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# 1

# Optics

In this chapter, several different mirror and lens materials will be considered. No matter what the material, however, it must be shaped into a smooth curve by grinding, polishing or some other fabrication technique. Astronomers say that it is a mark of intelligence to be able to grind a good mirror. It has also been quipped that a mark of stupidity is to grind a second one. Mirror grinders and other glass pushers become attached to their work, having spent many loving hours grinding a precise optical figure into the surfaces, testing, putting a final stroke or two on the glass, testing, making just one more correction, testing, getting it just right, testing. Mirror grinding (figuring) is an occupation for the terminally finicky. It is no wonder that cutting remarks can fly at a meeting of opticians. For instance, I am reminded of something overheard at the Riverside Telescope Makers Conference; "What'd ja polish that thing with, boy, peanut butter and a brick?"

## Rock, clay and ceramic mirrors

The primary component in telescopes is always either the mirror or the objective lens. Traditionally, these have been made of glass. Remember, however, that the original mirrors by Newton, Herschel and Lord Rosse were of speculum metal. A chief attribute of optics, no matter what the material, is that the optics be rigid and stable. Floppy disks may work in computers but floppy optics have seldom been popular in astronomy. Mirrors have been fabricated of glass, ceramic, even granite and obsidian.[4]

Obsidian and granite are clever mirror materials. Formed as molten ingots much like glass, these materials were cooled or annealed slowly over centuries and thus their internal grain structures have very few stresses. Several people have made mirrors from these materials but they report that obsidian and granite are much harder than glass and require considerably more work to polish correctly. Obsidian has a higher thermal conductivity than glass and thus the mirror tends to come to temperature more rapidly at the start of an observing run.[5] Chris Pratt of the San Jose

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[4] Obsidian mirrors are described in *Sky & Telescope*, August, 1981, p. 122 and November, 1979, p. 410.

[5] *Gems & Minerals*, June, 1966, p. 25.

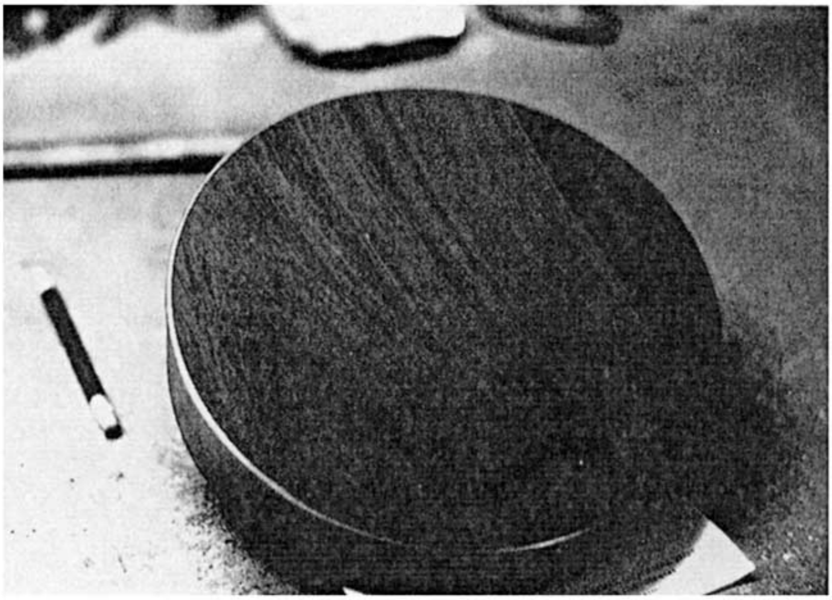

Figure 1.1. 20.32 cm (8 in) f/8.2 obsidian primary mirror before silvering. Note the grain of the obsidian. The mirror was made by Jackson T. Carle. Photo courtesy of Chris Pratt.

Astronomical Association reports very good results with the mirror shown in Fig. 1.1. The mirror was finished with an aluminum reflecting surface using conventional vacuum coating techniques.

