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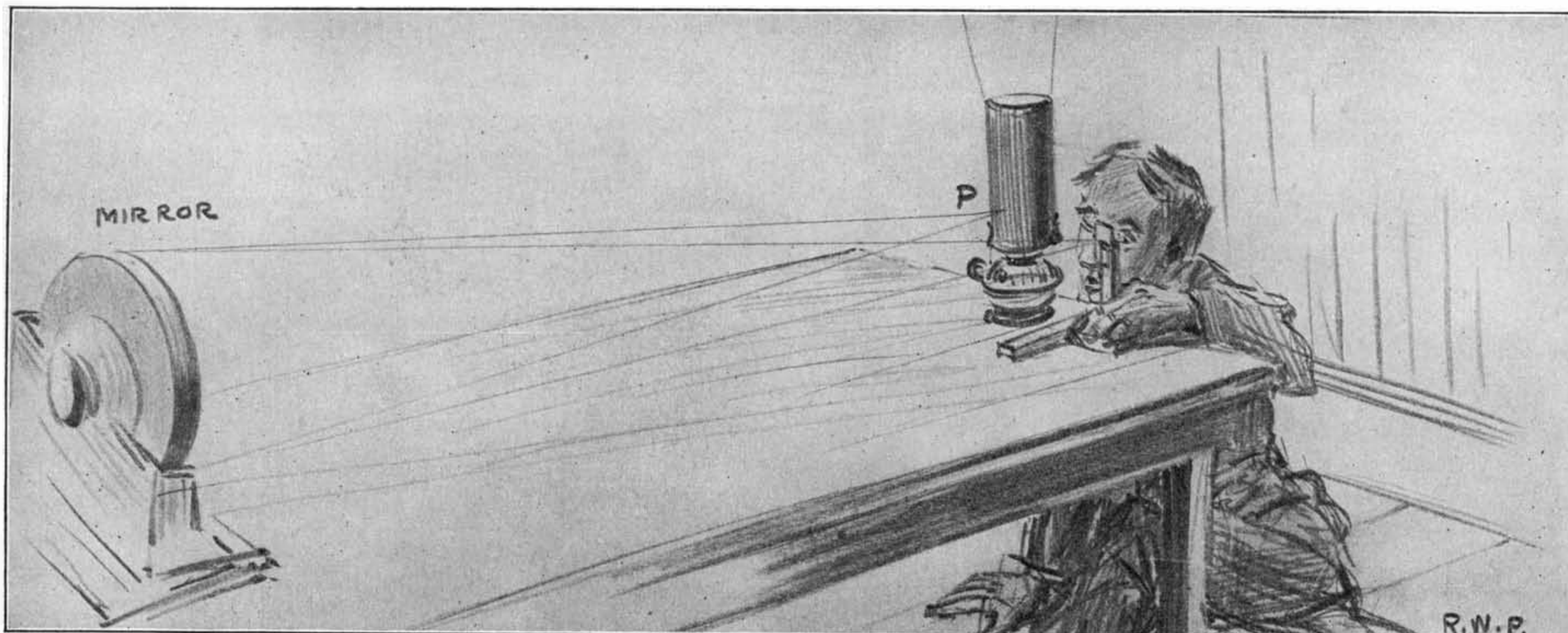

Drawing by the author

FIGURE 1: HOW THE KNIFE-EDGE TEST IS MADE. THE SIMPLEST EQUIPMENT SERVES AS WELL AS THE MOST COMPLICATED

Light from the pinhole, P, is reflected into the eye. The interposition of the knife-edge produces shadows on the mirror like the shadowgraphs at top of pages 88-89.

Mirror Making for Reflecting Telescopes

By Russell W. Porter, M.S.

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IN the reflecting telescope, *the mirror's the thing.* No matter how elaborate and accurate the rest of the instrument, if it has a poor mirror, it is hopeless. Conversely, a good mirror, even if it is crudely and simply mounted, makes a powerful and efficient astronomical tool.

We are concerned in this article with the shaping of the telescope mirror. This consists solely in giving the upper side of it a concave, polished surface. This surface is to be so nearly spherical that we shall first attempt to make it precisely so; and at the very last we shall alter it to the kind of surface familiar to us all in automobile headlight reflectors, and known among the highbrows as a paraboloid of revolution.

Such an automobile headlight has the property of throwing out from a concentrated source of light placed at a focal point near it, a beam of parallel rays. (See Figure 6.) We shall, however, use this reflector the other way around, that is, by receiving parallel rays of light from a distant object (star); and by reflecting them from a properly curved mirror we shall bring them to a point or focus (F, Figure 6).

Our curve, however, is so small a portion of this widely sweeping parabola (the black area represents the mirror) that it is extremely shallow, and so it nearly coincides with the superimposed spherical curve. At first, therefore, we shall seek to hollow out a spherical curve, later deepening it very slightly into the paraboloid.

Since the angle of incidence of a reflected beam of light is equal to the angle of reflection, the parallel, arriving rays will be reflected approximately to a focus whose length may be regarded as one-half of the radius of curvature, C-A, Figure 6.

Enlarging the mirror of Figure 6, A, we have in Figure 8 the essentials of the Newtonian, reflecting telescope. Light from a distant object falls down the tube to the mirror, and normally would, by reflection, produce an image at the focus, F. The converging rays are, however, intercepted at D by a small diagonal mirror or prism that delivers them to a lens called an eye-piece at the side of the tube, where the image is examined.

