries from the Mirror Laboratory. The telescope will be situated at Las Campanas Observatory, about 350 km north of Santiago, Chile, near La Serena. The primary will be an $f/1.4$ parabola. Observations will take place primarily at the Cassegrain focus, although provisions also are being made to instrument the Nasmyth foci. This is a fairly conventional telescope, which traces its origins back to the earlier 4- and 5-m telescopes. Two basic configurations are planned: a wide-field $f/6.45$ optical focus and an $f/15$ infrared-optimized focus. At $f/6.45$, the secondary mirror will be a 1.8-m hyperboloid. A large fused-silica corrector with an atmospheric dispersion corrector will be needed to deliver 0.25″ images over a 40′-diameter focal plane, the current design goal.

Two basic designs for the telescope structure have been developed: a standard yoke mount supported on a large ring by hydrostatic bearings and a "rocking chair" design, shown in Fig. 4, wherein the telescope is supported on two large wheels. The weight of the rocking chair design is estimated to be about 22,700 kg less than the standard yoke. The rocking chair design also has somewhat higher modal frequencies than the yoke mount. The choice of design has not been finalized.

The Columbus "Two-Shooter" Project (named after the Italian navigator) is a collaboration between the University of Arizona, Ohio State University, the University of Chicago, and the Arcetri Astrophysical Observatory in Italy. The two-shooter consists of two 8-m mirrors mounted side by side on the same structure in a configuration resembling a giant pair of binoculars. The equiv-
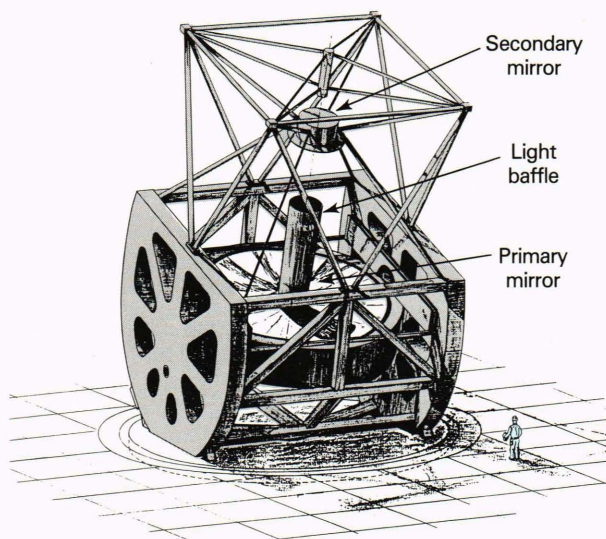

Figure 4—The Magellan Project 8-m telescope. The Johns Hopkins University is a key participant in the Magellan Project and is planning the construction of an 8-m-diameter single-mirror telescope. One possible mount is an altitude–azimuth rocking chair design, which rotates about a vertical azimuth axis, while "wheels" rotate about the altitude axis. The primary mirror is the circle in the center, and the secondary mirror is supported on the open structure. The axial cylinder in the center is a light baffle to prevent direct light from reaching the focal plane.

alent diameter of a single mirror is 11.3 m. This project also is in the definition/design phase. The telescope will be located at Mt. Graham, near Tucson, Ariz., a site approved by act of Congress on the last day of the 1988 session. A variety of foci will be instrumented, including the individual Cassegrain foci of the two primaries. A major impetus behind the Columbus design is the desire to use the telescopes for optical interferometry, thus making it possible to bring light from the two mirrors to a combined focus between the two primaries. With a baseline of 23 m, it should be possible in principle to resolve objects 0.005″ apart with Columbus. With the two primaries on the same structure, the optical path lengths remain the same as a celestial source is tracked across the sky, simplifying the challenge of interferometric observations. The rocking chair design for the Magellan Project may be required for the Columbus Project. The telescope will be within range of remote control from any of the locations of the four cooperating organizations.

Segmented Mirrors

The construction of larger-diameter telescopes using monolithic mirrors presents major problems: there are no existing facilities for casting such large blanks, they are fragile and expensive to repair, and there are logistical problems in transporting them. An alternative approach is to build up a single mirror out of a number of smaller segments.

There are two principal difficulties associated with the development of a large segmented mirror. First, each segment is an off-axis portion of a parabola, which has no axis of symmetry, making conventional polishing tech-

niques very expensive or impossible (for the same reasons that it is impossible for very fast monolithic mirrors). Second, if the segments are to operate as a single diffraction-limited mirror, they must be aligned relative to one another to the surface accuracy of a single mirror, that is, to within a fraction of the wavelength of light. Efforts to solve these problems, led by Jerry Nelson at the University of California, have been underway for over a decade. Since the University of California and the California Institute of Technology are constructing a 10-m segmented mirror to be installed in the Keck Telescope, we will discuss segmented technology in that context.