Donald Dilworth tried a slightly different approach to making a mirror. He formed clay into the correct approximate shape and then fired the clay with a glaze to produce a rigid ceramic mirror which could then be polished to the correct figure.[6] While the technique has not proved fruitful, many modern mirrors are being cast from temperature insensitive ceramics such as Zerodur®.[7]

The Astro Met Corporation has produced open cell ceramic foam mirror materials. The foam is much lighter than conventional glass and since air can flow through it, the mirror will stabilize in temperature much more rapidly. For the current technology, a thin aluminum front surface is bonded (glued) to the ceramic foam core and then the metal is polished. In the future, nonporous ceramic mirror materials for the reflecting surface may be formed with a foam ceramic backing. This would result in a very stable, lightweight mirror which responds quickly to temperature changes. Currently, the ceramic foam mirror is still in the research and development stage.

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[6] Dilworth's ceramic mirrors are discussed in *Sky & Telescope*, October, 1975, p. 259.

[7] A ceramic mirror by Patric Canan was shown at the 1983 Riverside Telescope Makers Conference. The 24 cm (9.5 in) f/3.8 mirror is described in *Telescope Making*, No. 20, Summer/Fall, 1983, p. 18.

Glass foam has also been used as a lightweight backing material in some mirrors. In most applications, a closed cell foam is used which acts like very hard Styrofoam®. In a typical application, a 1 mm thick flat sheet of silvered glass about a meter in diameter is bonded (glued) to the glass foam backing which has been pre-formed into the required concave parabola. The thin glass sheet is kept in contact with the curved glass foam backing by vacuum suction until the epoxy bond has cured. In order to protect the aluminum reflecting coat from the weather, it is usually placed on the back side of the mirror, much like a Mangin mirror. High precision optical surfaces have not been attainable with this method and mirrors made using this technique have usually been employed as solar collectors. There is, however, a class of low angular resolution, large aperture astronomical telescopes used to detect cosmic-rays and gamma-rays which use these mirrors extensively. Often hundreds of these mirrors are arrayed into a collector with an effective aperture of about 10 m (33 ft). These telescopes are discussed in the section on noncoherent multiple mirror light buckets in chapter 8.

## Plastic optics

Optical fabrication experiments have been made with plastic and similar materials such as Perspex™.[8] English astronomers John Wall and E. Dunlop have cautioned, however, that the plastic materials should be annealed before grinding and that the long-term stability of plastic optics is not yet established. Wall ground and polished a 0.91 m (36 in) f/12 aperture lens for a Schupmann (medial) refractor. After final polishing, however, the surface appeared rough under a Foucault test even though it appeared well polished to the eye. The project was abandoned but the lens still exists. Perspex™ and other plastics also have the disadvantage that they turn yellow after a couple of decades, discouraging their use for lenses. The original reason for using plastic – a lesser expense than glass – has now evaporated with rising prices for large plastic sheets. Wall also made a 15 cm (6 in) aperture f/3 mirror and found it easy to silver-coat the plastic.

In recent years the advent of cheap refractors with molded plastic lenses has given a bad name to the use of this material. Plastic lenses and mirrors larger than 10 cm (4 in) in aperture have not been made in quantity. There is a gray area as to where plastics end and composite materials, discussed below, begin.

## Metal and composite material mirrors

Speculum metal, an alloy of copper, tin, occasionally zinc and traces of arsenic, was the first choice of mirror makers. Long before glass-silvering technology was developed the white, hard metal was used to make reflecting surfaces. The exact

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[8] *Journal of the British Astronomical Association*, Dec 1977 Vol.88, No. 1 p. 28 and Aug 1978 Vol.88, No. 5 p. 517.

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mixture ratios of the ingredients were often kept secret by mirror makers, as were the identity of other seasonings in the recipe. William Parsons, the third Earl of Rosse, tried several exotic techniques in casting large metal disks over 0.5 m (19 in) across. He experimented in the late 1800s with soldering speculum metal plates on a solid brass backing fixture and then grinding the whole assembly to the proper curve.[9] Because of diffraction problems associated with the joints of the plates, he dropped the idea and developed methods for casting large specula, up to about 2 m (6 ft) in diameter.