I will take as our standard, a mirror six inches in diameter, having a four-foot focal length. The beginner is not advised to essay a larger mirror for his first effort, since his difficulties will be found to multiply quite disproportionately as the diameter increases. If two flat glass disks (A, Figure 7) are ground together, one over the other, with an abrasive between, lo and behold!—the upper one becomes concave, the lower one convex. This is because the center receives constant wear, while the outer portions, overhanging part of the time, receive less wear.

A straight, back-and-forth stroke, in which a given point on the upper disk moves across one-third the diameter of the lower, has the property of holding the two surfaces spherical. This is due to the fact that spherical surfaces are the only ones which remain in continuous contact at every point when moved over each other in any direction. This fact is a veritable godsend to the amateur—and to the professional, too, for that matter—for he may go confidently forward through the different stages of grinding and polishing with the knowledge that his mirror will come out nearly as it will be when it is finally deepened into a paraboloid.

The depth of the curve increases with grinding, and is gaged with a template of proper radius. Since by our rule, the radius, A-C, Figure 6, of the

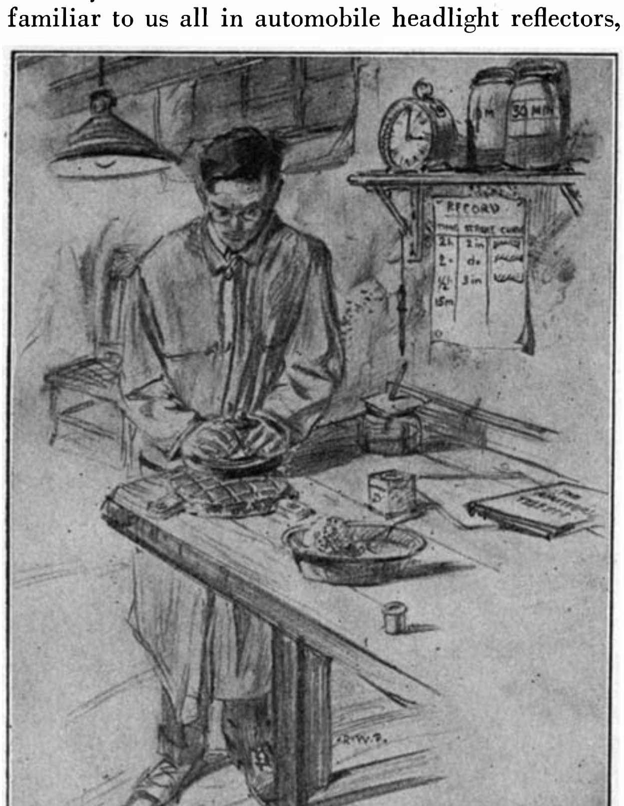

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FIGURE 2: THE AMATEUR AT WORK

The best place to work is the cellar, where the temperature is reasonably constant, an essential condition

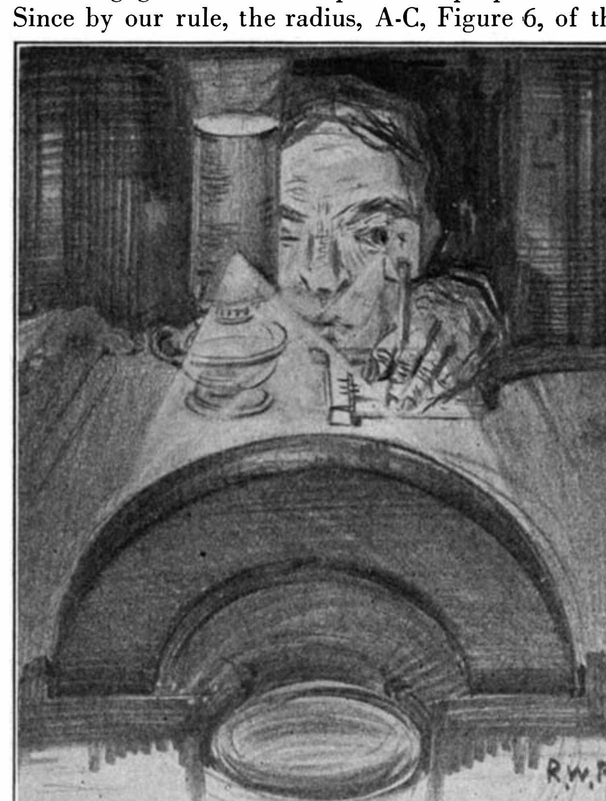

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FIGURE 3: THE FOUCAULT, KNIFE-EDGE TEST

With a lamp and razor blade, imperfections of the order of a millionth of an inch can be detected

Drawing by the author

FIGURE 4

Preparing the pitch lap, or polisher

curve of the glass is twice its focal length A-F, a template is made from tin, with a radius of twice 48 inches, or 96 inches. Therefore a stick of wood (not a string, which would be elastic) should be tacked to the floor at one end so as to pivot, and a knife point held at the opposite end, or a sharpened nail driven through at the proper distance, should be used to scratch the desired curve to which the tin should be cut. For our six-inch mirror the hollow will come to about .05 inch deep.

