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ON THE MODERN REFLECTING TELESCOPE, AND THE MAKING AND TESTING OF OPTICAL MIRRORS

BY

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CENTRAL PART OF GREAT NEBULA IN ANDROMEDA. PHOTOGRAPHED BY G. W. RITCHEY, YERKES OBSERVATORY. TWO-FOOT REFLECTOR.

Enlarged 5.26 times
from original negative.

ON THE MODERN REFLECTING TELESCOPE, AND THE MAKING AND TESTING OF OPTICAL MIRRORS.

By G. W. Ritchey.

INTRODUCTION.

The present paper describes the methods employed by the writer in the optical laboratory of the Yerkes Observatory in making and testing spherical, plane, paraboloidal, and (convex) hyperboloidal mirrors. On account of the very great importance of supporting mirrors properly in their cells when in use in the telescope, a chapter is devoted to the description of an efficient support system for large mirrors. Intimately related to this, and equally important, is the subject of the mounting—the mechanical parts—of a modern reflecting telescope; accordingly, the final chapter is devoted to a consideration of this subject.

CHAPTER I.

DISKS OF GLASS FOR OPTICAL MIRRORS.

No greater mistake could be made than to assume that cheap and poorly annealed disks of glass, or those with large striæ or pouring marks, are good enough for mirrors of reflecting telescopes. While I am not prepared to say that optical glass of the finest quality must be used for mirrors in order to secure the best attainable results, it is evident that a very high degree of homogeneity and freedom from strain is necessary in order that the figure of mirrors shall not be injuriously affected by changes of temperature. If it were not necessary to consider the question of cost, I should advise the use of the finest optical (crown) glass always, in order to be as free as possible from risk; usually considerations of cost would, in the case of large mirrors, make it necessary to choose between such an optical disk of a given size and a somewhat larger one of the kind furnished by the St. Gobain

Company, for example. The diagonal plane mirror of a Newtonian, and the convex mirror of a Cassegrain reflector, should always be made of the best optical glass, since the expense for these is comparatively slight.

The writer has used many disks made at the celebrated glass-works of St. Gobain, near Paris, of sizes from 8 inches in diameter and 1½ inches thick, to the great one shown in the plates accompanying this article, which is 5 feet in diameter and 8 inches thick, and which weighs a ton. All of these disks are beautifully free from bubbles and large striæ, and are fairly well annealed, considering their great thickness. It is a most encouraging fact that the quality of the 5-foot disk is not inferior in any respect to that of disks of 8, 12, 20, 24, and 30 inches diameter which I have used. The makers of the 5-foot disk have recently expressed their readiness to undertake for us a 10-foot disk, one foot thick, which they think could now be made as perfect in all respects as the 5-foot disk. In ordering these disks it is always specified that great care be given to thorough stirring and thorough annealing. I have no doubt that in the case of very large and thick disks the makers could be prevailed upon to give even greater care to these points than is now given.

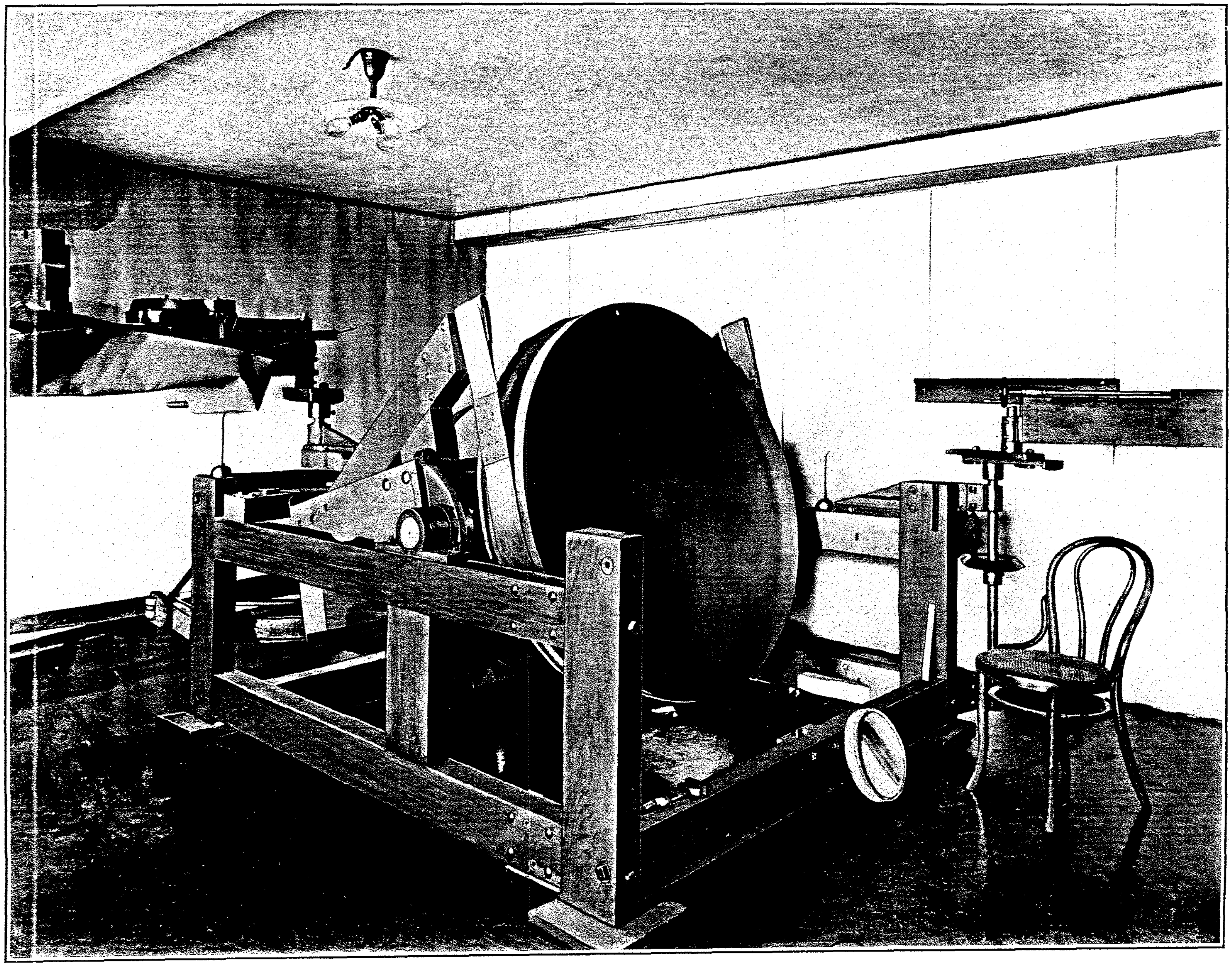
A very important point is in regard to the best thickness of optical mirrors. As a result of experience in making and using many mirrors of 24 and 30 inches diameter, in which the thickness of the several disks varies from one-twelfth to one-sixth of the diameter, I have no doubt that the thicker disks are always preferable, provided that they are as homogeneous and well-annealed as the thinner ones. The thinner mirrors suffer much greater temporary change of curvature from the very slight heat generated during the process of polishing; and they are undoubtedly more liable to suffer temporary disturbance of figure from changes of temperature when in use in the telescope. In the cases of the large paraboloidal mirror of a reflecting telescope, and the large plane mirror of a coelostat or heliostat, which should always be supported at the back to prevent flexure, the thickness should not be less than one-eighth or one-seventh of the diameter; in the writer's opinion the latter ratio leaves nothing to be desired. In the cases of the small diagonal plane mirror and the small convex mirror, which cannot easily be supported at the back, the thickness should be not less than one-sixth of the diameter.

All mirrors should be polished (not figured) and silvered on the back as well as on the face, in order that both sides shall be similarly affected by temperature changes when in use in the telescope; for the same reason the method of supporting the large mirror at the back, in its cell, should be such that the back is as fully exposed to the air as possible.

CHAPTER II.

THE OPTICAL LABORATORY OF THE YERKES OBSERVATORY.

A LARGE, well-lighted room, 70 feet long by 20 feet wide, in the north basement of the Observatory, was designed for the optical laboratory. The floor,



FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING METHOD OF TIPPING GLASS ON EDGE FOR TESTING.

which is nearly on a level with the ground outside, is of cement and is heavily painted. The walls are of brick, are about two feet thick, and are covered with two layers of heavy ceiling paper arranged so as to give two tight one-inch air-spaces for constant-temperature purposes. All joints of the paper are lapped and are nailed down with strips of wood. The ceiling of the room is heavily varnished.

The large room is divided into three rooms connected by large doors; these doors are so arranged that the entire length of the large room and of a wide hall opening from it, making an apartment 165 feet long, can be utilized for testing. The east and middle rooms of the three are used for grinding and polishing. The large windows of these rooms are fitted with storm sash on the inside; these are built in permanently and are made air-tight by means of ceiling paper. The west room contains the motor which supplies power to the grinding and polishing machines in the inner rooms; power is transmitted by a long shaft which runs the entire length of the rooms; this shaft is built in air-tight (to prevent dust) beneath the long work-bench which runs along one side of the rooms.

With these arrangements temperature, moisture, and freedom from dust can be controlled in the grinding and polishing rooms with all necessary refinement. In other respects, however, three great improvements could be made in planning an ideal optical shop; two of these relate to the comfort and health of the optician. First, the rooms should be arranged so that direct sunlight could be admitted to them during all parts of the optical work in which this would not be injurious to the work itself. Second, provision should be made for supplying to the rooms an abundance of fresh air, of a definite temperature, and washed free from dust. Third, for constant-temperature purposes, walls and partitions covered with a heavy layer of asbestos plaster (commercially termed Asbestic) would be preferable, on account of the superiority of the insulating and fire-proofing qualities of this material, to those of ceiling paper with air-spaces.

CHAPTER III.

GRINDING AND POLISHING MACHINES.

The grinding and polishing machines used by the writer are somewhat similar in principle to Dr. Draper's machine, shown in Fig. 25 of his book, but are more elaborate. I shall describe here the machine used in making the 5-foot mirror, both because it embodies most of the essential features of a grinding and polishing machine, and also because it is the only one of my machines of which I have a series of photographs for illustration. A good idea of this machine may be gained from the views of it shown in Plates II, III, IV, and VI.

The massive turntable upon which the glass rests consists of a vertical shaft or axis five inches in diameter, carrying at its upper end a very heavy triangular casting, upon which, in turn, is supported the circular plate upon which the glass lies. This plate is of cast-iron, weighs 1,800 pounds, is 61 inches in diameter, is heavily ribbed on its lower surface, and is connected to its supporting triangle by means of three large leveling screws. The surface of the large plate was turned and then ground approximately flat; two thicknesses of Brussels carpet are laid upon this, and the glass, with its lower surface previously ground flat, rests upon the innumerable springs formed by the looped threads of the carpet. No better support for a glass during grinding and polishing could be desired.