In general, metal mirrors have problems maintaining the required dimensional stability over a normal range of temperatures. On the other hand, they can be made much thinner and thus more lightweight than glass. This is because speculum metal is stiffer and stronger than glass, which is really just a very viscous liquid.[10] There are some applications in which metal mirrors are required, such as in spacecraft where weight is a premium.[11] Beryllium is often used instead of aluminum because beryllium is stiffer and has better dimensional stability. It is, however, a hazardous metal with which to work since beryllium dust and metal shavings are highly poisonous.

Until recently, fabrication of glass mirrors over 5 m (16 ft) in diameter was nearly impossible. Thus, for those applications involving lesser requirements for optical surface smoothness, as in infrared and radio applications, metal mirrors were considered because of the low cost involved in making large metal surfaces.

As an example, the laser-ranging telescope of the Tokyo Observatory uses a 3.8 m (150 in) metal dish as shown in Fig. 1.2. Note that the secondary support struts pierce the primary mirror, a feature not often seen on glass telescope mirrors.[12] This telescope, which has the same aperture as the Mayall Telescope, largest telescope at Kitt Peak, was built for a fraction of the cost. While the metal mirror telescope has significantly less resolution than a glass mirror, the requirements of laser ranging are simply that the mirror act as a large aperture, not as a precision imaging system. Telescopes designed for maximum aperture are often referred to as light-buckets.

With the advent of exotic materials designed for the space and defense industries, some of these were bound to find their way into telescopes. Daniel Vukobratovich of the University of Arizona Optical Sciences Center has designed a 30.48 cm (12 in) aperture, 4.5 kg (10 lb) telescope made largely of metal matrix composites; as shown in Fig. 1.3. The structural members are made of SXA, a new class of dimensionally stable composites made of aluminum and fine silicon carbide particles. The mirror is

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[9] *The History of the Telescope*, Henry C. King, Dover Publications, 1955, p. 207.

[10] The fact that glass is a viscous liquid can be demonstrated by measuring the thickness of a window pane in an old house. The bottom will be thicker than the top because the glass, over a period of decades, is flowing to the bottom of the window. It has been theorized that glass mirror or lens telescopes which are always stored on a particular side should develop an astigmatism after a century or so. The effect, however, has never been observed.

[11] A typical beryllium mirror for use in an infrared spacecraft telescope is described in *Sky & Telescope*, November, 1976, p. 340.

[12] A description of the Tokyo laser-ranging telescope is in *Sky & Telescope*, November, 1975, p. 280.

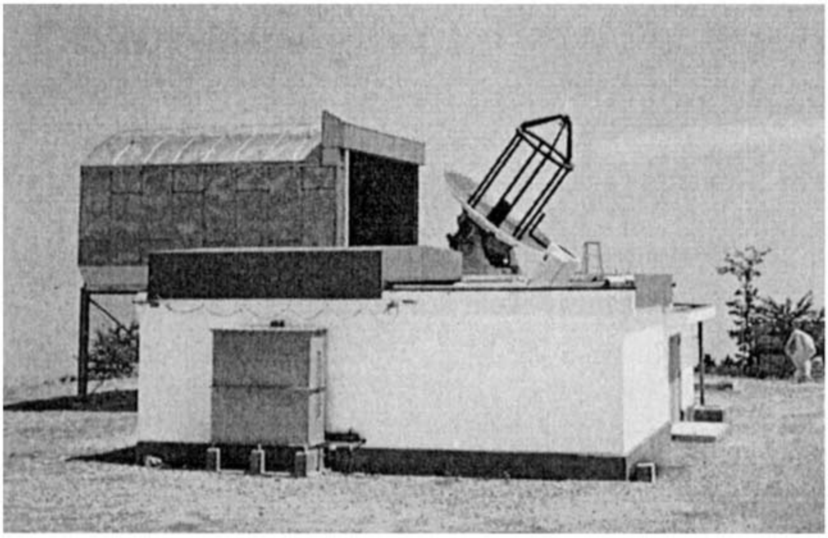

Figure 1.2. Tokyo Observatory 3.8 m (150 in) metal mirror telescope used for lunar ranging with a laser. Photo courtesy of Yoshihide Kozai, National Astronomical Observatory, Mitaka, Tokyo.