The lower disk of glass is fastened to a pedestal or to a weighted barrel so that one can walk around it in grinding, or it may be held between one removable and two fixed buttons on the corner of a stout bench or table. (See Figure 2.) Using melted pitch, a round handle is attached to the upper disk, which is first heated in cold water to a slightly unpleasant warmth for the hand, taking care that no cold water drops fall on the warmed disk, for they might break it.

The grinding is done by placing wet carborundum grains of successively finer sizes between the two disks, care being taken after each size is used to wash all parts of the work entirely free of the larger sized grains, which would otherwise scratch the disk. The strokes are straight forward and back, the center of one disk crossing that of the other. The glass also rotates bit by bit in the hands, in order to present a new direction for each stroke; and from time to time, in order to prevent the wearing of the glass unsymmetrically, the worker shifts positions around the pedestal; or, if working on a bench, he turns the lower disk, called the "tool" (we shall discard this tool at the end) to a new position.

Each grade of abrasive is used long enough to remove the coarser pits left by the preceding grade, and it will save much time and labor in the polishing if a small quantity of washed 6F ("sixty minute") emery is used after the Number 600 carborundum.

All the preceding work is covered in great detail by Ellison in his book, "The Amateur's Telescope," which at the present time is the only modern book of this nature available. [Editor's note: See list of literature and materials, prepared by Mr. Porter and printed in the Digest department of the present issue.]

The bench and both disks are now thoroughly washed in order to remove all traces of grit, preparatory to polishing.

Pitch is melted over a stove. It is tempered by adding (not over the fire) sufficient turpentine until a cooled sample placed between the teeth will just "give" slowly without crumbling, or will show a slight indentation of the thumb-nail under moderate pressure. The pitch is poured (Figure 4) over the tool, which has been warmed in water, and dried, and when it is partly cool, the glass is wetted (in warm water) and pressed down on the pitch until perfect contact is obtained between glass and pitch. V-shaped channels an inch apart are now cut across the pitch at right angles to each other, to allow free access of the rouge and water to all parts of the glass. Do not center this system of channels or you may produce zones in the mirror. See Figure 11.

Rouge mixed with water is now substituted for the carborundum and the polishing is carried on to completion, using the same strokes as in grinding. The time thus far consumed in grinding should be about five hours; polishing may require nine hours, divided into "spells." Through all these operations Ellison, the author of "The Amateur's Telescope," goes with painstaking care, anticipating the pitfalls into which the tyro inevitably falls. Were I to emphasize one caution over another, it would be the care required in preserving complete contact between the glass and the pitch lap surfaces while polishing.

If one-third strokes have been maintained in grinding and polishing, the surface of the glass will be nearly spherical. How shall we find out? The method I shall now describe is one of the most delicate and beautiful tests to be found in the realm of physics. By it, imperfections of a millionth of an inch on the glass can be detected, and all the tools required are a kerosene lamp and a safety razor blade! This method of testing mirrors, called the Foucault knife-edge test, was unknown until about 1850; before that time mirror makers were groping in the dark. Even the great Herschel—father of the reflecting telescope—did not know when his mirrors were right, except by taking them out and trying them on a star.

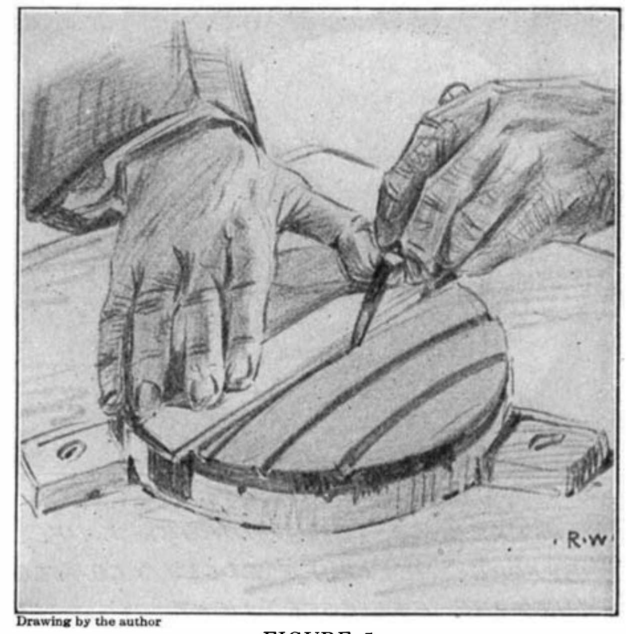

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FIGURE 5

Cutting channels in the pitch lap

If an artificial star made by a tiny pinhole (use a needle point) in a tin chimney on a kerosene lamp (an electric lamp will not be suitable) were placed at the center of the sphere of which the mirror's curve is a very small part, all of that portion of the light that emerges from the pinhole and strikes the mirror, is reflected back to the pinhole; for these light rays are all radii of the sphere, and by reflection they must return as radii back to their source, the pinhole.