With an aperture diameter of 10 m, the Keck Telescope is the largest single-mirror telescope under construction or, indeed, planned. Also, of the new generation of large telescopes, it is the first to be fully funded and the closest to completion. Design began in 1977, and construction began in 1985 upon receipt of a $70 million gift from the W. M. Keck Foundation to the California Institute of Technology, which is working with the University of California on the construction of the telescope. "First light" is expected in 1990. Operating funds for the telescope will be provided by the University of California. The telescope is atop Mauna Kea, Hawaii, at an altitude of 4145 m.

The primary mirror comprises 36 hexagonal segments (see Fig. 5) that fit together to produce the 10-m-diameter primary with an *f* number of 1.75. The center segment is missing to allow passage of the beam from the secondary mirror.[11] The telescope has been designed to allow a variety of *f*/15 foci, including Nasmyth, Cassegrain, and bent Cassegrain positions. The secondary mirror is monolithic. Infrared observations will be possible at *f*/25 at a forward Cassegrain focus, located roughly at the same position as the Nasmyth tertiary mirror.

The completed dome of the Keck Telescope is shown in Fig. 6. Its structure is a welded steel space frame supporting the telescope inside an altitude–azimuth mounting. The total moving weight of the telescope, only 245,000 kg, is supported on an azimuthal journal 17 m in diameter on four hydrostatic oil bearings. The lowest resonance frequency for the structure will be about 5 Hz. The size of the dome, an important cost consideration, is less than the sizes of the domes of several telescopes in the 3- to 4-m range.

Each mirror segment of the Keck primary has a maximum dimension of 1.8 m and a thickness of only 7.5 cm, a compromise between the weight and the complexity of supporting the surface so that no distortions can occur. Thus the segments are quite thin, having a diameter-to-thickness ratio of about 24 and an overall ratio for the 10-m aperture of about 133. Thin mirrors are required for the figuring process and have the advantage that the resulting mirror is very light, since each segment weighs only 400 kg. The segments are being fabricated of ultralow-expansion glass (Zerodur), which avoids the thermal expansion problems associated with Pyrex. The segments and their support structure are designed so that the individual segments are easy to re-
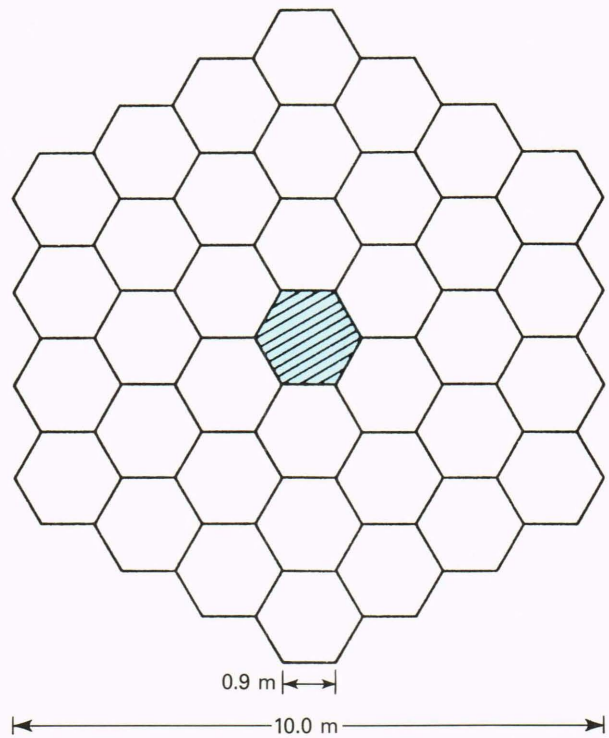

Figure 5—The segmentation geometry of the Keck 10-m primary mirror. The mirror will consist of 36 individually mounted thin mirrors held in precise optical alignment to provide a single effective aperture of approximately 10 m in diameter. The center segment is absent to allow passage of the beam. The entire array is curved into a paraboloid with a focal length of 17.5 m. (From Ref. 11. Reproduced by permission, Keck Observatory.)

move (for aluminizing) and replace. The use of a small coating chamber is a significant advantage of segmented mirrors, since aluminization costs for 8-m monolithic mirrors can constitute up to 20% of the telescope's total cost.

To overcome the problem of polishing the off-axis parabolic mirror segments, a new polishing technique called stressed-mirror polishing was developed. It is complementary to the stressed-lap polishing technique used by the Mirror Laboratory. A full-scale demonstration of stressed-mirror polishing was carried out by the Kitt Peak National Observatory in the early 1980s.