made of a sandwich of metal foam with solid metal plates for the mirror and back plate. The design is interesting in that the primary mirror has a curve formed into it on both the front and the back sides. The reason for this is so that the slump of the mirror due to self weight and the change in curvature due to thermal stresses are minimized.[13]

In most conventional mirrors, the light strikes the surface almost at right angles. Photons of higher energy, however, will not focus properly with this type of mirror. In fact, they will probably penetrate the mirror surface and be absorbed rather than reflected. Thus, in the extreme ultraviolet and soft X-ray regions photons are difficult to focus. These higher energy photons will reflect if they strike the mirror at a shallow or grazing angle, say less than about 5°. A reflecting mirror can then be built in which the photons just barely graze the surface.[14] Since the cross-section of the collecting aperture of the telescope tends to be a narrow annulus, the effective collecting area is rather small. This can be increased by nesting concentric mirrors inside one another as shown in Fig. 1.4.

Each of the annular segments is actually a small section of a deep parabolic mirror with all of the mirrors having a common focus. The assembly could be considered a multiple mirror telescope design taken to the extreme. The completed telescope thus

[13] A description of the lightweight telescope is in *Optical Engineering*, the journal of the Society of Photo-Optical Instrumentation Engineers, February, 1988, p. 97.

[14] Grazing incidence optics are discussed in *Sky & Telescope*, January, 1969, p. 14 and May, 1969, p. 300.

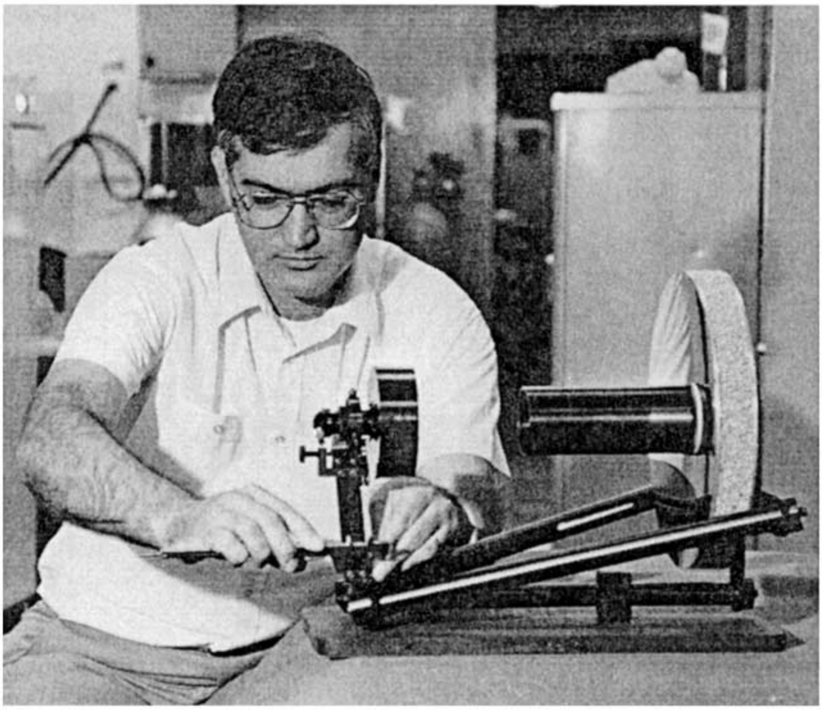

Figure 1.3. Lightweight telescope of 30.48 cm (12 in) aperture weighing only 4.5 kg (10 lb). Photo courtesy of University of Arizona.

resembles a cookie cutter for making extremely thin donuts. The requirement that as many mirrors as possible be nested implies that the mirrors should be as thin as possible. Typically, metal optics have been used extensively in this application since glass optics would need to be much thicker in order to retain the desired stiffness.