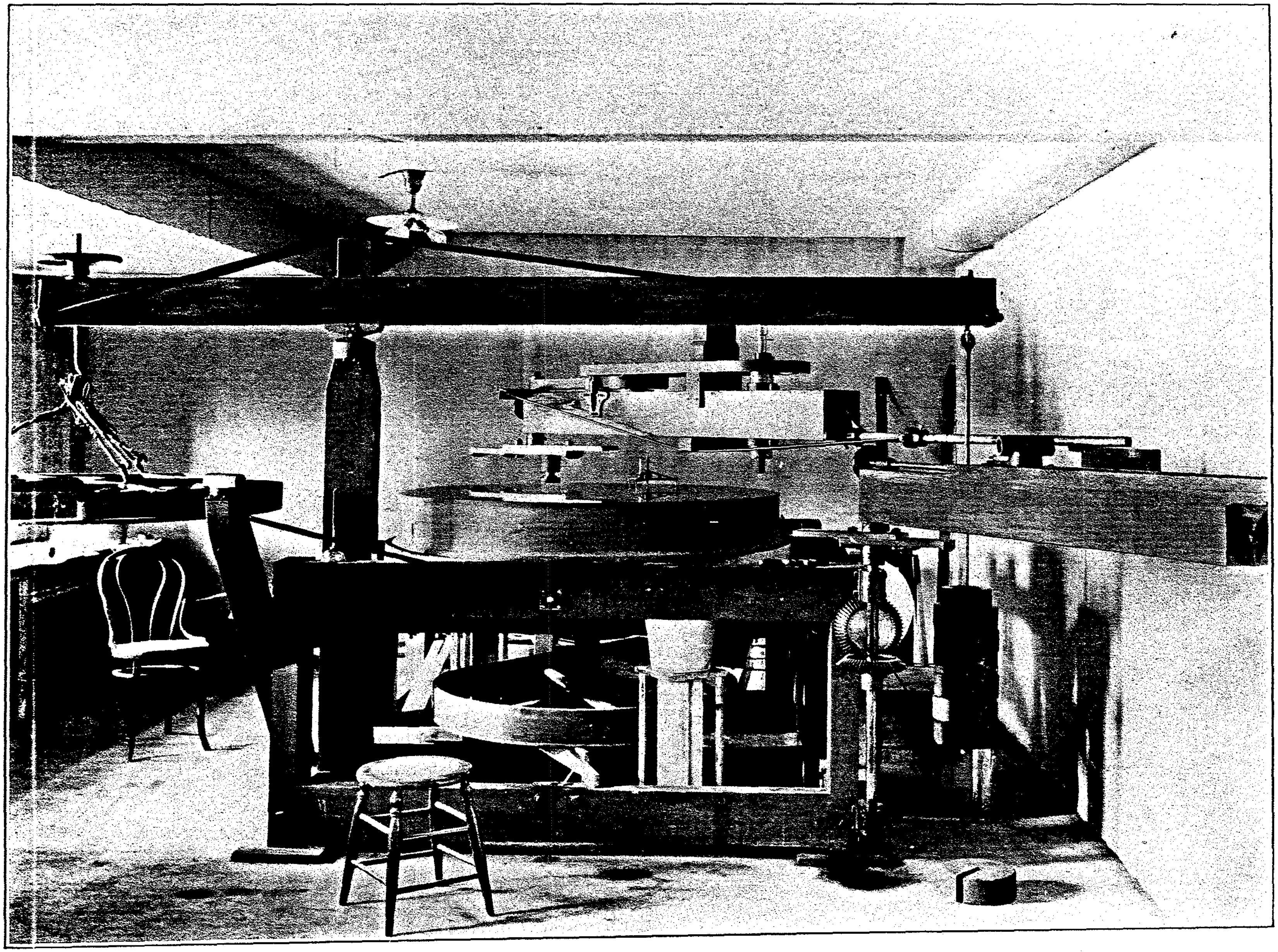
Three adjustable iron arcs at the edge of the glass serve for centering the latter upon the turntable, and prevent it from slipping laterally.

The entire turntable, with the heavy frame of wood and metal which supports it, can be turned through 90° about a horizontal axis, thus enabling the optician to turn the glass quickly from the horizontal position which it occupies during grinding and polishing, to a vertical position for testing. This is shown in Plate II.

The turntable is slowly rotated on its vertical axis by means of the large pulley below (Plate III). This rotation is effected by means of belting from the main vertical crank-shaft on the east end of the machine; this shaft is well shown at the left in Plate IV. At the upper end of this shaft is the large crank, with adjustable throw or stroke, which moves the large and strong main arm to which the grinding and polishing tools are connected, and by means of which they are moved about upon the glass. This I shall always refer to as the main arm. It is a square tube of oak wood, and is strong enough to carry the counterpoising lever shown in Plate IV, and the weight of any of the grinding tools, when fully or partially counterpoised. This main arm also carries the system of pulleys and belts by which the slow rotation of the grinding and polishing tools is rigorously controlled; these, and the manner in which this rotation is effected, are well shown in Plate IV.

The west end of the main arm consists of a strong steel shaft which slides in a massive bronze swivel-bearing which corresponds to the "elliptical hole in the oak block *p*" of Dr. Draper's machine (see his Fig. 25). But this bearing is not stationary as in Draper's machine; it is not only mounted on a long slide (which I shall refer to throughout this article as the transverse slide), so that it can be slowly moved for several feet across the west end of the machine by means of a long screw, but this bearing and slide are carried upon a secondary strong arm, which is moved by a secondary crank at the southwest corner of the machine. Unfortunately there is no photograph which shows this part of the machine as it appears when in use; Plates II and III show the secondary crank well, but the secondary arm is shown swung around with one end resting on a bracket on the wall, in order to have it out of the way.

The arrangement of the west end of the machine is the result of experience with several machines, and is found extremely serviceable and convenient. The long transverse slide on the secondary arm allows the grinding and polishing tools to be placed so as to act on any desired zone of the glass, from the center to the edge; and this setting can be changed as desired while the machine is running. The secondary crank, which turns at the same speed as the large one which drives the main arm, enables the optician to change as desired the width of the (approximately) elliptical stroke or path of the tool with reference to the length of this



FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING LEVER FOR HANDLING HEAVY GRINDING AND POLISHING TOOLS.

stroke; this change is especially desirable when figuring the glass; it is, of course, impossible when only one driving-crank is used.

I regard the transverse slide, or something equivalent to it, as absolutely necessary to the success of a grinding and polishing machine; it will be noticed that its purpose corresponds, in some measure, to that of the long slot in the main arm of Draper's machine; I have used both arrangements and have found the transverse slide to be far more effective and convenient in use; its use will be described in the chapters on grinding and polishing.

The secondary crank, while very desirable and convenient, for the reason given above, is not indispensable; I have used several smaller machines which have given good results without it.

The manner in which the grinding and polishing tools are connected to the main arm is shown in Plate IV. A vertical shaft, $1\frac{3}{8}$ inches in diameter and 24 inches long, both rotates and slides (vertically) freely in bronze bearings attached to the main arm. The grinding and polishing tools are connected to the lower end of this shaft through the medium of a large universal coupling,—a gimball or Hooke's joint,—with two pairs of horizontal pivots at right angles to each other; this allows the tools to rock freely in all directions in order to follow the curvature of the glass. The tools are lifted, for counterpoising them, by the lever above (see Plate IV), through the medium of the vertical shaft and the universal coupling. In the case of very massive grinding tools of moderate size, like that shown in this illustration, the universal coupling is connected directly to the back of the tool; but in the case of all large tools which are to be used for fine work this connection is made through the medium of a system of bars and triangles, so that the tools are counterpoised without the slightest danger of changing their shape. A small coupling with ball bearings at the upper end of the vertical shaft allows the latter to rotate freely with reference to the link which connects it to the counterpoise lever.

To recapitulate briefly: this method of connecting the grinding and polishing tools allows them to be controlled in all of the following ways simultaneously: (1) the stroke of the tool is given by the motion of the main arm; (2) the slow rotation of the tool is rigorously controlled by the belting above; (3) the tool is allowed to rock or tip freely by means of the universal coupling, in order that it may follow the curvature of the glass; (4) the tool rises and falls freely by means of the sliding of the $1\frac{3}{8}$-inch vertical shaft in its bearings, in order that it may follow the curvature of the glass; (5) the tool is counterpoised by means of the lever on the main arm, through the medium of the same vertical shaft and universal coupling.

In Plate III is shown the large lever by which the 5-foot glass, which weighs a ton, is lifted on and off the machine, and by means of which, also, the large grinding tools are handled. One of the full-size grinding tools, weighing 1,000 pounds, is shown suspended by the lever. The arrangements are so convenient that the optician alone can do all parts of the work.

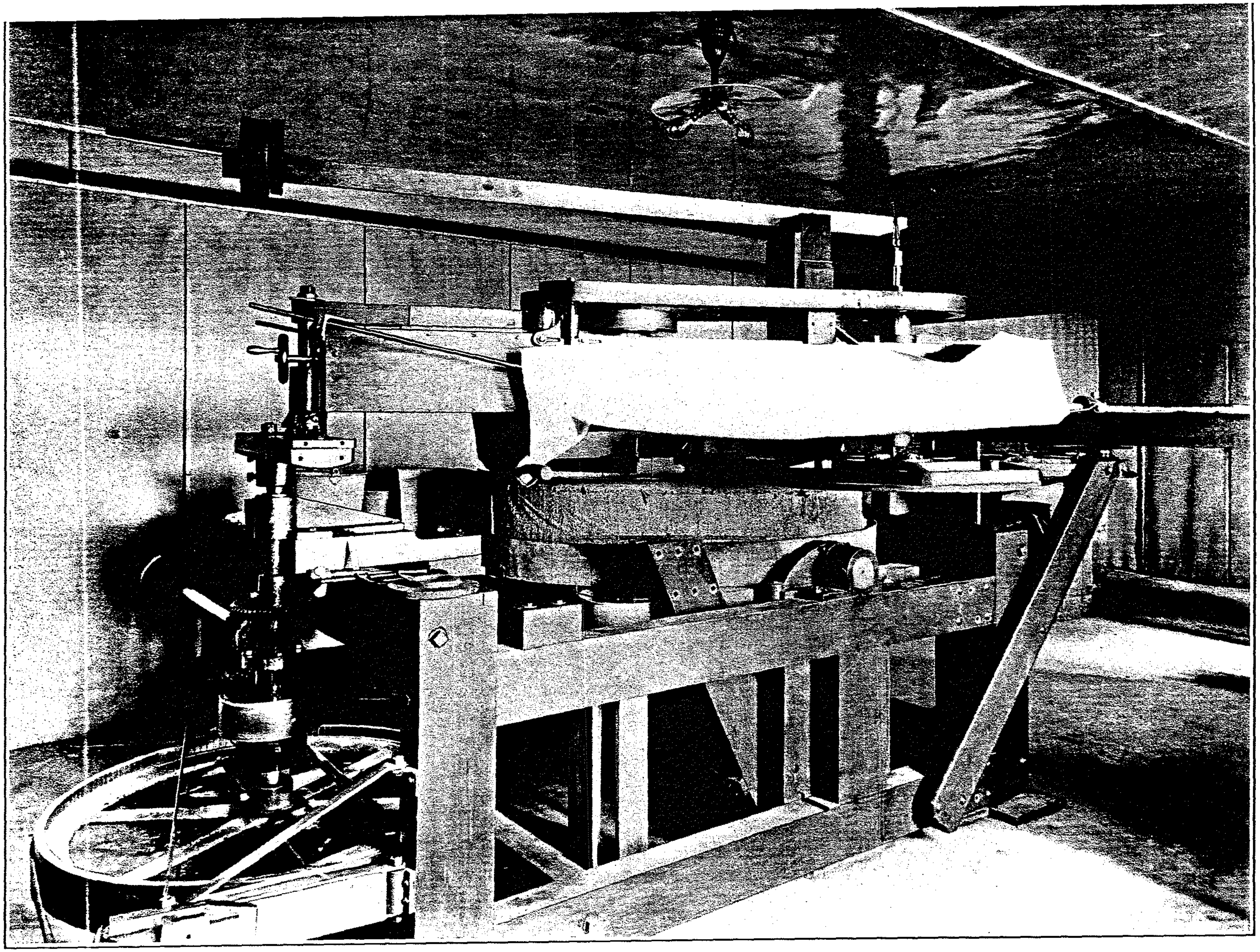
CHAPTER IV.