The generation of each mirror segment begins with the casting of a Zerodur blank having a 2-m diameter and a 10-cm thickness. The initially flat blank is machined so that it has about the right meniscus shape, reducing its thickness to 7.6 cm. Twenty-four supports are cemented around the periphery of the blank (which is still circular), the mirror segment is mounted in a fixture as shown in Fig. 7, and external loads are applied by placing weights in the buckets below the radial arms. By calculation and experimentation, the weights have been determined that will deform the surface by an amount corresponding to the difference between the desired shape and a sphere. A spherical surface is then polished onto the blank, the forces are removed, and the mirror relaxes into the desired asymmetric shape. The

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Figure 6—The dome of the Keck Telescope as it looked in July 1988. It is located atop Mauna Kea, Hawaii. The inset is a photograph of a scale model of the telescope. The enormous size is demonstrated by the size of the figures included with the model. (Photographs courtesy of John Gustafson, Calif. Assoc. Res. Astron.)
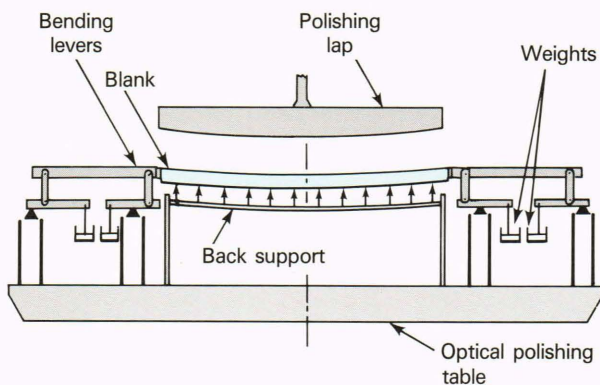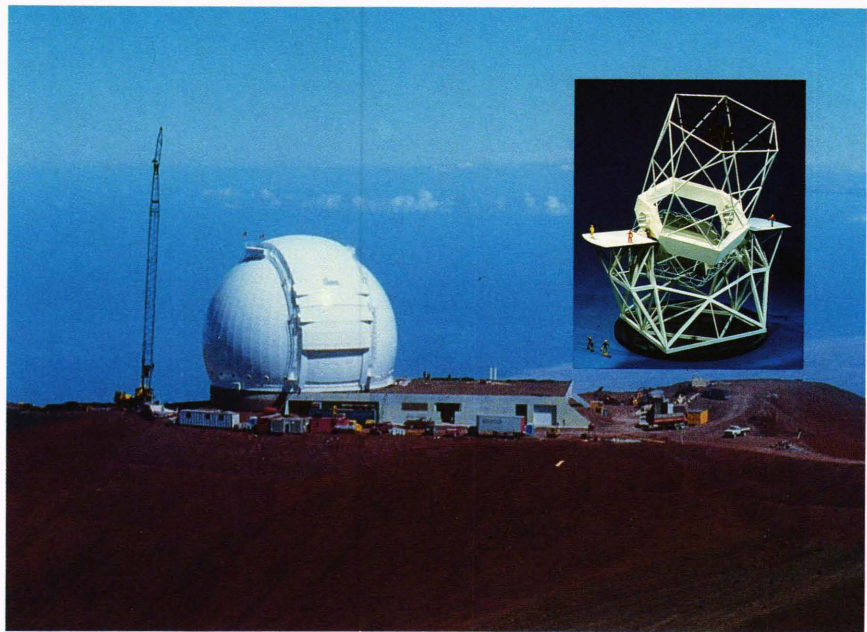

Figure 7—In the configuration used for stressed-mirror polishing, weights are applied to levers bonded to the edge of the glass blank to apply forces and moments around the edge. These weights, in combination with back supports, warp the blank in a controlled manner. A spherical surface is polished onto the blank, the forces are removed, and the blank relaxes into the desired off-axis parabolic shape. (From Ref. 11. Reproduced by permission, Keck Observatory.)

final step is to cut the mirror into a hexagonal shape with a diamond saw.

Completed hexagons must be mounted into and aligned in the telescope to produce a single mirror of optical quality. Each segment is supported by a passive mechanical support system consisting of a combination of axial and radial supports. Axial support is provided by three whiffletrees, each having 12 points of contact with the rear of the blank. This uniform support prevents distortions across the surface of the blank. A radial support post mounts into a cavity machined into the rear of the segment and allows the freedom of movement needed for the active alignment system. The segments are mounted with spacings of a few millimeters between them.