In practice, the pinhole is pushed over a little to the right of the center of curvature so that the cone of reflected light may clear the chimney and enter the eye, as shown in Figures 1, 3 and 9. The mirror is placed on its edge on some suitable support, at table height, in a fairly darkened room. The lamp

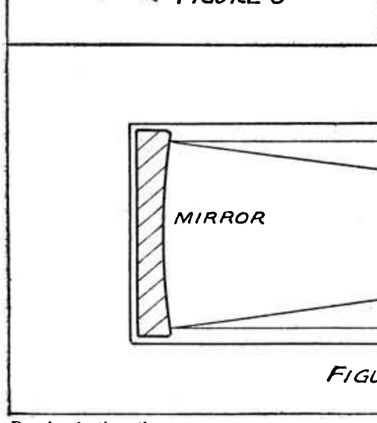


FIGURE 6

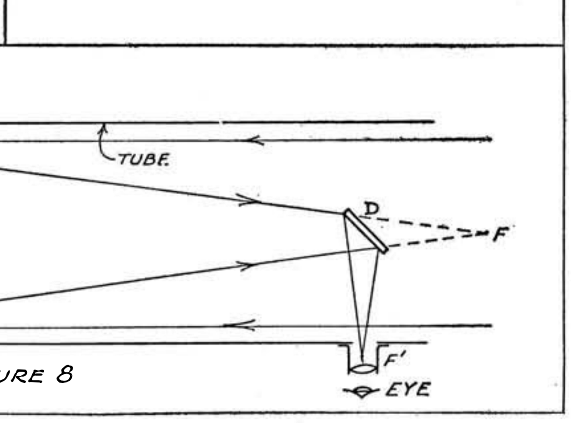


FIGURE 7

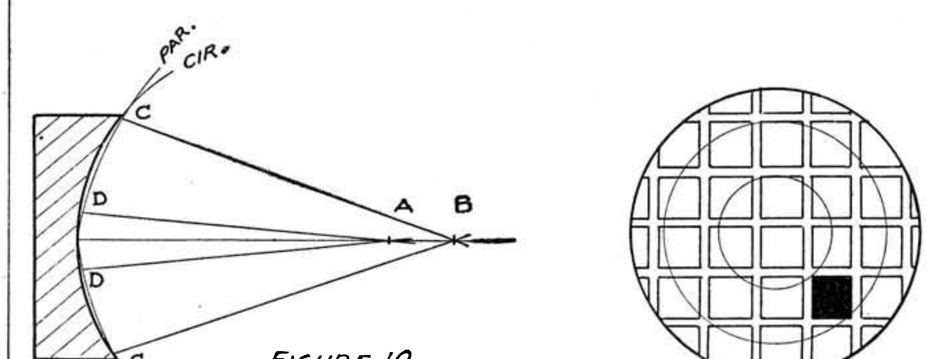


FIGURE 9

FIGURE 8

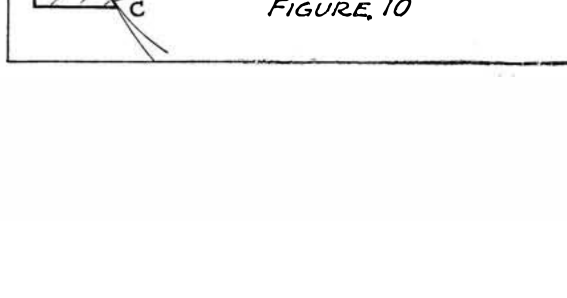


FIGURE 10

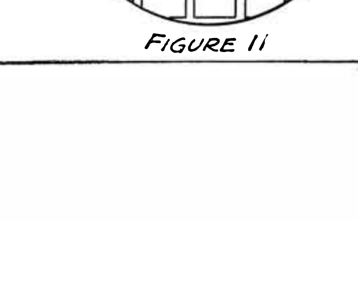
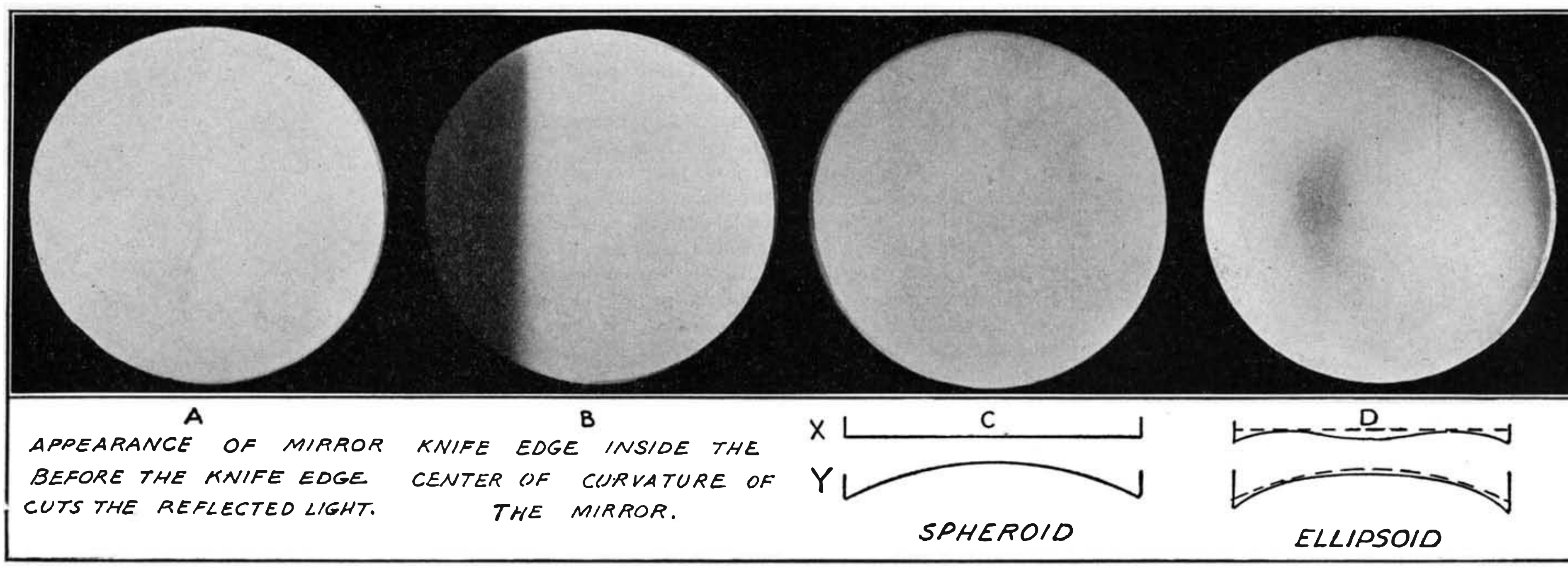