GRINDING TOOLS.

While grinding tools of glass were used in much of my earlier work, and are still used for small work, I now use cast-iron grinding tools for all large work. These are cast very heavy, with ribs on the back; the ribs are made heavy, but not deep (or high). For large work iron tools are cheaper than glass ones; they are more easily prepared; they are more easily and safely counterpoised, which is always necessary in the fine-grinding of large work; and they produce on the glass a fine-ground surface fully as smooth and perfect as can be obtained with glass tools.

An important question is in regard to the size of grinding tools,—whether they should be of the same diameter as the mirror. For mirrors up to 24 or 30 inches in diameter full-size tools are generally used. For concave mirrors larger than 30 inches in diameter I use grinding tools whose diameter is slightly more than half that of the glass, *i. e.*, a 16-inch tool for a 30-inch glass; a 32-inch tool for a 60-inch glass. These I shall refer to as half-size tools. Full-size tools are, of course, much more expensive and difficult to make; they are many times heavier than half-size tools of equal stiffness; and they require a much stronger grinding machine to counterpoise them properly; grinding can be done with them, however, more quickly than with the smaller tools. Half-size tools are economical and are quickly prepared; they are easily counterpoised; and a much greater variety of stroke can be used with them, so that with a well-designed grinding machine I have found it easier to produce fine-ground surfaces, entirely free from zones, with half-size than with full-size tools. If temperature conditions and uniform rotation of the glass are carefully attended to, the surface of revolution produced by the smaller tools is fully as perfect as that given by the larger ones; I always take the precaution, however, to work a full-size approximately flat tool on the glass before beginning to excavate the concave, so as to start out with a surface of revolution.

Grinding tools for concave and convex mirrors are always made in pairs, one concave, the other convex. Grinding tools for plane mirrors are made in triplicate. These iron tools, when being cast, are "poured" face down, so that the faces will be clean. I shall describe the preparation of a pair of iron tools for a concave mirror, leaving the description of tools for plane mirrors until the making of plane mirrors is discussed. The convex and concave tools are turned in a lathe to the proper curvature as shown by templets. The convex tool, which is, of course, to be used on the concave glass, is now placed on a planing machine, and has a series of grooves cut across the convex surface. These grooves are usually $\frac{1}{4}$ inch wide, and run in two directions at right angles to each other; these divide the surface into squares, which are usually made about one inch on a side. These grooves serve to distribute the grinding material uniformly, and entirely obviate the tendency of the tools to cling to the glass in fine-grinding. No grooves are cut in the concave tool. A number of holes are now bored through both tools, in such positions that wooden cups or funnels can be inserted into the holes from the back or ribbed side



FIVE-FOOT MIRROR AND GRINDING MACHINE.
SHOWING HALF-SIZE GRINDING TOOL SUSPENDED ON MAIN ARM.

of the tool, without interfering with the ribs; these cups serve for the introduction of the grinding material during the process of grinding; they should be thoroughly varnished.

The convex and concave tools are now ground together on the machine, with fine grades of carborundum (which is much more effective for this purpose than emery) and water. This eliminates the circular marks left by the lathe, and enables the optician to secure the exact curvature desired. A very important point is that by grinding with the concave tool on top, the radii of curvature of both tools can be gradually shortened; when the convex tool is used on top the curvature of both is gradually flattened. By this means, and the use of very fine grades of carborundum, a most perfect control of the curvature of the tools may be had.

The curvature of the tools and of the glass is measured by means of a large spherometer; this is shown in Plate v, resting upon a 12-inch glass grinding tool. The spherometer is of the usual three-leg form; the legs terminate in knife-edges, the lines of which are parts of the circumference of a 10-inch circle. The central screw is very carefully made; it was ground in its long nut (which was made adjustable for tightness) with very fine grades of emery such as are used in optical work; screw and nut were then smoothed and polished by working them together with rouge and oil. The screw is of $\frac{1}{2}$ millimeter pitch, and the head, which is 4 inches in diameter, is graduated to 400 divisions. On fine-ground surfaces settings can be made to one-half or one-third of a division, corresponding to a depth of $\frac{1}{40000}$ or $\frac{1}{60000}$ of an inch, approximately.

CHAPTER V.

POLISHING TOOLS.

After experience with polishing tools of various kinds, the tools which I now use exclusively for large work consist of a wooden disk or basis constructed in a peculiar manner, and covered on one side with squares of rosin faced with a thin layer of beeswax. The wooden disk may be replaced, in the case of small polishing tools up to 12 or 15 inches diameter, by a ribbed cast-iron plate so designed as to be extremely light and rigid; the bases of larger tools may be made of cast aluminum, but this, in order to be strong and rigid, must contain 15 % or more of other metals; such a basis for a 30-inch polishing tool weighs about sixty pounds, and the rough casting alone costs about fifty dollars. It is possible that a metal basis possesses an advantage over a wooden one in that its surface is less yielding. Tools properly constructed of wood, however, are light and extremely rigid, are easily made, and are economical in cost. As their proper construction is a matter of the utmost importance, I shall describe, somewhat in detail, the method of making wooden bases of from 15 to 40 inches diameter.

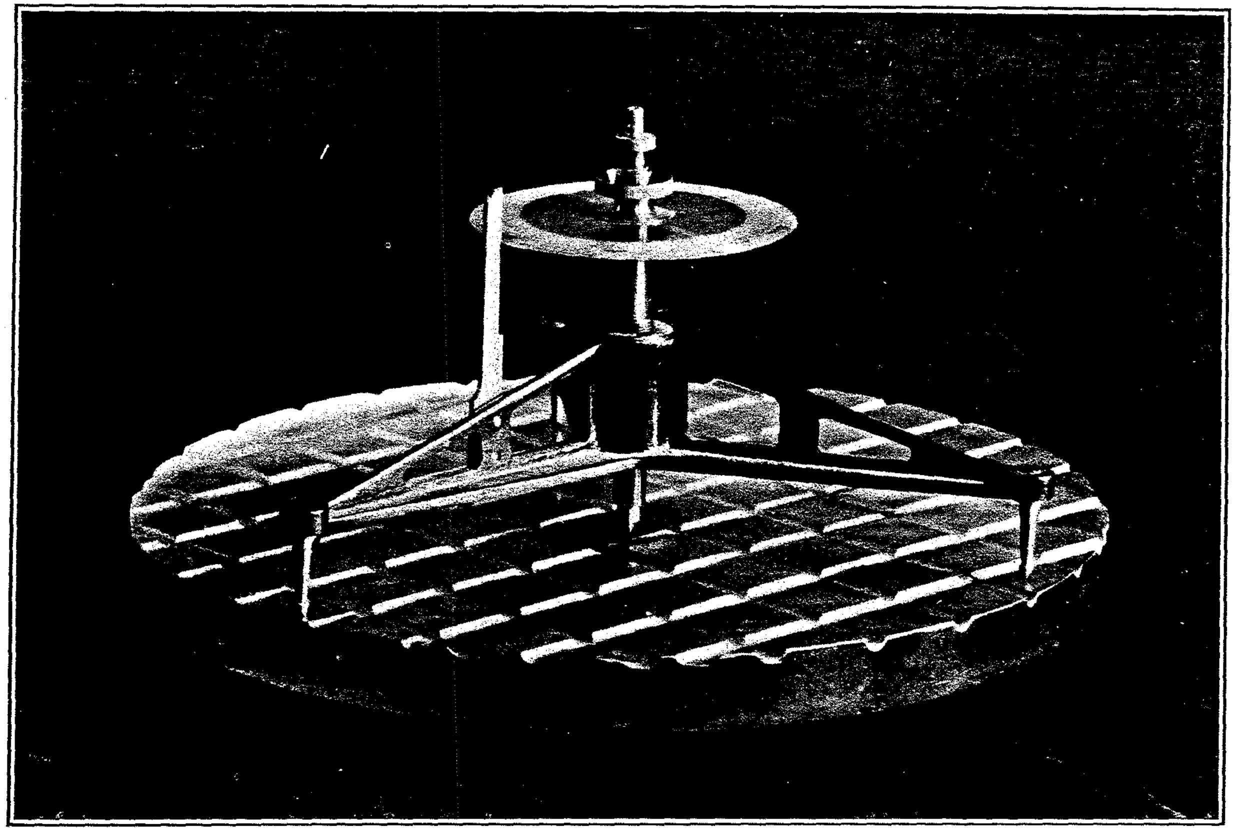
A large number of strips of dry and straight-grained pine wood $1\frac{1}{4}$ inches wide and $\frac{5}{16}$ inch thick are prepared; the wooden basis is built up of successive layers of these strips. The strips in all layers except the two outer ones are laid just $\frac{1}{4}$ of an inch apart. Those of each layer are placed at right angles to those of the next layer below, and are glued and nailed down with long wire brads. The best cabinet-maker's glue is used, and the strips are warmed before the glue is applied. Each crossing of the strips in the successive layers (*i. e.*, each of the $1\frac{1}{4}$-inch squares), is nailed with at least two nails. The upper surface of each layer is carefully planed flat before the next layer of strips is applied. For a 20-inch tool six layers of pine strips (each $\frac{5}{16}$ inch thick) are used; for a 24-inch tool, seven layers; for a 36-inch tool, ten layers. Next, one layer of thoroughly seasoned strips of hard straight-grained cherry wood about $\frac{3}{8}$ inch thick and slightly less than $1\frac{1}{2}$ inches wide is added, to form the outer layer at the back of the tool; these strips are laid almost touching each other. In the case of tools for flat mirrors, a precisely similar layer of cherry strips is added to form the outer layer at the front or face of the tool. But in the case of tools for concave or convex mirrors the strips composing the front layer must be made thicker, to allow for the curvature of the face of the tool. If this curvature is great, the cherry strips forming the front layer are made of double width (*i. e.*, slightly less than 3 inches wide), in order that the width of their bases shall be greater as compared with their thickness; this is usually done when the depth of the curve is greater than $\frac{1}{4}$ inch. The gluing and nailing of the outer layers of strips are done with the greatest thoroughness, four of the long fine nails being driven through into each of the squares of pine wood beneath. For tools less than 20 inches in diameter thinner strips and a larger number of layers are used. The entire thickness of the wooden disk or basis built up in this way should be between one-tenth and one-eighth of its diameter.