The passive mechanical support system reduces the gravitational deformation across the 10-m mirror to less than 1 mm, and an active segment control system aligns the surfaces to optical tolerances (i.e., to better than 50 nm or 0.1 wavelength). The active control system is shown in Fig. 8. A total of 168 displacement sensors are mounted on the rear surface along the boundaries between segments. These capacitative displacement sensors consist of a sensor drive paddle on one segment that fits within the sensor body of the adjacent segment. The sensor operates at a 10-nm resolution over a range of 1 mm. A control algorithm running on a multiprocessor computer system uses the sensor readings to determine the actuator motions needed to adjust the segment positions to correct for gravitation- and temperature-induced changes. Each segment has three actuators that comprise a motor-driven screw and an optical shaft encoder mounted to the whiffletree supporting the mirror. Significantly, the purpose of the active control system is not to provide the initial alignment of the segments, but to maintain the alignment, which is determined using a bright star.

Monolithic, Thin Meniscus Telescope Mirrors

The third technique for producing a large mirror is to cast or assemble a monolithic, thin meniscus mirror with a shape close to the final figure. The glass with greatest potential is fused silica. Casting an 8-m blank in a single operation is beyond present technology, so techniques for welding small hexagonal pieces have been developed. An 8-m blank is merely an extension of existing technology. A second possible material is Zerodur, which is being used in the Keck Telescope. Assembling a blank from smaller pieces, however, is more complex with Zerodur than with fused silica, since vitreous ceramics can lose their ideal thermal properties if subjected to remelting. Borosilicate glass is a less likely alternative;
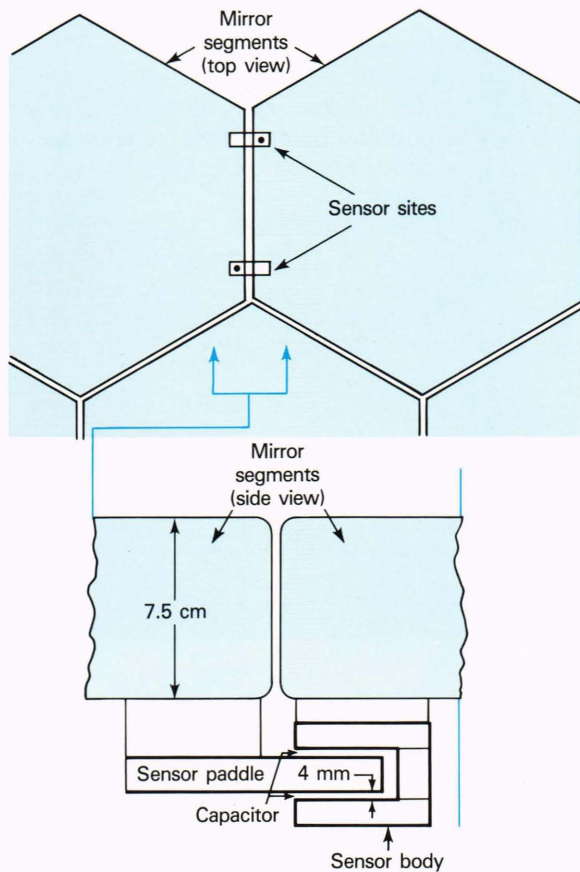
Figure 8—For the 36 segments of the Keck Telescope to operate as a single mirror, they must be aligned to within a fraction of the wavelength of light. The relative position of adjacent segments is sensed using two capacitative displacement sensors along each edge. Each sensor consists of a paddle on one segment and a body on the adjacent segment. The position of the paddle can be sensed to an accuracy of about 10 nm over a range of 1 mm. (Reproduced by permission, Calif. Assoc. Res. Astron. From J. R. Gustafson and W. Sargent, "The Keck Observatory: 36 Mirrors are Better than One," *Mercury*, Mar–Apr 1988.)

there is concern that its relatively high coefficient of thermal expansion may cause problems.

To minimize weight, the mirrors must be less than 30 cm thick, so thin that the mirrors will deform under their own weight. To maintain good image quality under conditions of gravitational and thermal changes, optical misalignment, and atmospheric variations, a telescope with such a mirror requires a system for correcting the alignment and the figure of the primary mirror over a low-frequency range of 0 to 0.033 Hz. This is active optics. An upper limit of about 30 s is needed to average the variations of atmospheric seeing.