FIGURE 11

Drawings by the author



and the knife-edge (mounted on a block of wood) are placed on a table as shown, and about eight feet from the mirror, viz., at its center of curvature.

At first, considerable difficulty may be encountered in picking up with the eye the reflected cone of light. One way is to replace the tin chimney with a glass one, walk away from the lamp, keeping it in line with the mirror, when the image of the lamp will be seen in the mirror itself. Then bring the eye forward slowly, keeping the lamp image in view, and move the knife-edge to the right until it cuts off half of the image. The tin chimney is then put on and the image of the pinhole may be picked up somewhere near the edge of the safety razor blade. An alternate method is to use a piece of ground glass, which can be prepared by rubbing it with carborundum, to explore the neighborhood of the lamp, picking up the bright spot of light on it. As the eye approaches the position shown in the figures, this pinhole image begins to expand until a position is reached where the mirror is flooded with light over its entire surface—almost dazzling. (See shadowgraph A, above.)

Now comes the remarkable knife-edge test. The razor blade is moved in from the left until it cuts into the reflected cone of rays. If at a, Figure 9, that is, *inside* of the center of curvature, a shadow will come in on the mirror from the left, as might be expected (shadowgraph B). If, however, it cuts the rays at c, Figure 9, that is, *outside* the center of curvature, the shadow will advance over the mirror from the right, giving an appearance the reverse of shadowgraph B (or as B appears with the page turned upside down). But *at* the center of curvature, b, the mirror, if spherical, darkens simultaneously over its entire surface, becomes evenly gray (like shadowgraph C), and as the knife-edge is moved farther, it quickly vanishes. This is the simple test for a spherical surface, but it would be sheer luck if one's mirror appeared thus at the first test.

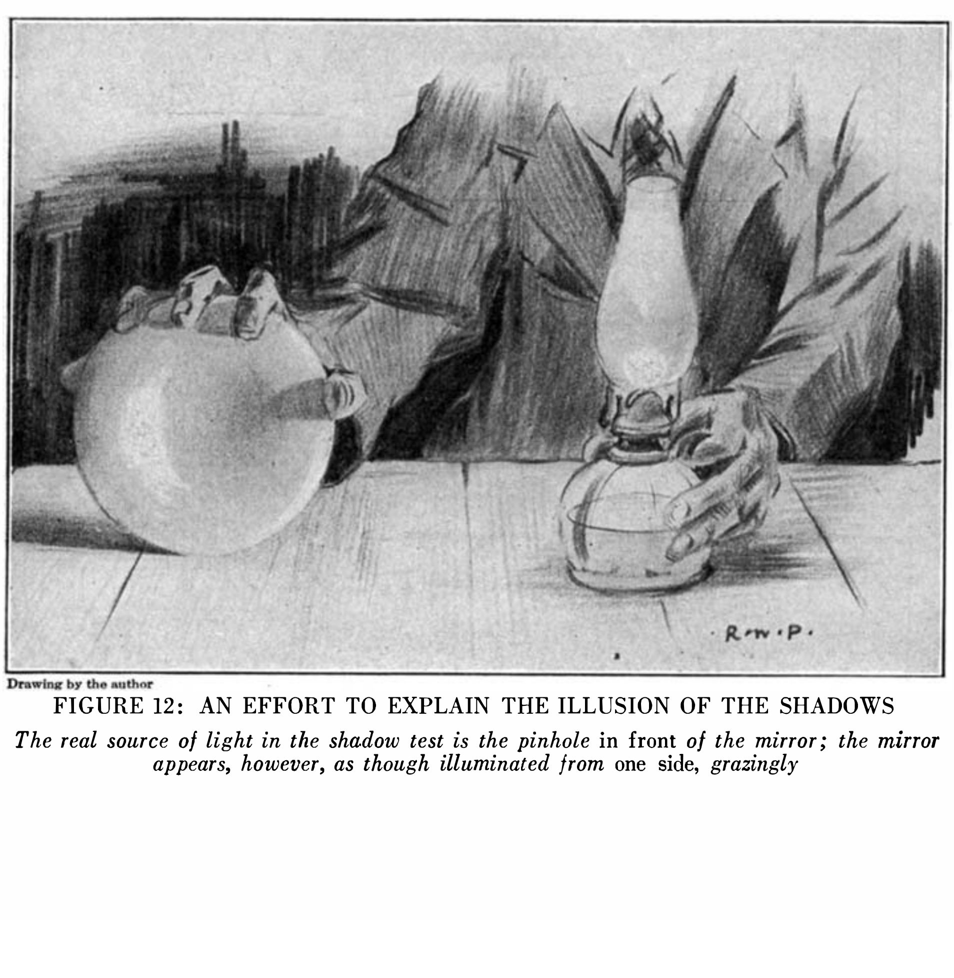
Viewed as just described, the surface of the curved mirror does not seem curved, but has the strange illusion of being flat. The observer *knows* it actually has a section like Y, under shadowgraph C, but it *appears* flat, like apparent section X, same place.