This wooden basis is next placed in a large lathe, the edge is turned smooth and to the proper diameter, and the face is turned to fit the curvature of the glass to be polished.

A round pan of galvanized iron large enough to contain the wooden disk having been prepared, enough hard paraffin is melted in it so that the disk can be soaked in the liquid paraffin; the latter must not be hotter than 150° Fahrenheit, otherwise the strength of the glue-joints will be injured. It is best to melt the paraffin on a gas or gasoline stove, so that the degree of heat can be easily controlled. The tool should soak for several hours, being moved continually and turned over often. Since the construction of the wooden basis is such that a great number of openings extend entirely through it, the melted paraffin permeates the entire tool thoroughly. The wooden tool prepared in this way is lighter than any metal tool of the same degree of stiffness, and is entirely impervious to the moisture which is necessary in the polishing room. The question of lightness is a most important one, as will be seen when the work of polishing is described later.

The front or face of the wooden basis is now lightly scraped with a wide, sharp chisel, to remove any excess of paraffin, and is then marked off for $1\frac{1}{4}$-inch squares of rosin, with grooves $\frac{1}{4}$ inch wide between them; the grooves should come exactly above the $\frac{1}{4}$-inch spaces left between the pine strips beneath.

The preparation of the rosin squares is usually a very troublesome matter, but



LARGE SPHEROMETER ON TWELVE-INCH GLASS GRINDING TOOL.

becomes easy when the following directions are observed. A clean, flat board, having an area about twice that of the polishing tool, is prepared. One face of this is covered with clean paper. Long strips of wood $\frac{1}{4}$ inch square are fastened upon the paper by means of fine brads; these strips are placed just $1\frac{1}{4}$ inches apart, and the ends of the grooves thus formed (grooves $1\frac{1}{4}$ inches wide, $\frac{1}{4}$ inch deep, and of any convenient length) are closed with strips of wood. The board is now carefully leveled. The rosin, when melted and softened to the proper degree, is to be poured into these grooves, which serve as moulds.

A quantity of rosin sufficient to fill all of the grooves is melted in a clean pan. Even when only a small quantity is needed it is best to melt at least ten pounds of rosin, since the entire process of "tempering" and pouring is more easily and satisfactorily carried on with large quantities than with small. Only lumps of clear, clean rosin should be used. A gas or gasoline stove is very convenient for melting the rosin, since the degree of heat can be easily controlled. When the rosin is melted the pan is removed from the stove and a quantity of turpentine, equal in weight to about $\frac{1}{25}$ of the rosin used, is added, and the mass thoroughly stirred. A tablespoonful of the liquid is now dipped out and immersed for several minutes in a bucket of water at the temperature of the polishing room, which should be about 68° Fahrenheit. The spoonful of rosin is now taken out, and its hardness tried with the thumb-nail. If the rosin is brittle at the thin edges it is still too hard, and a little more turpentine must be added; if, however, it is soft like wax or gum, it is too soft, in which case the pan of rosin must be hardened by boiling for a few minutes; this drives off the excess of turpentine. When the rosin is of the proper hardness an indentation about $\frac{1}{4}$ inch long can be made in it by moderate pressure of the thumb-nail for five seconds. When the proper degree of hardness has been obtained it is often necessary to heat the pan of rosin again so that it will not be too thick to pass readily through the strainer; this is a long, narrow bag of cheese-cloth through which the rosin is strained as it is being poured into the grooves or moulds previously described. If such heating is necessary it must be done gently and without boiling; otherwise the rosin will be hardened. Enough is poured into each groove to just fill it.

After being poured, the rosin should cool for six or eight hours. Then the nails which held the quarter-inch strips of wood to the board below are removed, and the layer of rosin, wooden strips, and paper is carefully lifted from the board, when the paper is easily stripped from the rosin, to which it does not adhere closely. With care the thin strips of wood can now be removed, one after the other, and the long strips of rosin, $1\frac{1}{4}$ inches wide and $\frac{1}{4}$ inch thick, are secured without chipping or breaking. These are now readily cut into squares with a hot knife.

The squares are attached to the previously marked wooden basis by quickly warming one face of each square over a flame and then pressing it gently against the tool with the fingers. The tool is now ready for rough-pressing.

Three strong eyes are screwed into the back of the tool, and it is suspended, face down (by means of wires connected to the ceiling of the room), so as to hang about two feet above the flame of a gas or gasoline stove. The tool can now be swung about so that the rosin squares are warmed uniformly. When the squares are slightly soft and very slightly warm, *but not hot*, to the touch, the tool is placed upon the previously ground glass which is to be polished, the glass having just previously been thoroughly wet with distilled water so that the rosin will not stick to it. Slight pressure may be exerted to assist in pressing the rosin surface to fit the glass. The tool will have to be slightly warmed and pressed several times before good contact is secured all over. I always prefer to "rough-press" the rosin tools on an iron grinding tool having the same form as the glass, if a sufficiently large one is available; but the precaution is always taken to cover the iron tool with clean wet paper.

The rosin squares will have spread somewhat irregularly during the rough-pressing; so the surface is marked with a straight-edge and knife, and the edges of the squares are trimmed so that the grooves between them are straight and of uniform width. This trimming is best done with a sharp knife, held so as to make an angle of about 60° with the surface of the tool, and drawn quickly toward the workman.

The rosin squares are now ready for coating with wax. A pound of best beeswax is melted in a large clean cup and is very carefully strained through several thicknesses of cheese-cloth into a similar clean cup. A brush is made by tying several thicknesses of cheese-cloth around the end of a thin blade of wood $1\frac{1}{4}$ inches wide. Each rosin square is now coated with a thin layer of wax, by a single stroke of the brush; the wax should be very hot, otherwise the layer will be too thick.

The tool is now ready for "cold-pressing" or "fine-pressing," a matter of the most vital importance, which will be more properly described later, in connection with the work of polishing the glass.

The work of making a large concave mirror will now be described in detail.

CHAPTER VI.

ROUGH-GRINDING THE FACE AND BACK OF A ROUGH DISK OF GLASS, AND MAKING THE SAME PARALLEL.

The rough disk of glass is placed upon the carpeted turntable, and a long strip of thin oilcloth is drawn around its edge; the upper edge of the oilcloth is securely fastened to the glass by means of a strong cord, and the junction between oilcloth and glass is made water-tight by means of water-proof adhesive tape. The oilcloth strip is wide enough to hang several inches below the edge of the iron plate on which the glass rests, so that the circular trough of galvanized iron, which can be seen in Plates IV and VI, catches all of the emery and water which are washed over the edges of the glass during grinding; this circular trough is stationary, has two holes in its bottom above the buckets, which can be seen in the plates, and is kept scraped clean by two scrapers which reach down into it from the revolving turntable. Several important results are thus secured: the carpet cushion under the glass is kept dry; the entire machine is kept perfectly free from the dripping of the grinding material; and all of the latter material is caught in buckets and is used again and again in the later and finer grinding.

The large irregularities of surface of large rough disks are usually ground away with coarse emery and a heavy, flat, half-size iron tool without grooves, the surface of which is rounded up considerably at the edge, so that the tool may rise easily over obstructing irregularities without breaking them. The grinding machine is set so that the half-size tool moves over the glass well out to one side of the latter; the rotation of the turntable of course brings all parts of the glass in succession under the tool; if the setting of the machine is such that the half-size tool passes in much beyond the center of the glass at every stroke, the surface of the latter will become concave.

When the marked irregularities of surface are ground away, the full-size, flat, grooved iron tool is put on. A tool of this kind is almost indispensable in making a mirror. Emery and water are supplied through the cups at the back of the tool, and the glass is quickly ground approximately flat. The glass is now turned over, and the other side is ground in a precisely similar manner.

The thickness of the glass is now tried, all around, by means of calipers. The approximately flat surfaces will probably be found to be far from parallel. If this is the case, the thick side may be ground down as follows: The belt which drives the turntable is loosened, until it will just rotate the latter, and a brake is arranged so that the workman can stop the rotation of the turntable at any desired point by pressing on the brake with his foot. A flat, half-size grooved tool is put on, and set so as to work far out to one side of the glass. A medium grade of emery (No. 70) is used, and the machine started. As the thick side of the glass, which has been marked, comes beneath the moving tool, the turntable is slowed down or stopped, so that a great excess of grinding is done on the thick side at each revolution. By distributing the grinding carefully, and trying the thickness often with the calipers, the upper surface is easily made parallel to the lower one. When this is done the full-size tool is again used for a short time. The glass is then ready for edge-grinding.

CHAPTER VII.

GRINDING EDGE OF GLASS.—ROUNDING OF CORNERS.

In order that an efficient edge-support, which will be described later, may be given to the glass, it is desirable that the edge of the latter be ground truly circular and square with the face. The manner in which this is accomplished is shown in Plate VI. The glass lies upon three large blocks of wood, which hold it several inches above the surface of the circular iron plate. Thin oilcloth is arranged about the blocks and over the iron plate, to keep them dry. A smooth, flat, iron face-plate is mounted (so as to rotate in a vertical plane) on a heavy lathe head-stock; the latter is carried upon a strong slide which can be moved toward the glass by means of a fine pushing-screw. The lathe and face-plate are driven at a high rate of speed by means of a belt. In the case of the 5-foot glass the face-plate used was 24 inches in diameter and made 1,000 revolutions per minute. For a 24-inch glass, $3\frac{1}{2}$ inches thick, a face-plate 11 inches in diameter, making 1,800 revolutions per minute, is used. A frame of wood, covered with oilcloth, is built around the face-plate, so that the grinding materials will not be thrown about the room. The glass rotates slowly with the turntable, as usual. Emery and water, or sand and water, are heaped upon the horizontal surface of the glass, and are slowly scraped toward and over the edge, so as to come between the revolving face-plate and the glass; a small jet of cold water, brought from the hydrant by means of a rubber tube, greatly assists in the uniform feeding of the emery, and also in preventing the generation of heat. But there is in reality no danger of heating, for the revolving face-plate *never actually touches the glass.* As the irregularities of the edge are ground away the face-plate is gradually moved forward by means of the slide and pushing-screw.