An active optics system requires four components: an optical train and image detector, a wavefront sensor, a servocontrol system, and a phase-shifting optical element. The system concept is shown in Fig. 9. After the light has passed through the three telescope mirrors, part of the light (either from the target star or from an offset guide star) is picked off and directed into a wavefront sensor (Fig. 10). The sensor compares the image with
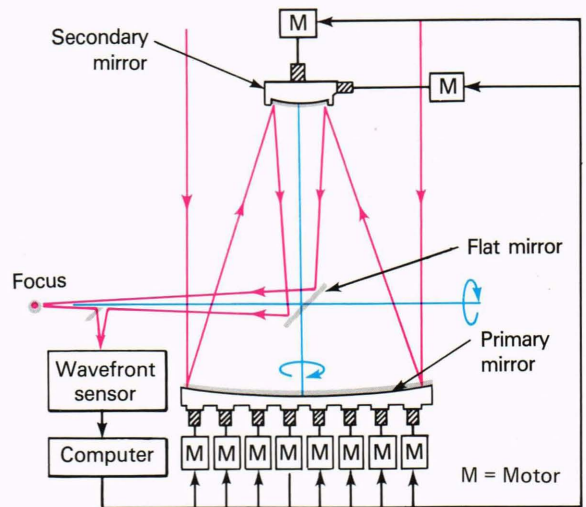

Figure 9—The light of a star is reflected by the primary mirror, which is supported by many motorized levers that determine its shape. The light is then reflected by the secondary mirror, the position of which can be adjusted by motors, and finally brought to a focus by a third flat mirror. Some of the light is analyzed by a wavefront sensor coupled to a computer that determines the corrections to be made for optimal imaging. Instructions are sent to the appropriate motors to change the shape of the primary mirror and the position of the secondary mirror. (From *VLT, The ESO 16-m Optical Telescope*, European Southern Observatory, Feb 1986.)
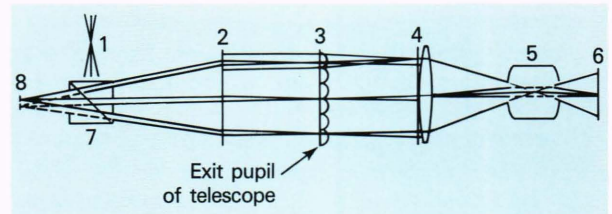

Figure 10—A diagram of an image analyzer or wavefront sensor. The focal plane of the telescope falls at (1). A lens (2) collimates the beam and images the exit pupil of the telescope onto a raster of weak lenses (3). Because this is an image of the telescope exit pupil, each portion of the image plane represents a particular area of the primary mirror. Each lens in the array (3) images the star in a plane at (4). An optical transfer system, lens (4), and objective lens (5) reduce the image plane to the size of a charge-coupled-device array (6). This image consists of an array of points, each being an image of the star as produced by a different portion of the primary aperture. The locations of these points are compared with the locations of points in a reference array introduced by the beam splitter (7) and the source (8). (From *2nd Workshop on ESO's Very Large Telescope,* European Southern Observatory, p. 421, Sep–Oct 1986.)

a reference image, and a computer calculates the corrections that must be applied to the optics to cancel any errors. Error correction is accomplished by moving the secondary mirror to correct focus and coma caused by decentering, and by using a set of push–pull actuators to change the figure of the primary mirror, which becomes the phase-shifting element.

The goals of the European Southern Observatory (ESO) system (see below) are to place 80% of the light

from a star into an image 0.15" in diameter at a wavelength of 500 nm and to be diffraction-limited at 5 μm. The limiting magnitude of the guide star is 14.5. The wavefront sensor will operate at 5 Hz, and mirror correction will be at 2 Hz. Between 250 and 350 actuators will be needed for each mirror.

THE ESO VERY LARGE TELESCOPE

The most complex and technologically sophisticated telescope project under consideration is the ESO Very Large Telescope (ESO–VLT). The objective is to produce an aperture with an effective diameter of 16 m by combining the beams from a linear array of four 8-m telescopes. Also, the project will include some major technical innovations, such as thin mirrors with active figure control, interferometry with combined beams from pairs of telescopes, automatic guidance accurate to 0.05", and remote operation from Europe. The preliminary study for the project began in 1978, a design group was organized in 1983, and unanimous agreement by the eight ESO member nations to proceed with construction was reached in December 1987. The first unit is expected to be completed in 1993, and the total array will be finished at a cost of over $180 million by the year 2000. (This is 10% of the cost of the Hubble Space Telescope for 50 times the collecting area, making the Hubble Space Telescope 500 times more costly for each meter of mirror surface.) The proposed site of the VLT is La Silla, Chile, but other locations are also being considered.