The surface having been brought to a sufficiently fine polish and to a spherical curve, the remaining work on the mirror, known as the "figuring," consists in slightly deepening this spherical surface into a paraboloidal surface, and this is done by polishing away the center faster than the edge. The final goal is to make the mirror appear, when the razor blade is beginning to cut off the light, like the shadowgraph E, F, or some intermediate depth, depending on the focal length, which need not be exact.

A common imperfection will be a raised or depressed zone, appearing like G and H in the shadowgraphs, whose true (lower) and apparent (upper) sections are shown beneath them. In the case of the raised zone the shadow has all the reality of a flat surface on which is a raised portion in the shape of a ring, the left slopes a, a, shadowgraph G, being in shade, the right slopes b, b, being in the light, *as though* the mirror were illuminated by a lamp placed on the opposite side of the glass from the knife-edge, as at X, in Figure 9. Figure 12 is an attempt to show how this imaginary lighting, at grazing incidence, *would* produce these shadows. Here the shadow of the man's fingers is superposed over the knife-edge shadow of a paraboloid. Conversely, a depressed zone (shadowgraph H) will have its lights and shades reversed.

Other characteristic shadowgraphs shown indicate curved surfaces well known to geometers under mouth-filling names. I would refrain from repeating them here for fear of throwing the novice into a panic of discouragement, but they must, nevertheless, be labeled for purposes of identification. Perhaps it will refresh the student's memory to note again the relations of these curves as shown in conic sections (Figure 14).

We have already considered the sphere whose section gives a circle (near top of cone, Figure 14). Its neighbors above (unlabeled) and below are the ellipsoid whose shadowgraph, shown at D of the shadowgraph series, presents a raised center and edge. The next curve is the parabola, its corresponding surface being the paraboloid, having an appearance the reverse of the ellipsoid, that is, an



Drawing by the author

FIGURE 12: AN EFFORT TO EXPLAIN THE ILLUSION OF THE SHADOWS

The real source of light in the shadow test is the pinhole in front *of the mirror; the mirror appears, however, as though illuminated from* one side, *grazingly*