If the edge of the rough disk be very irregular, as is usually the case, the surface of the iron face-plate will have a circular groove worn in it, by the time the rough-grinding of the edge is done; in this case the face-plate should be turned flat and true again, and smoothed on a flat iron grinding-tool, before the edge of the glass is fine-ground. Several fine grades of emery are now prepared by the process of washing to be described later, and the edge-grinding is finished by the use, in succession, of three such grades of emery as flour, three-minute washed, and ten-minute washed. Care should be taken throughout the process that the edge of the glass is ground square with the face; any error in this respect can be corrected by slightly raising or lowering the outer end of the slide which supports the lathe head-stock.

Edge-grinding is accomplished very quickly in the manner described. The edge of a 24-inch disk four inches thick, even when very rough and irregular, has been ground and smoothed in ten hours of actual grinding. Despite the great speed of the rotating face-plate, I have never had any chipping of the glass or accident of any kind occur.

Before beginning the fine-grinding of the face and back it is well to round the corners at the edge of the glass. This is done by means of a smooth flat strip of sheet-brass of the size and shape of a large flat file; this is worked over the corners of the glass by hand, while the disk rotates slowly, emery and water being used for cutting. A "quarter-round" corner is usually made. Finer and finer grades of emery are used for smoothing the quarter-round. This rounding and smoothing are very necessary, as particles of glass from a sharp or rough edge are liable to be drawn in upon the surface by the action of the grinding tool during fine-grinding.

The wooden blocks are now removed and the glass replaced upon the carpeted turntable.

CHAPTER VIII.

FINE-GRINDING AND POLISHING THE BACK OF THE MIRROR.

Before discussing the work of fine-grinding I shall describe briefly the making of the fine grades of emery. I never buy finer grades than "flour." The latter grade is used with the full-size flat grooved tool to give a moderately fine surface to the glass after the rough-grinding previously described has made the front and back approximately flat and parallel. The residue of emery, fine ground glass, and water, resulting from the grinding with flour emery, is caught in buckets, as previously described. This residue is mixed with an abundance of water, in (for a large mirror) three or four clean granite-ware buckets, which are marked *A*. The contents of these buckets are thoroughly stirred, and are allowed to settle for two minutes; during this time all coarse particles will have settled to the bottom, and "two-minute" emery and finer grades remain in suspension in the water. The liquid is now quickly siphoned off, by means of a rubber tube, into other clean granite-ware buckets marked *B*, from which the handles have been removed. The contents of the latter are allowed to settle for four minutes, when the greater part of the liquid in each is carefully poured back into the buckets *A*. The contents of the latter buckets are reserved. The sediment remaining in the buckets *B* is the "two-minute" washed emery, with which the fine-grinding of the back is begun. After the grinding with this grade is finished, the residue from this grinding is mixed with what was reserved in the buckets *A*, the whole is stirred again and allowed to settle for five minutes, the liquid is siphoned off, and thus "five-minute washed" emery is secured. In a similar manner emeries which have remained in suspension in water for 12, 30, 60, 120, and 240 minutes are secured. In this way the large quantities of the finer grades which are necessary for large work can be secured as the work progresses. If accumulations of residues from previous work are available, some time will be saved by washing out all of the fine grades desired before the fine-grinding is begun.

Plane and concave mirrors are finished approximately flat on the back, as this form is most convenient for the application of the support-system. Fine-grinding of the back is usually done with the full-size, flat grooved tool, as this works rapidly. In this part of the work, in which the greatest refinement is not necessary, it is my custom to use the fine grades of emery (when these have all been prepared in advance) in succession, without stopping the machine or taking off the tool between grades for the purpose of cleaning the tool and the glass. The emery and water are supplied through the wooden cups at the back of the tool.

For a 24-inch mirror and its full-size tool, strokes varying from 6 to 8 inches in length are used with the 2-, 5-, and 12-minute washed emeries; shorter strokes, from 4 to 6 inches in length, are used with the finer grades. Considerable lateral displacement of the tool, amounting at the greatest to 2 or 2½ inches on the glass, is given at short intervals, by means of the transverse slide. On an average 20 double strokes per minute are given in fine-grinding a 24-inch mirror with full-size tool. Between 7 and 8 double strokes occur for each revolution of the glass and turntable.

With regard to counterpoising the tools during fine-grinding, the following statements may be made: My full-size iron tools for a 24-inch mirror weigh about 150 pounds, or $\frac{1}{3}$ pound for each square inch of area. This weight, or even $\frac{1}{2}$ pound to the square inch, is not objectionable with emeries down to 5-minute or 10-minute washed; but when this weight is allowed with finer emeries, scratches are liable to occur; indeed, with 30-minute washed and all finer grades they are almost certain to occur. The pressure on the glass is therefore decreased, by counterpoising the tool, to approximately $\frac{1}{5}$ pound to the square inch for 12- to 20-minute emeries, $\frac{1}{8}$ pound per square inch for 30- to 60-minute emeries, and about $\frac{1}{12}$ pound per square inch for 120- and 240-minute emeries. *This rule is followed, approximately, in all fine-grinding, whether of back or face.* This obviates, to a great extent, the danger of scratches in grinding, provided that thorough cleanliness is practiced in the preparation and use of the fine emeries. The apparatus by which the counterpoising is effected has already been described (page 5).

In fine-grinding a 24-inch glass, the 2-minute and 5-minute emeries are used for three-quarters of an hour each; the 12- and 30-minute emeries for one hour each, and the 60-, 120-, and 240-minute emeries for one and one-half hours each. The fine-ground surface resulting is so exquisitely smooth that it takes a full polish very readily.

The back of the glass is now ready to be polished. This is done with a half-size or two-thirds size polishing tool, which is moved about on the glass by the action of the machine precisely as a half-size grinding-tool would be. Optical rouge and distilled water are used, instead of emery and water. The work of polishing will be described in detail later, in connection with the work of finishing the face of the glass.

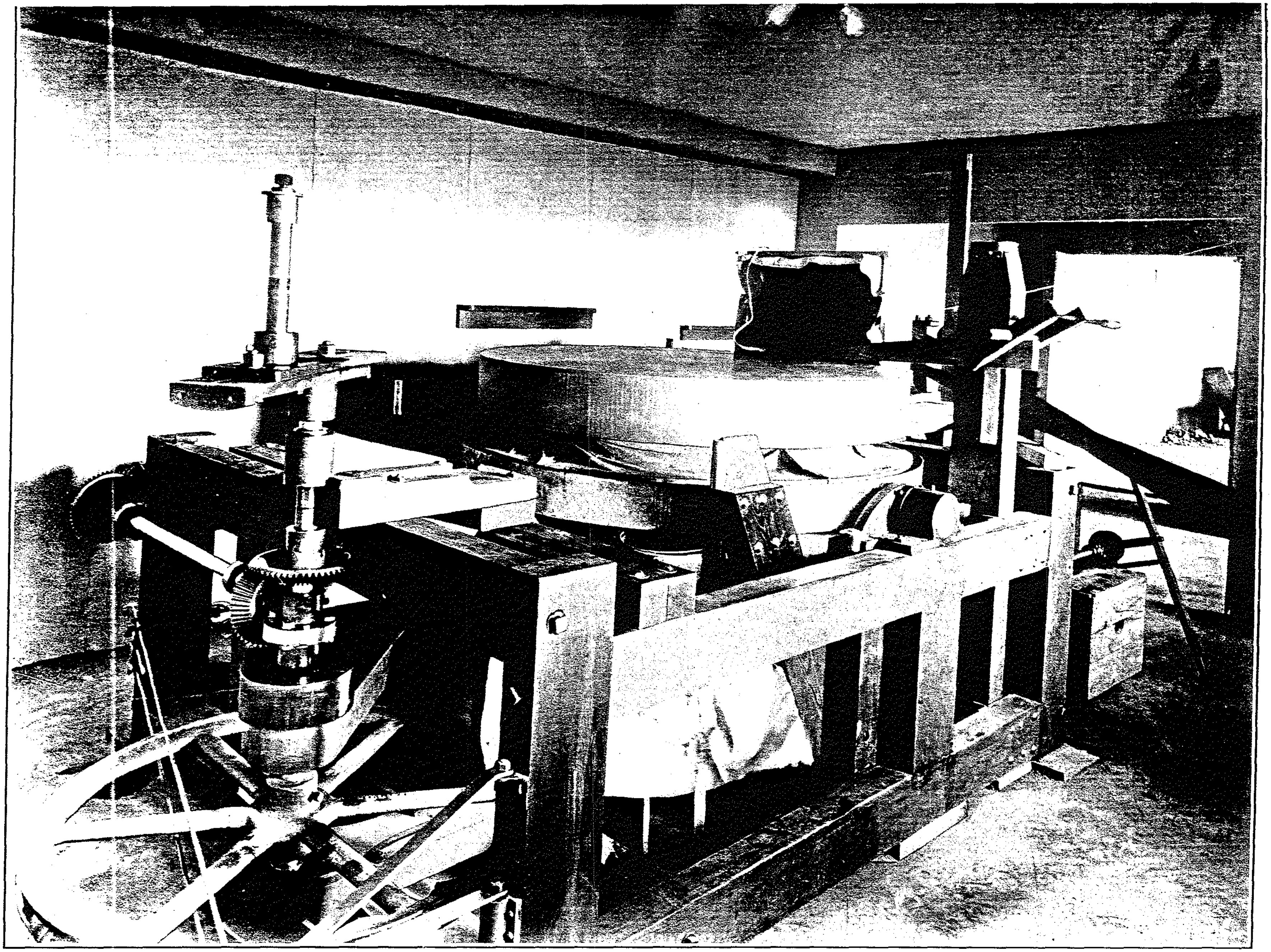
It is an excellent plan to fine-grind and polish the front surface of a disk also, approximately flat, as has been described for the back; the optician is then able to examine carefully the internal structure of the disk. Usually there is no choice as to which side shall be used for the face of the mirror, but this can readily be determined when both sides are polished. Plate VII shows the 5-foot disk with both sides ground and polished in this manner.

CHAPTER IX.

GRINDING THE CONCAVE SURFACE.

As before stated, it is my practice to use full-size grinding tools for concave mirrors up to 24 or 30 inches in diameter. For larger concave mirrors half-size tools are generally used. I shall first describe the grinding of a 24-inch concave.