The VLT four-telescope linear array shown in Fig. 11 has some important advantages. It provides great flexibility in that the telescopes can point independently at different targets, they can all point at the same target and use different instruments, or their beams can be combined incoherently into a single beam at the Coudé
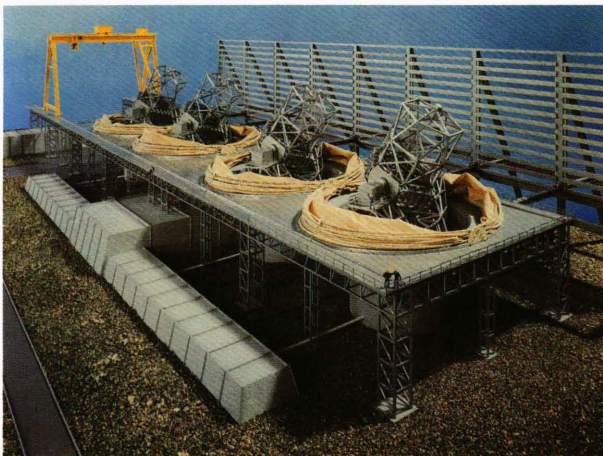
focus to give the effective aperture of 16 m. During construction, the first telescope completed can operate while work on the others proceeds. The presence of several telescopes provides redundancy, so some observations will always be possible. By operating the telescopes in pairs and by adding the beams coherently (assuming this proves to be possible), long baseline interferometry with different spacings is planned as a major scientific endeavor of the array. The disadvantages of the linear array are that it requires a longer site than a square array of four telescopes, the optical and mechanical tolerances required to combine the beams are very severe, and the telescope field of view at the combined Coudé focus is only 10".

The ESO is taking an incremental approach to developing the active optics. It was first demonstrated successfully on a 1-m mirror (the actuators are shown in Fig. 12) and has been incorporated on the ESO's 3.5-m New Technology Telescope. This telescope has a Zerodur mirror 24 cm thick, whose figure can be changed by 75 actuators. Its moving weight is only 109,000 kg, considerably less than a conventional telescope; for example, the 3.5-m German–Spanish telescope constructed at Calar Alto, Spain, uses a conventional mirror and has a moving weight of 209,000 kg.

The VLT has no dome in the conventional sense. Each telescope is exposed to the environment during observations, which has the operational advantage of rapidly bringing the telescope into thermal equilibrium with the environment. When the telescopes are not in use they will be covered by inexpensive roll-on/roll-off shelters or by the inflatable covers shown in Fig. 11. The open dome leaves the telescopes exposed to the wind. The selected location in Chile has a significant advantage, however, in that the wind is predominantly from one direction, the north. Thus, the use of an active wind
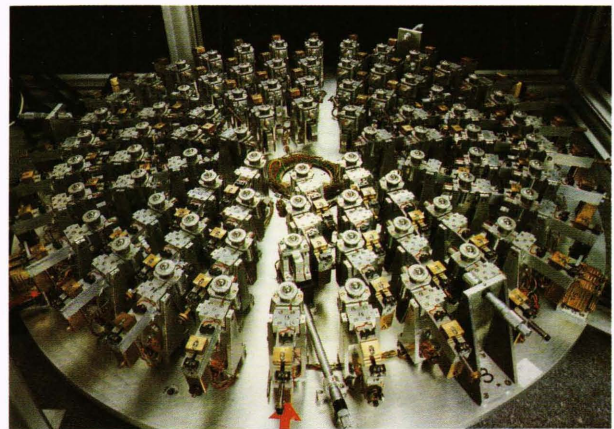

Figure 11—A model of the complete array of four 8-m telescopes making up the ESO–VLT. When in use, the telescopes are completely exposed; they are protected only by the wind screen behind them. When not in use, the telescopes are covered by inflatable shelters. The building below the telescopes is the interferometric laboratory. (From *VLT, The ESO 16-m Optical Telescope*, European Southern Observatory, Feb 1986.)

Figure 12—A scaled-down version of the support system of ESO's New Technology Telescope has been used to support a 1-m-diameter mirror with a thickness of only 20 mm. The laboratory tests at ESO have successfully confirmed the feasibility of the concept. This photograph shows the transducers that apply forces to the rear surface of the mirror to change its shape. (From *VLT, The ESO 16-m Optical Telescope*, European Southern Observatory, Feb 1986.)

shield, both to protect the telescopes from wind loading and to produce a smooth airflow over them, is being studied. The telescopes will be able to operate in winds up to 9 m/s.

The telescopes can operate in either of two modes: (1) the beams can be reflected to the individual Nasmyth foci along the altitude axes, or (2) they can be relayed to the Coudé focus in the optical experimental facility below the telescopes. Figure 13 shows the path of light to the optical facility from two of the four telescopes. It is anticipated that five to seven reflections will be used to reach the combined Coudé focus. Because this will result in a serious reduction in optical efficiency, three sets of mirrors will be selectable, each set coated to give maximum efficiency in one of three spectral regions: 300 to 470, 380 to 700, and above 700 nm. A built-in laser alignment system will monitor the optical system. The mirrors will be mounted in helium-filled tubes to maintain the quality of the optics. The beams can be combined into a single focal plane with a 10″ field of view using figured mirrors, or a fiber-optics system can be used to combine the beams or distribute the signal between instruments.