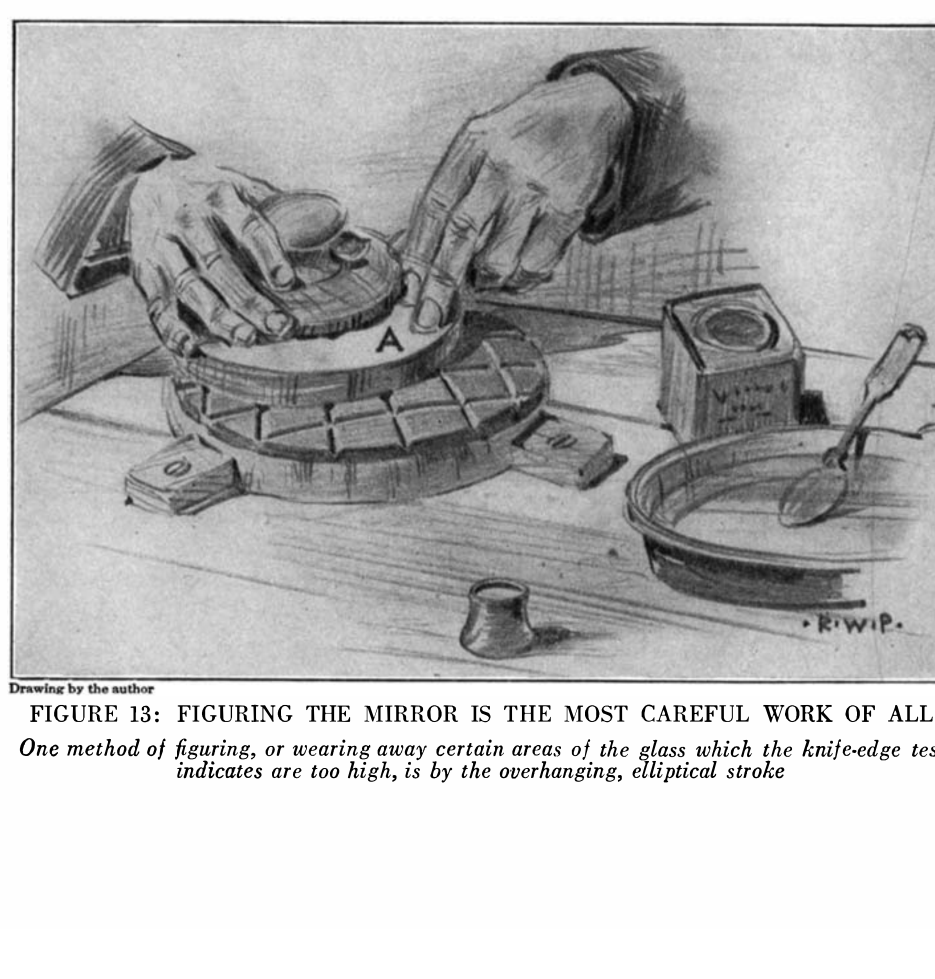


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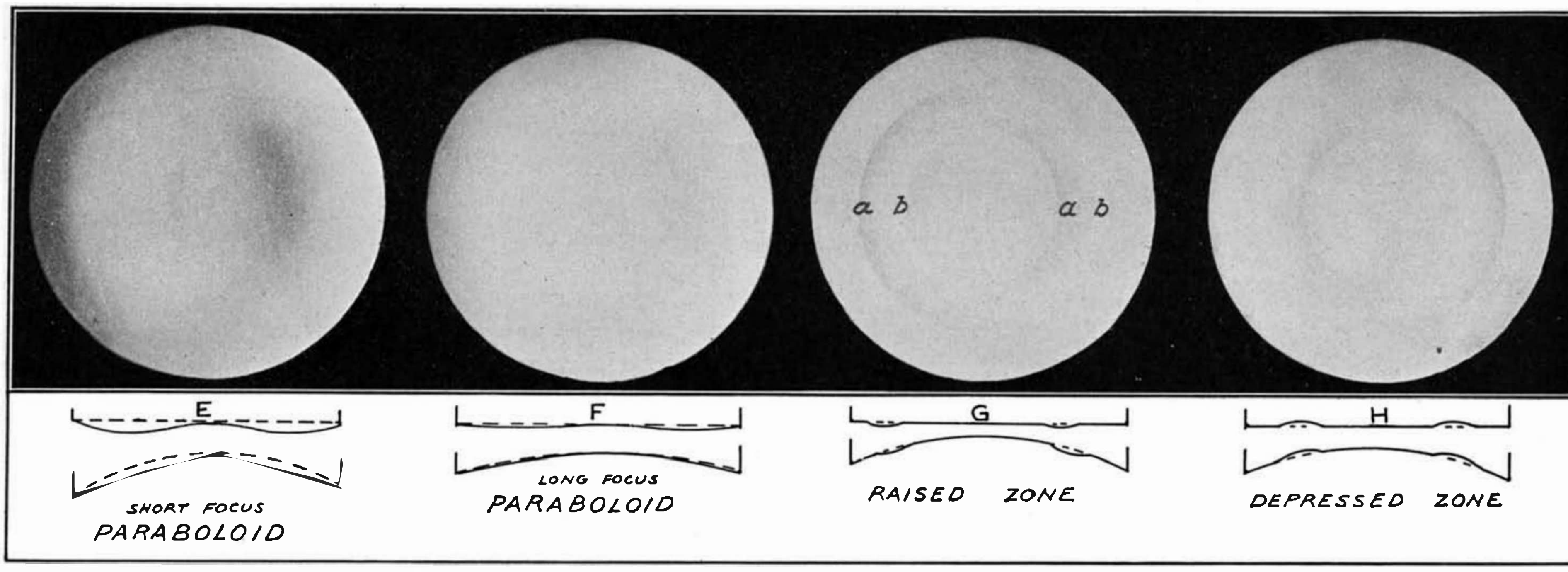
FIGURE 13: FIGURING THE MIRROR IS THE MOST CAREFUL WORK OF ALL

One method of figuring, or wearing away certain areas of the glass which the knife-edge test indicates are too high, is by the overhanging, elliptical stroke



apparently depressed center and edge, like a "Life Saver" candy with its central hole filled in. *This is the surface of a perfect telescope mirror.*

A paraboloidal mirror of short focus gives the stronger shade (shadowgraph E); a mirror of long focus gives a fainter shade (shadowgraph F). Our mirror, with focal length approximately six times its diameter, is about intermediate. The hyperboloid, corresponding to the hyperbola (Figure 14) is not shown in any of the shadowgraphs; its shadows are those of an exaggerated paraboloid, that is, quite dark, with the crest of the raised area nearer the edge of the mirror.

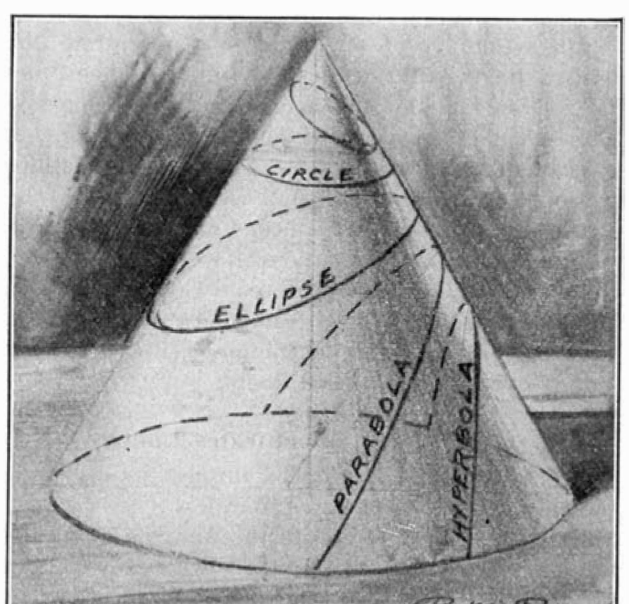
There is something uncanny about these shadows and shadowgraphs. As before mentioned, they should all be interpreted *as though* illuminated by light coming in from the right. But if one can force one's self to imagine these shadows as produced by light coming from the left, they will give an impression exactly the obverse. For example, in the case of the zone (shadowgraph G), one can change its appearance from a bas-relief to an intaglio, like shadowgraph H, by imagining it lighted from the left; and with a little experience one can make it perform in either manner at will. The rule is to consider the light coming from a direction opposite to the knife-edge. Ellison is almost unique among mirror workers in placing the light on the left and the knife-edge on the right.