The glass must be carefully *centered* by means of the three adjustable arcs attached to the supporting plate; these arcs must not be screwed tightly against the glass, lest the latter be strained; several thicknesses of heavy drawing paper are used between arcs and glass.



FIVE-FOOT MIRROR AND GRINDING MACHINE.
METHOD OF GRINDING EDGE OF GLASS.

The glass must also be carefully *levelled* (by means of the three large adjusting screws of the turntable) so that its upper surface is accurately at right angles to the axis of rotation; this is determined by rotating the turntable, and trying the surface with a surface-gauge. The band of thin oilcloth is securely bound around the edge of the glass, to keep the polished back and the cushion clean and dry.

The excavation of the concave is begun with moderately coarse emery (if the concave is to be quite deep) and a lead tool; this is a lead disk about 10 inches in diameter and $1\frac{1}{2}$ or 2 inches thick; it is easily turned in a lathe to the proper curvature; it is used on and near the center of the glass until a depression of approximately the desired curvature (as determined by the spherometer) and of 12 or 13 inches diameter is produced. A heavy iron tool about 13 inches in diameter, which has been turned and ground to the proper curvature, is now put on with about No. 90 emery. By giving careful attention to the length of stroke, and to the position of the tool on the glass as determined by the setting of the transverse slide, and by frequent trials of the curvature of the excavation with the spherometer, the diameter of the excavation is gradually increased, while its *curvature* is continually kept very near that which is desired for the finished mirror; this keeps the iron tool of proper curvature also.

The stroke used in this work should vary from 6 to 10 inches in length. As the size of the excavation increases, the setting of the transverse slide is continually changed so that the tool acts farther and farther to one side of the center of the glass; otherwise the radius of curvature will be shortened. When the diameter of the excavation has increased to about 22 inches, flour emery is substituted for the No. 90, and the grinding is continued as before. Care is now taken to make the curvature read exactly right with the spherometer. When the excavation becomes about 23 inches in diameter, the 13-inch tool is taken off, and the full-size, convex, grooved iron tool is put on; this has previously been fine-ground to the proper curvature on the corresponding concave tool. With this tool and washed flour emery the diameter of the concave on the glass is increased to $23\frac{5}{8}$ or $23\frac{3}{4}$ inches.

The fine-grinding or smoothing of the concave is now done with the full-size tool. The same grades of emery, the same lengths and speed of stroke, and the same rules in regard to counterpoising are used as have already been described in the case of fine-grinding the back of the glass (page 13). The length of stroke is changed every eight or ten minutes, and the lateral displacement of the tool (given by means of the transverse slide) is changed slightly at the end of every two or three complete revolutions of the glass. The tool is taken off after each grade of fine emery is used, and the tool and glass are carefully cleaned. With the assistance of the counterpoise lever the removal of the tool is effected easily and safely, without disconnecting it from the main arm of the machine; this is well shown in Plate IV, in which the grinding tool is shown hanging at one side of the glass.

The surface of the glass is examined with a microscope after each grade of emery is used, to make sure that no pits from previous grades remain.

During all fine-grinding and machine-polishing a large sheet of heavy clean paper or pasteboard is attached to the main arm in such a way that no particles of dust from the belts which control the slow rotation of the tools can fall upon the glass.

The process of grinding larger concave surfaces without the use of full-size tools is precisely similar to that described for a 24-inch mirror, up to the point of substituting the 24-inch convex tool; from this point the grinding is carried on by a continuation of the use of a half-size, convex grooved tool; this may be the same iron tool which has been used for enlarging the excavation. When the diameter of the excavation approaches that of the glass, the tool should be tested with the spherometer for curvature, and, if necessary, ground in its corresponding concave iron tool until its curvature is uniform and of exactly the desired radius. The grinding of the glass is then continued with washed flour emery until the edge of the excavation is within $\frac{1}{8}$ inch of the edge. Experience in the previous use of the half-size tool, in enlarging the excavation and in keeping the curvature of the glass uniform and of the desired radius, will enable the optician to decide upon the various lengths of stroke and the various settings of the transverse slide necessary in this grinding and in the finer grinding to follow.

In fine-grinding a 30-inch concave with a 16-inch tool, strokes varying from 6 to 12 inches in length are used; for a 9-inch stroke the *normal* setting of the transverse slide (*i. e.*, one which would tend neither to lengthen nor shorten the radius of curvature of the glass) would be such that the outer edge of the tool overhangs the glass about 3 inches in the forward stroke, while the inner edge of the tool passes about one inch on the other side of the center of the glass on the return stroke.

Throughout the entire process of fine-grinding with the half-size tool the length of stroke is changed once every eight or ten minutes; at the end of every two or three revolutions of the glass the setting of the transverse slide is changed, a little at a time, for a considerable distance on either side of the *normal* setting; the setting of the slide can be changed without difficulty, while the machine is running, by merely turning a hand-wheel. By these means the formation of zones of unequal focal length can be entirely avoided.

The same grades of emery are used, and the same rules in regard to counterpoising observed, as with full-size tools. Notwithstanding the fact that the length of stroke can be considerably greater than with full-size tools, each grade of emery must be used for a longer time, on account of the smaller area of the grinding surface. Glass and tool are thoroughly cleaned, and the surface of the former examined, after the use of each grade of emery, as before described.

Care must be taken during this work that the belts which rotate the turntable are kept tight, so that no irregularity in the rotation of the turntable with reference to that of the crank-shaft can occur. It is absolutely necessary that all of the fine work on large mirrors be done in rooms where no sudden changes of temperature can occur, and that nothing be allowed which might affect the temperature of the glass locally.

If the concave mirror is intended for a paraboloidal one, the fine-ground surface should be spherical, with its radius of curvature $2\,F + \frac{R^2}{4F}$, where F is the desired focal length of the finished paraboloid and R is the semi-diameter of the mirror; the reason for this is fully explained later. I have never attempted to parabolize while fine-grinding; it is possible that it might be well to do this in the case of very large mirrors of short focus, but my practice has been to fine-grind and polish to a spherical surface, free from zones, and then to parabolize by means of suitable polishing tools.

CHAPTER X.

POLISHING.

THE preparation of polishing tools has already been described. The polishing rouge which I use is of the quality which is used in large quantities commercially in polishing plate-glass. I prefer the powdered form always. This grade of rouge is not expensive (it costs about 30 cents per pound), but, like all rouge which I have seen, it contains hard, sharp particles which may cause scratches. It must therefore be thoroughly washed in the following manner:

In a clean, deep bowl *C* enough rouge is placed to fill it about one-third full; the bowl is then nearly filled with distilled water. The mass is very thoroughly stirred with a clean wooden paddle, and allowed to settle for about twenty minutes. The water above the rouge will now be perfectly clear; this water is siphoned off. With a clean spoon the light and fine rouge constituting the upper one-third of the precipitated mass is removed, and placed in a second clean bowl *D*. The rouge remaining in *C* may be again stirred up with an abundance of distilled water, and allowed to settle as before, the water siphoned off, and the upper one-fourth of the precipitated rouge removed and placed in *D*. The heavier rouge which remains in *C* is about half of the original quantity taken; this is usually reserved, and, after further washing, is used for polishing the backs of mirrors, and for similar work. Only the contents of the bowl *D* are used for fine work, and these are stirred up again and again with distilled water during the process of polishing, and only the fine, soft cream which remains on the top of the mass of rouge, when it settles each time, is used for polishing.

The thin cream of rouge and distilled water is applied to the glass by means of a wide brush consisting of a thin paddle of wood with clean cheese-cloth wrapped and tied about one end. Brushes of the usual kind should not be used.

By taking these precautions, and by the use of the wax surface on the rosin squares, scratches in polishing can be entirely avoided. It is true that the very light, fine rouge polishes more slowly than the heavier and coarser rouge, but an exquisitely fine polished surface is produced on the glass by its use. The wax surface also polishes more slowly than a bare rosin one, but it has the very great advantage that its action is more smooth and uniform than that of the rosin surface; the latter often tends to cling to the glass, and this unequally in different parts of the stroke.

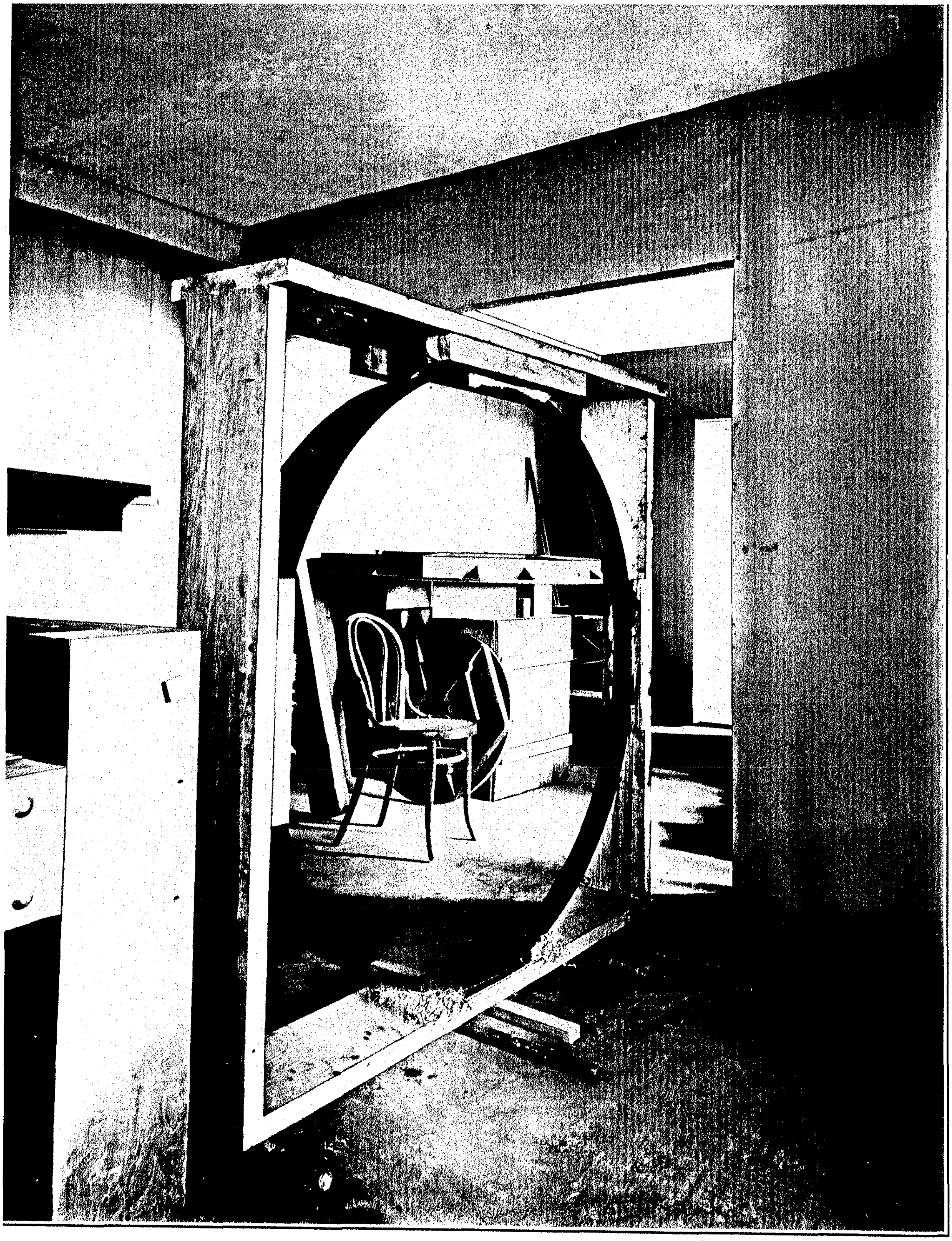
The same question arises in regard to the size of polishing tools as in the case of grinding tools,—whether they shall be full-size or smaller. In the writer's opinion fine plane and spherical surfaces up to about 36 inches in diameter are best polished with full-size tools, which are moved by hand, by the optician and one or two assistants, upon the surface of the slowly rotating glass. The upper parts of the machine are, of course, removed during such polishing, which I shall call manual polishing.