It is interesting to note that the mirrors are made by machining the metal on a special highly accurate diamond turning lathe. Mirrors such as this have also been made with a machined surface of lithium fluoride. X-rays diffract when encountering this crystal by means of Bragg diffraction, thus forming a diffracting, rather than a refracting telescope. Since the Earth's atmosphere absorbs most of the extreme ultraviolet and soft X-rays, these telescopes have typically been used on either balloon-borne payloads or on spacecraft.

## Glass/metal mirrors

In an effort to decrease the costs of glass on larger telescope mirrors, several attempts have been made to use either thin mirrors or mirrors made up of several smaller

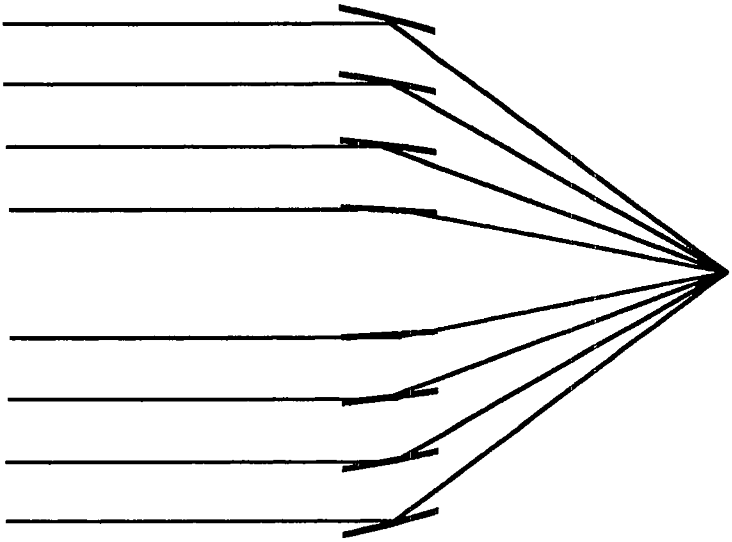

Figure 1.4. X-ray telescope composed of several nested grazing incidence mirrors.

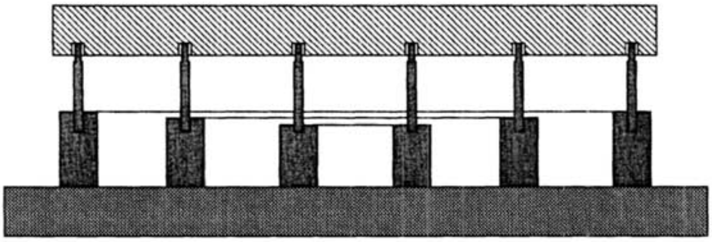

Figure 1.5. Hairbrush mirror mount.

pieces. Thin mirrors have the problem that they are not dimensionally stable as the telescope moves around the sky unless elaborate mechanisms such as multi-point flotation cells and complex edge supports are used to keep them from deforming under their own weight. In telescopes over a meter in aperture, these mechanisms can drive the cost of the telescope out of bounds.

Eric Mobsby of Dorset, England, has taken a different approach. He has made very thin mirrors but has attached them with epoxy to a cast aluminum back plate which has many rods supporting the mirror, as shown in Fig. 1.5. Eric calls this the hairbrush mirror mount and the idea is to let the aluminum casting expand at its own rate which is slightly different from the glass. The short vertical rods will then bend slightly to make up the difference. There are three concentric rings of rods and each base ring is cast into a backing structure which allows air to circulate freely through the assembly.[15] This technique should not be confused with active mirror supports in which the length of each of the metal rods might be adjusted independently to control the mirror surface. Such mirrors are covered in the section on flexible mirrors in this chapter. The metal rods in Mobsby's mirror support are bonded with epoxy into shallow holes drilled in the back side of the thin mirror. Grinding and polishing is done after the mirror blank is attached to the casting. His mirrors, which are up to 30.5 cm (12 in) in diameter and about 1 cm (0.4 in) thick have been subjected to some rather brutal environmental tests (how many people deliberately leave their telescope mirrors in the freezer for a while?). The results to date have been good but replacing a complex mirror cell and support mechanism with a complex custom casting probably isn't advantageous unless volume production methods are used.