Now all of these possible surfaces into which one's mirror may develop, are to be treated in the same way—the apparently raised portions are worn down to an apparently flat surface. There are several ways of accomplishing this result and all are described by Ellison in his book, at greater length than the present space could possibly permit. In general, a zone may be reduced by removing a part of the pitch lap, for it is evident that a square of pitch removed as shown in Figure 11 would tend to raise a zone on the mirror. The danger here is in producing unexpected zones, and the drawback of having to remake the lap (always a fussy job) if the altered pitch fails to correct the glass. Suffice it to say that, as explained in Ellison's book, there are several strokes and positions of the glass overhanging the tool that will bring almost any surface to that of the desired sphere, ready for the slight deepening into a paraboloid, without changing the lap.

This is the hardest, but at the same time the most fascinating, part of mirror making. Any one of these surfaces is so close to the sphere that no mechanical means could detect a difference between them. And yet, under the knife-edge, each type stands out glaringly with its own characteristic shadow—never to be forgotten when once seen.

Let us now assume that the mirror has been brought spherical—that it appears flat, under test. The curve now to be sought belongs to type E, F (shadowgraphs). This is very close to the sphere—so close that but a few moments polishing with a long stroke, or by letting the glass overhang the tool sidewise, will produce it. *Frequent testing is therefore essential during this crucial work of figuring the mirror.*

In Figure 10, the two curves represent sections of a sphere and of a paraboloid. It is evident that the parabolic curve is flatter at the margins, C, C, of the glass than at the central portion, D-D. Therefore light reflected from the pinhole will bring the



Drawing by the author

FIGURE 14

The curves we are dealing with are sections of a cone

rays from C and C to a point at B, on the axis of the mirror, further away than the point where the deeper part of the curve, D-D will focus them.

The distance between A and B is given from the equation, AB equals the square of the radius of the mirror, divided by its radius of curvature. Substituting for our six-inch mirror of four-foot focal length, we have, AB equals $(3)^2$ divided by 96, or 9/96, which is about one-tenth of an inch.

We now diaphragm out all of the mirror except a half-inch around the margin, and mark on the table the position of the knife-edge when the light darkens equally over the exposed portions. All of the mirror is then covered except a central portion two inches in diameter, and the knife-edge test is again applied similarly. This time, if the surface is correctly parabolized, we shall have to move the knife-edge toward the mirror one-tenth of an inch, as above determined. In both of the above tests, what we are really doing is to select limited parts of the parabola and regard each part as locally spherical; and then determine the degree of parabolization by ascertaining the difference in focal length of the respective spheres.

Silvering is now in order. The Bureau of Standards at Washington will provide, for the asking, a pamphlet describing the silvering process—how the glass is properly cleaned, the necessary chemicals and how they are used. Ellison also gives directions for silvering. It was some time before I produced a good, tough, silver coating, but if I had had access to the pamphlet referred to, there would have been no trouble.

Finally, if a lacquer (see appendix in Digest department), diluted six times with amyl acetate, is poured over the mirror and allowed to dry with the glass on its edge, the lustre of the silver will be prolonged for years, without in any way impairing its optical properties.

Nothing has been said here about scratches, effects of changed temperature on the glass, where best to work, testing with an eye-piece, testing at the focus, the dreaded turned-down edge, sticking of the glass, the various strokes and altered laps, and so on. Ellison covers them all.

Sir Howard Grubb, the well-known English maker of telescopes, is credited with the remark that "when the mirror has been brought to a complete polish, the work is about one-quarter done." And while it is true that the long interval of figuring with its interminable testing, tries the soul of the amateur, let him take pride in the fact that he is dealing with —and controlling—minute errors a thousand times smaller than those dealt with by a mechanic or machinist; and in the satisfaction of knowing that with this mirror made with his two hands he will be able to see the polar caps of Mars, Jupiter's bands, Saturn's rings, nebulæ, clusters and double stars—an instrument that would have excited the envy of even Galileo and Newton.

My experience has been this, that anyone who can use his hands, is possessed of moderate patience and sufficient reasoning ability to interpret the knife-edge shadows, can make a good mirror. Without these attributes he had better forego the venture.

Mirror making has many points to commend it. The tools are easy to make. The cost of materials is (compared to results) low. The work may be carried on at odd moments, day or night and in any available room of the home. In short, it contains the elements of a real indoor sport.

¶ *Next month Mr. Porter will describe a number of mountings suitable for the amateur's telescope.*