A 24-inch polishing tool, prepared as already described, with its wooden basis $2\frac{3}{4}$ inches thick, weighs about 25 pounds; this is not heavy enough for the best action in polishing; so about 50 % additional weight is put on in the form of 12 lead blocks which are distributed uniformly and screwed to the back of the tool. This gives a weight of about $\frac{1}{12}$ pound for each square inch of area, which is found to work well for all large tools. For tools 18 inches or less in diameter somewhat greater pressure per square inch of area may be used. A 36-inch tool, with wooden basis $3\frac{3}{4}$ or 4 inches thick, weighs 75 or 80 pounds, and needs no additional weighting.

The work of polishing a 24-inch mirror with full-size tool will now be described. Six strong knobs of oak wood are screwed to the back of the wooden basis, each knob being at the center of weight of each sixty-degree sector of the tool. These knobs serve for pushing, pulling, and lifting.

The polishing tool, which, with the glass, should have cooled over night after the warm-pressing or rough-pressing previously described, is now to be cold-pressed. Cold-pressing is absolutely necessary in all fine work on large optical surfaces. In warm-pressing, both tool and glass are distorted by even slight warming, and when they become cool a perfect fit cannot be expected. The glass is carefully wiped with clean cheese-cloth, and an abundance of very thin mixture of rouge and water is spread upon it. The tool is now placed upon the glass and allowed to lie for several hours, being moved about slightly every ten minutes to redistribute the rouge and water, and to prevent the latter from drying around the edges. The pressing may be assisted at first by means of a 20- or 30-pound weight, the pressure of which *must* be distributed by some such means as three bars laid upon the six knobs, and a triangle, carrying the weight, laid upon these. The final cold-pressing must be done by the weight of the tool alone. The tool is taken off and examined occasionally; when it is sufficiently pressed the wax surface appears uniformly smooth and bright. So perfect a fit is secured in this way that there is no danger of injuring the form of the glass when polishing is begun. This applies to all stages of polishing and figuring. A fresh supply of rouge and water is now spread upon the glass.

The stroke of the 24-inch polishing tool is easily given by the optician and one assistant, who sit on opposite sides of the machine; the glass slowly rotates with the turntable, making about 2 revolutions per minute. The knobs on the back of the tool are held in the hands, and the stroke is given by alternately pushing and pulling; no vertical pressure whatever should be given by the hands. In addition, a considerable side-throw is always given, first to one side, then to



FIVE-FOOT MIRROR WITH FRONT AND BACK POLISHED APPROXIMATELY FLAT.
LOOKING THROUGH THE GLASS.

the other; this greatly assists in preventing the formation of zones of unequal curvature. Polishing may be begun with a stroke 6 inches in length, which of course causes the tool to overhang the glass 3 inches at the ends of the stroke; between 20 and 25 double strokes per minute are given. The side-throw used with this length of stroke is about 2 inches, *i. e.*, the tool is made to overhang the glass about 2 inches, first to the right, then to the left; the time occupied in passing from the extreme right to the extreme left is about what is required for 4 double strokes. This stroke and side-throw are continued while the glass makes exactly 2 revolutions; the tool does not rotate with the glass, of course, while the stroke is being given; the last stroke should end with the tool central upon the glass.

Tool and glass are now allowed to rotate together for $\frac{5}{6}$ of a complete revolution, and each optician then grasps the pair of knobs next to that which he held before, so that the stroke is now given along a diameter of the tool 60° from that last used; the length of stroke is now changed to 7 inches, and the side-throw to $2\frac{1}{2}$ inches, and polishing is again carried on during exactly 2 revolutions of the glass. Tool and glass are again allowed to rotate together for $\frac{5}{6}$ of a revolution, and polishing during 2 revolutions is now done with a stroke of 8 inches and side-throw of 3 inches. During the next periods of polishing, each of 2 revolutions of the glass, the stroke and side-throw are gradually shortened until a stroke of 4 inches or less is reached; then the length of stroke is increased again.

When polishing has been carried on during 6 or 8 periods of 2 revolutions each, it will be found necessary to supply more rouge. The only entirely satisfactory method of doing this, when a full-size polishing tool is used, is to remove the tool from the mirror, and quickly spread the thin cream of rouge and water upon the glass as uniformly as possible with the cheese-cloth brush. The removal of the tool is effected by the two opticians carefully sliding it off the mirror, and lifting at the same time. The tool should be allowed to remain off the glass for only as short a time as possible, so that the form of the latter shall not be altered as a result of a change of temperature of the surface, caused by evaporation. For this and other reasons, such as the prevention of dust, the air in the polishing room should be kept moist by keeping the floor well sprinkled.

When the tool is replaced on the mirror it is lifted by both opticians so that only a very small part of its weight remains on the glass, and is lightly moved about, for 30 seconds or more, to distribute the rouge and water thoroughly before polishing is continued. As before stated, the method just described is the only entirely satisfactory one, known to the writer, of supplying rouge during the polishing with a full-size tool. All methods of supplying rouge at the edge, or through holes in the tool, are inadmissible when the greatest refinement of figure is required.

It is in order that they may be easily handled in the manner described that full-size polishing tools should be made light. It would, of course, be possible to devise mechanism by which tools of any size and weight could be sufficiently counterpoised, could be moved about upon the glass, and could be removed from the latter for the purpose of supplying rouge. The simple and economical method which I have described, however, works well for mirrors up to 36 or 40 inches in diameter. For larger mirrors it is more economical, in the opinion of the writer, to use half-size tools for obtaining a fully polished spherical surface, and the same and smaller tools for parabolizing. The method of using these will be described later.

In general, it is much easier to prevent the formation of zones, and to eliminate zones already present, with full-size polishing tools than with smaller ones. The method of manual polishing just described, in which the length of stroke and the amount of side-throw are very frequently changed, tends to give a spherical surface, except for a zone around the edge of the mirror one-half an inch or less in width; this part of the surface will be of too great focal length, *i. e.*, will turn down or back slightly, unless means are taken to prevent it. This tendency is most pronounced when a long stroke is used to excess, or when the rosin squares are too soft. It is entirely prevented by diminishing the area of the rosin squares around the edge of the tool, by trimming their edges to such a form as is shown in Fig. 4, page 28. The exact amount of trimming required depends upon the length of stroke, hardness of rosin, and temperature of polishing room, and therefore can be exactly determined only by experience.

A 24-inch mirror which has been properly fine-ground with emeries down to 2-hour or 4-hour washed, is readily brought to a perfect polish with a full-size tool in from 2 to 4 hours of actual polishing. If several broad zones of different focal lengths have resulted from the fine-grinding, as frequently happens, these zones can be gradually eliminated by a continuation of the use of the full-size polisher as above described.

Attention must be given to the rosin squares, which gradually press down so that their edges must be trimmed to keep the grooves of their original width and of uniform width. When the bare rosin begins to show at the corners or edges of the faces of the squares, which will occur after 6 or 8 hours' use of the tool, a new coat of wax must be applied, and the tool must again be thoroughly cold-pressed. It must not be supposed, however, that cold-pressing is necessary only at such times; in all fine work this pressing must be done whenever the tool has remained off the glass for more than a few minutes; after hanging face down during the night the tool is always cold-pressed for about 2 hours before polishing is begun in the morning.

Polishing with half-size or smaller tools is best done with the machine, instead of by manual work. These tools do not have to be removed from the glass in order to renew the supply of rouge; they are therefore connected to the machine and used very much as half-size grinding tools are used; in my work they are made of such weight that they need not be counterpoised. Very large or unusually heavy polishing tools of this kind can, of course, be easily counterpoised when desired.

Great experience, constant attention to very frequent changing of the position of the tool by means of the transverse slide, and frequent testing of the form of the mirror surface are necessary in polishing with half-size or smaller tools, in order to preserve the uniform curvature of the surface. This is greatly facilitated by trimming the rosin squares at and near the edges of the tool, as in the case of full-size tools, but to a greater extent; the effect of the action of the edges of the tool is thus softened or blended.

When a half-size or smaller tool has just been coated with wax, or is known to be far from the exact form desired, it is first cold-pressed in the usual way on the center of the glass. But the final cold-pressing of such tools should be done as follows: The entire surface of the glass is painted with rouge and water, and the machine is set to give a "normal" stroke, *i. e.*, one by which the tool is made to cover the entire surface of the mirror as uniformly as possible (without an excess of action on any zone) as the glass revolves; the machine is run extremely slowly, and the setting of the transverse slide is changed often; after pressing the tool for an hour or two in this way, polishing or figuring is to be begun.

CHAPTER XI.

TESTING AND FIGURING SPHERICAL MIRRORS.

Before describing the work of figuring concave mirrors, which is done with polishing tools, it will be necessary to consider methods of testing. The principles involved in testing concave mirrors at their center of curvature by Foucault's method have been thoroughly explained and illustrated by Draper on pages 13–19 of his book, and by Dr. Common in his book *On the Construction of a Five-Foot Equatorial Reflecting Telescope.* Foucault's original paper on this subject may be found in Vol. V of the *Annals of the Paris Observatory.*

All mirrors, when being tested, are placed on edge, so that the axis of figure is nearly horizontal, large mirrors being suspended in a wide, flexible steel band, lined with soft paper or Brussels carpet; for glass mirrors larger than 30 inches in diameter it is very desirable to have the grinding and polishing machine so constructed that the glass can be turned down on edge for testing, in the manner shown on Plate II, without removing it from the machine. A 30-inch glass mirror 4 inches thick weighs about 260 pounds; mirrors larger than this are difficult to handle without suitable mechanism.