Eric Mobsby had earlier tried making lightweight mirrors from glass top and bottom plates, separated by either glass or metal spacers. The problem usually encountered was that the differential expansion between the glass plates and the metal spacers was excessive. Corrugated metal spacers were tried on the assumption that the folded metal would bend sufficiently to accommodate the differential expansion.[16] This type of construction has proven successful if the plates and spacers are made of the same material and fused together, as has been done for years with fused silica and more recently fused Pyrex®.[17]

G.W. Ritchey made several mirrors up to 1.52 m (60 in) in diameter by glueing glass support ribs to the back of a single thin primary mirror blank which had been rough-ground to the correct shape.[18] The mirrors did not hold together for more than a few years before the glue deteriorated. Recent attempts to epoxy glass plates side by side in order to make larger mirrors have met with mixed success, largely due to problems at the epoxy joints.[19]

In a similar effort, Dr Sherman W. Schultz of Macalester College, Minnesota, is assembling a 0.86 m (34 in) f/3 mirror as shown in Fig. 1.6. The original objective in his explorations into mirror fabrication technology was to decrease the quantity of

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[15] The hairbrush mirror mount is described in *Sky & Telescope*, December, 1978, p. 569.

[16] A description of Mobsby's experiments with epoxied mirrors is in *Sky & Telescope*, November, 1964, p. 305.

[17] Some of the original development of the techniques for fusing Pyrex® blanks is described in an article by John M. Hill and Roger Angel in *Telescope Making*, No. 14, Winter, 1981/1982, p. 24. The Hextek Corporation of Tucson, Arizona and Star Instruments, Inc. of Flagstaff, Arizona have pioneered in the technology of producing fused Pyrex® mirror blanks. For more information, see *Sky & Telescope*, July, 1984, p. 71 , January, 1986, p. 100 and December, 1988, p. 698.

[18] *The Development of Astrophotography and the Great Telescopes of the Future*, G. W. Ritchey, Astronomical Society of France, 1929.

[19] As with Rosse's attempts to make large speculum metal mirrors from several smaller ones, the joints are not completely smooth between adjoining plates. These joints cause diffraction and thus decrease the effectiveness of the mirror in terms of resolution. See *Sky & Telescope*, December, 1984, p. 558.

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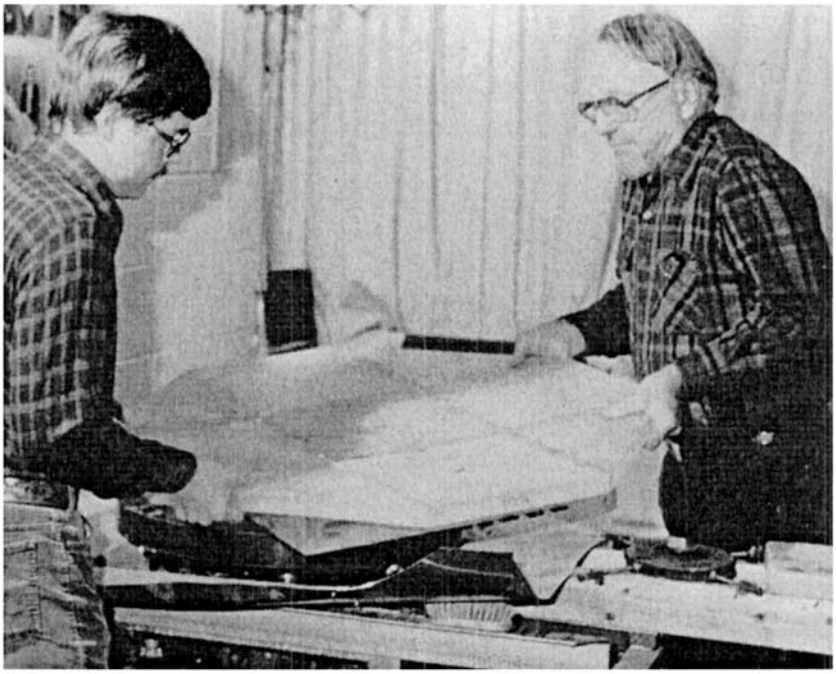