One exciting aspect of the VLT is its potential for intererometry. Interferometry on this scale is unproven to date, however. Although the technique has been used with very long baselines for radio astronomy, the precision required at optical wavelengths means that only recently has there been an interest in performing interferometry with pairs of telescopes. Initial attempts will be restricted to the infrared at wavelengths longer than 3 μm, with possible future developments to shorter wavelengths. The VLT provides a baseline between the extreme telescopes of 104 m, which should yield a resolution of 0.045″ at 20 μm and 0.00075″ in the blue part of the spectrum. To extend this range and make it con-

tinuously variable, two auxiliary telescopes with 1.5-m apertures will be used external to the main array. These telescopes will run along two tracks, one parallel to the main array (thus extending the baseline) and the second in a perpendicular direction, giving resolution in a second coordinate. The telescopes can operate independent of the main array and can be dedicated to interferometry, which will be performed in a separate laboratory attached to the telescope facility. Other major new telescopes with multiple apertures are being designed to the tolerances necessary to permit interferometry, so that this technique is expected to become an important branch of astronomy in the next century.

CONCLUSION

For 25 years the 5-m telescope was the largest optical telescope in the world, and for the past 15 years it has remained in second place. By the end of the century, it will have fallen farther down the list of largest telescopes. The change in the list reflects the revolution that is starting to take place in astronomy. Several of the new large telescopes are funded; the Keck Telescope is nearing completion, and the ESO–VLT received the go-ahead from member nations in 1987. Other projects such as the National New Technology Telescope will not proceed because of funding problems. During the 1980s, several other proposals and design studies have been performed for large telescopes. Some have made little progress, such as the United Kingdom's two-mirror telescope,[12] the spectrographical MMT of a French team, and the University of Texas large telescope.[13] Other projects are still active; for example, the Japanese National Large Telescope[14] is a single-mirror telescope in the 8-m class. Pennsylvania State University[15] plans to build a pointable (but not steerable) telescope by assembling a spherical mirror from 73 spherically figured segments, each
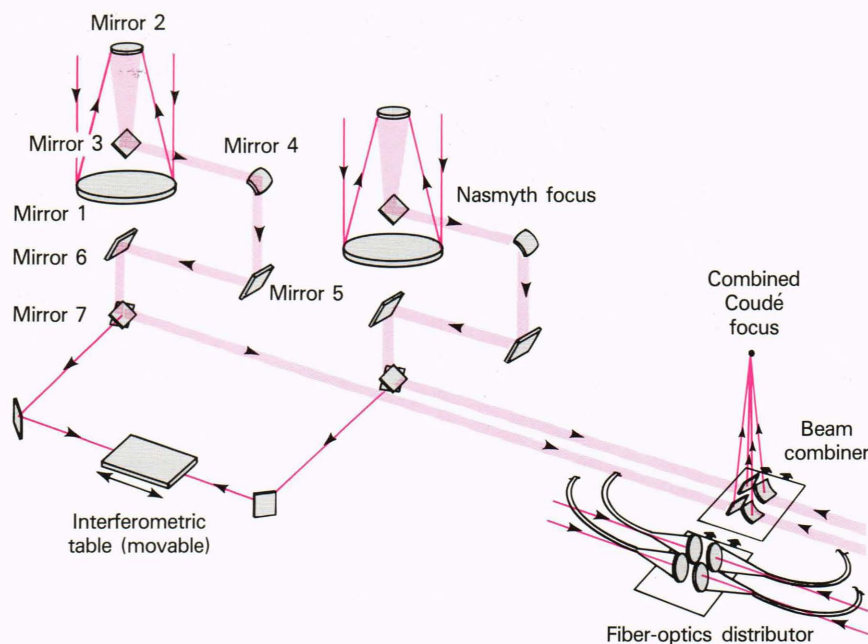

Figure 13—A long optical path makes it possible to combine the beams from the four telescopes of the ESO–VLT (two are shown here). Up to seven mirrors can be used to bring the beams from the four telescopes to a combined Coudé focus or to a fiber-optics system that will distribute the light between instruments. (From *Proc. IAU, Very Large Telescopes, Their Instrumentation and Programs,* Colloquium 79, p. 776, 1984.)

with a diameter of 0.9-m and a 26-m radius of curvature. The effective diameter will exceed 7 m and will be used for spectroscopy only.

The size and expense of these telescopes mean that no single organization will be able to build its own facility. The Magellan Project is a consortium of three organizations, the Columbus Project has four, and the ESO has eight member nations. Large groups, each with an interest in a particular telescope, will become the common approach, thus placing a burden on the communication channels and raising problems in satisfying many diverse scientific objectives.

The Hubble Space Telescope will receive most of the public interest in the next decade, and, within certain scientific areas, it will reign supreme. It will not be equaled in image quality or ultraviolet access by any foreseeable instrument. The real astronomical revolution will occur on the ground, however. Many important scientific problems can be tackled from ground-based facilities just as well, if not better, than from space. The number of investigations and questions to which we seek answers means that all available telescopes will be in full-time use.

Although the new telescopes are possible because of lower cost–manufacturing techniques, their expense is still formidable, and they include more high technology in their operation. Maximum exploitation of these telescopes will require high reliability. At times, such as with the 10-m Keck Telescope, failure of the mirror-alignment mechanism can make it valueless. For the VLT, however, such a failure will cause only a reduction in performance. The involvement of many groups with each system requires remote viewing and diagnostics, sophisticated data acquisition and analysis, and on-line data reduction. Clear and organized observational programs and interfacility cooperation will be needed to enhance the scientific return.

Within the next 20 years, some facilities described in this article will have a decade of operational experience, and, possibly, the astronomers will be dreaming of the next new generation of large ground-based optical telescopes.

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THE AUTHORS
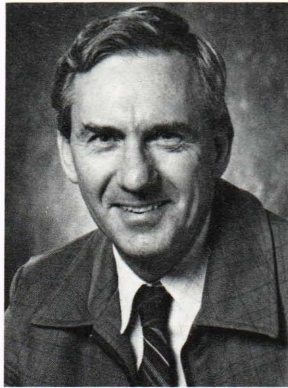
KEITH PEACOCK was born in Hull, England, in 1940. He received a B.Sc. in physics from Durham University in 1961, an M.Sc. in radioactivity from Birmingham in 1962, a Ph.D. in astronomy from Manchester University in 1967, and an M.S. in technical management from The Johns Hopkins University in 1984. Before coming to APL in 1979, Dr. Peacock worked on a variety of space and remote-sensing programs at the Bendix Aerospace Systems Division in Ann Arbor, Mich., and on laser fusion at the Los Alamos National Laboratory. For his first eight years at APL, he worked on the Submarine Security Program in the Submarine Security Department. He joined the Space Sciences Instrumentation Group in the Space Department in 1988. Before joining the Space Department, he was the recipient of the Lawrence Hafstad Fellowship, which he spent at the Center for Astrophysical Sciences working on optical problems connected with the Magellan Project telescope described in this article. His primary field of interest is optics. Dr. Peacock is now doing optical design for various Space Department programs and teaches classes in applied and modern optics at the G.W.C. Whiting School of Engineering, The Johns Hopkins University.
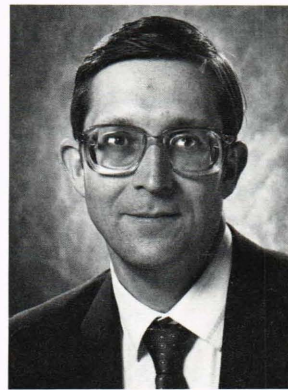
KNOX S. LONG is a research scientist in the Department of Physics and Astronomy at The Johns Hopkins University. He attended Harvard College, where he was awarded an A.B. in 1971, and the California Institute of Technology, where he received a Ph.D. in physics in 1976. From 1975 to 1981, he was a postdoctoral fellow and assistant professor of physics at Columbia University. Since his arrival at Johns Hopkins, he has served as a member of the senior research staff, working primarily on space-based astronomical instrumentation. He is the project scientist and a co-investigator on the Hopkins Ultraviolet Telescope, a major shuttle instrument designed to study astronomical objects in far and extreme ultraviolet, which was built jointly by The Center for Astrophysical Sciences and APL.

Dr. Long has conducted research at X-ray, ultraviolet, visible, and radio wavelengths on a variety of astronomical objects. He is currently interested in the properties of evolved stellar objects—stars in mass-exchanging binary systems, white dwarf stars, and the remnants of supernova explosions. While at Columbia using the Einstein Observatory, he carried out the first detailed X-ray survey of the Large Magellanic Cloud, as well as the first large-scale survey of the X-ray properties of normal galaxies.

Dr. Long is a member of the Science Working Group for the Magellan Project. He is also a Visiting Adjunct Associate of the Carnegie Institution of Washington. As such, he has observed frequently at Las Campanas in recent years, having just completed a successful search for supernova remnants in nearby spiral galaxies in the southern hemisphere.

Dr. Long is a member of the American Astronomical Society and the International Astronomers Union. He has been a Visiting Fellow of the Australian National University and a National Defense Education Act Fellow. He is also a Fellow of the Center for Astrophysical Sciences at Johns Hopkins.