Figure 1.6. Primary mirror built up by epoxying glass plates together. Photo courtesy of Sherman Schultz.

glass which had to be removed by grinding. This is especially important with lower f number systems where telescope makers joke that they are making salad bowls.[20] Sherman's approach was to assemble the mirror from several 30.5 cm (1 ft) square plates side by side. The plates were first rough-ground to the desired spherical shape and then assembled face down on a form with the correct convex curvature. The separate plates were then bonded together with a special epoxy for glass. On the back side of each joint there is a fiberglass strap epoxied over each joint to add strength.

The assembled mirror was then ground with a sub-diameter tool. Initial results, while promising, pointed to the need for more support on the back side since the

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[20] A novel approach to pouring mirror blanks which do not require heavy grinding to rough out the basic curve has been taken by Roger Angel of the University of Arizona. He makes "spin-cast mirrors" in which the melting and annealing oven rotates like a merry-go-round, allowing the glass to solidify with a parabolic surface, much like the rotating mercury mirrors described in the section on liquid mirrors. Two meter mirrors have been made with this technique and mirrors of up to ten meters are planned.

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entire assembly flexed during grinding. More rear supports have been added to the mirror and final grinding is proceeding at the time of this writing.[21]

### Flexible mirrors

#### *Liquid mirrors*

I mentioned earlier that telescope optics should be rigid. With the advent of flexible and liquid optics (yes, I mean liquid optics) perhaps a more accurate phrase would be that telescope optics should be stable.

Both lenses and mirrors have been made of liquids. In the late 1700s it was well understood that in order to correct lenses for color aberrations, at least two lenses of two different indices of refraction were required. The technology was available to produce relatively large blanks of crown glass but flint glass was scarce in larger sizes.[22] Euler experimented with liquid lenses during this period. Typically, the liquid was used as a refractive medium only and was held in place with meniscus zero power lenses. Robert Blair, a Scottish Naval surgeon, experimented with water and metal salts as a refractive medium. Between 1827 and 1832 Peter Barlow constructed several liquid-filled objectives with apertures ranging from 15.2 cm to 20.3 cm (6 in to 8 in). Tests comparing liquid lenses with conventional glass optics showed the two technologies were competitive.[23] There was always the fear, however, that the lenses would leak or change color with time. In addition, there was concern that some of the acids used as refracting media would etch the glass which contained them. Many of the telescopes, however, were used for years without serious problems. With the advent of more modern glass materials in the early 1800s the development of liquid lenses was abandoned.

A flat pan of mercury has been used for years in zenith telescopes worldwide. A typical example from the US Naval Observatory is shown in Fig. 1.7. The zenith tube is used to observe the meridian passage of stars for timing and geodetic location purposes.[24] It is a requirement that the telescope be pointed absolutely vertical. The pan of mercury, acting as a mirror, is guaranteed to be flat (to within the radius of the curvature of the Earth) and perpendicular to the vertical direction. No adjustment is required. The objective lens in the top of the tube and a downward looking photographic plate holder located just under the lens rotate about the axis of the tube. This rotation allows exposures to be made with one edge of the lens toward the East and then, after rotation, toward the West. Thus, instrument errors are calibrated out of the system in this manner.

[21] A photograph of the partially completed mirror is in *Sky & Telescope*, December, 1984, p. 559. A description of the mirror design effort is in *Telescope Making*, No. 24, Fall, 1984, p. 41.

[22] *The History of the Telescope*, Henry C. King, Dover Publications, 1955, p. 155.

[23] *The History of the Telescope*, Henry C. King, Dover Publications, 1955, p. 190.

[24] The application of a photographic zenith tube telescope is described in *Astronomy*, Robert H. Baker, Van Nostrand Company, Inc, 1964, p. 74.