A small, brilliant source of light, or "artificial star" may be produced by placing in front of the flame of an oil lamp a thin metal plate in which a very small pinhole has been bored. If the illuminated pinhole be placed about an inch to one side of the principal axis of the mirror, and at a distance from the mirror equal to its radius of curvature, a reflected image of the pinhole will be formed on the other side of the axis, and at the same distance from it and from the mirror as the corresponding distances of the pinhole itself. If the surface of the mirror is perfectly spherical, and if there are no atmospheric disturbances in the course of the rays, the reflected image, when examined with an eyepiece, will be found to be a perfect reproduction of the pinhole, with the addition of one or more diffraction rings around it, minute details of the edge of the pinhole appearing as exquisitely sharp and distinct as when the pinhole itself is examined with an eyepiece. If the eyepiece be moved outside and inside of the focus, the expanded disk in both cases appears perfectly round. Nothing can be more impressive than to see such a reflected image produced by a fine spherical mirror having a radius of curvature of 100 feet or more. Several such mirrors of 2 feet aperture have recently been finished here.

The use of an eyepiece is interesting for such experiments as that just described, and is important as a check upon the test with an opaque screen. The latter test, however, which I shall call the knife-edge test, is used almost exclusively for mirrors of all forms; it is far more serviceable than the eyepiece test in determining the nature and position of zonal irregularities, and is far more accurate in determining the radius of curvature either of a mirror as a whole, or of any zones of its surface.

If the eye be placed just behind the reflected image of the illuminated pinhole, so that the entire reflected cone of light enters the pupil, the polished, unsilvered mirror surface is seen as a brilliant disk of light. Let an opaque screen or knife-edge be placed in the same plane through the axis as the pinhole, and be moved across the reflected cone *from the left*, and just in front of the eye; if a dark shadow is seen to advance across the mirror from the left, the pinhole and knife-edge are inside of the best focus, and must be moved together away from the mirror; if, however, with the knife-edge still moved across from the left, the shadow advances across the mirror from the right, pinhole and knife-edge are outside of the focus and must be moved toward the mirror. By repeated trials a position is found from which the shadow does not appear to advance from either side, but the mirror surface darkens more or less uniformly all over: this is the position or plane of the best focus, and it is with this position of the knife-edge that irregularities of the surface, if any exist, are seen in most highly exaggerated relief; with this position of the knife-edge, the mirror, if perfectly spherical, is seen to darken with absolute uniformity all over as the screen is moved across the focus, and the impression of a perfectly plane surface is given to the eye.

If, however, the mirror is not perfectly spherical, but contains several zones of slightly different radii of curvature, a very common case, these zones will appear as protuberant or depressed rings on an otherwise plane surface. The reason for this is evident; the light from some parts of such zones is cut off by the knife-edge *before*, from other parts *after*, the illumination from the general surface is cut off; the surface is therefore seen in light and shade, *i. e.*, in enormously exaggerated relief. The mirror must be regarded as being illuminated by light shining very obliquely along the surface from the side opposite that from which the knife-edge advances across the focus. The interpretation of lights and shades becomes easy after a little experience; not only is the character of a zone—whether it is an elevation or depression—readily seen, but its diameter and its width are readily determined.

If the disk of glass is of sufficient thickness and of proper quality, and if attention has been given to the uniform rotation of the turntable and to the protection of the glass from abnormal conditions of temperature during grinding and polishing, all irregularities of figure which occur are perfect zones or rings concentric with the edge of the glass; that is, the surface is always a perfect surface of revolution. If, however, these precautions have not been taken, or if the glass has been improperly supported during grinding and polishing, or if it has been cut out of thick *rolled* plate-glass, so that it is weak in the direction of one diameter, an astigmatic mirror may be produced, in which the radius of curvature is slightly different along two diameters at right angles to each other.

Astigmatism is easily recognized with either the knife-edge or the eyepiece test. Let the plane of the apparent focus be determined with the knife-edge advancing from the left, then from above, then from the right, then from a number of directions between these three; if astigmatism exists the planes of the various foci thus found will not coincide; and the directions of greatest and least curvature of the surface are readily determined. When the eyepiece test is used, an astigmatic mirror does not give a sharp image even at the best focus; if the eyepiece be moved outside and inside of this focus the expanded disk becomes elongated, and is not uniformly illuminated; the direction of elongation outside is at right angles to that inside, and the distribution of light in the expanded disk is entirely different outside and inside of the focus.

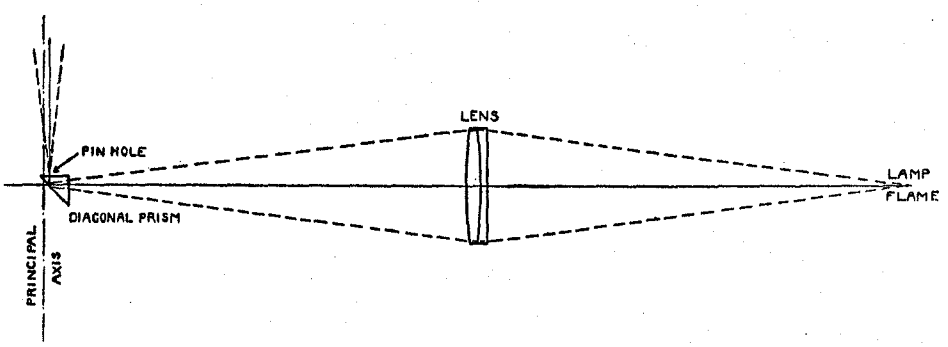


FIG. I.

ARRANGEMENT BY WHICH ARTIFICIAL STAR IS USED VERY CLOSE TO OPTICAL AXIS.

The general character of the tests having now been described, let us consider some important matters of detail which are necessary for the greatest refinement in testing all forms of mirrors.

By the use of a small lens and a diagonal prism, in the manner shown in Fig. 1, the lamp can be kept well out of the way, and the illuminated pinhole and its reflected image brought very near to the axis of figure of the mirror. This is of much importance in testing mirrors of short focus or of great angular aperture, as the danger of errors in testing due to working considerably out of the axis of figure is avoided. As may be seen in the figure the pinhole is now placed at the surface of the diagonal prism nearest to the mirror being tested. The arrangement should be such that the cone of rays proceeding from the lens is considerably larger than is needed to fill the concave mirror.

When being figured, mirrors are usually tested while unsilvered, since very frequent tests are desirable. While the amount of light reflected from the polished unsilvered surface is surprisingly great, a much more brilliant "artificial star" than that given by the oil lamp is required for the greatest refinement and accuracy with the knife-edge test, especially in the cases of plane, paraboloidal, and hyperboloidal mirrors, in which there are two reflections from the unsilvered surface. It might be supposed that a larger pinhole could be used, and thus a more brilliant illumination of the mirror surface secured; but a large pinhole allows an apparent diffusion of light over the mirror surface, which obliterates all the more delicate contrasts of illumination due to minute irregularities of surface. With feeble illumination of the surface the eye is entirely unable to detect slight contrasts which with brilliant illumination become strong and unmistakable. When the knife-edge test is used with an extremely small pinhole of between $\frac{1}{250}$ and $\frac{1}{500}$ inch in diameter, illuminated by acetylene or (what is much better) oxy-hydrogen or electric-arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with large pinhole or insufficient illumination. With the arrangement of lens and diagonal prism (Fig. 1) either of the sources of light named can be used without difficulty; disturbances of the air from their heat should be prevented by placing the light behind a partition with a window of thin plate glass.

With the best conditions of apparatus just described, the degree of accuracy to be attained with the knife-edge test is surprising. With a mirror of 2 feet aperture and 50 feet radius of curvature, the plane of the center of curvature can be easily located to within $\frac{1}{100}$ inch, and with care to within half of that amount. With the dimensions given, a change of $\frac{1}{100}$ inch in the radius of curvature corresponds to a change of $\frac{1}{500,000}$ inch in the depth of the curve of the mirror surface. There can be no doubt that zonal irregularities of surface of half of this amount are readily recognized.

We are now ready to consider the finishing of a spherical mirror. As before stated, a continuation of the use of the full-size polishing tool tends toward the gradual elimination of zonal irregularities. This work is often slow and laborious, however, for when the mirror becomes nearly finished, so that any zones, when seen with the knife-edge test, appear as extremely slight elevations or depressions, the improvement becomes exceedingly slow. The work may be facilitated by the local use of very small polishing tools upon protuberant zones. These tools are usually from 2 to 4 inches in diameter, and consist of squares of rosin upon a basis of brass; their faces are waxed and cold-pressed, and the squares around their edges are trimmed in order to soften or blend the action of the edges; small local tools with their surfaces trimmed as shown in Fig. 13 (in which the shaded parts represent the rosin) are excellent for the purpose. These local tools are used as follows: the positions and width of any protuberant zones are carefully determined by the knife-edge test, and the glass is replaced on the rotating turntable; stationary pointers are clamped to the machine, and overhang the glass so as to indicate the exact positions of the zones; the surface is painted all over with rouge and water, and the optician works the small tools on the high zones by hand; the rubbing is done on each zone during several revolutions of the glass, the length and direction of the stroke being changed after each complete revolution. Great care and judgment must be used in this work, and the surface must be tested very often, otherwise a wide zone will usually give place to several narrow ones. After the protuberant zones have been softened down in this way the full-size polisher is again used for finishing the surface.

A large and perfect spherical mirror is an indispensable part of the equipment of an optical laboratory, as it affords what is in my opinion the most satisfactory means of testing large plane mirrors. On account of the ease of rigorously testing a concave spherical surface, this is the form which should be first attempted by beginners in optical work.

CHAPTER XII.

GRINDING, FIGURING, AND TESTING PLANE MIRRORS.

THE making of large plane mirrors of fine figure is usually regarded as much more difficult than that of large concave mirrors. The difficulty has been, in the past, largely one of testing. With a satisfactory method of testing the large plane surface *as a whole*, in a rigorous and direct manner, the problem is greatly simplified. So far as the writer is aware, no such test has hitherto been fully developed. In *Monthly Notices*, Vol. 48, p. 105, Mr. Common suggests, very briefly, the testing of plane mirrors in combination with a finished spherical mirror, and gives a diagram in illustration; but no details in regard to the method are given. This method has been developed and used for many years by the writer in testing plane mirrors up to 30 inches in diameter. When this test is used, the difficulty of making a 24-inch plane mirror which shall not deviate from perfect flatness by an amount greater than $\frac{1}{500,000}$ inch is neither greater nor less than that of making a good spherical mirror of 2 feet aperture and 50 feet radius of curvature, when it is required that the radius of curvature shall not differ from 50 feet by a quantity greater than $\frac{1}{100}$ inch.

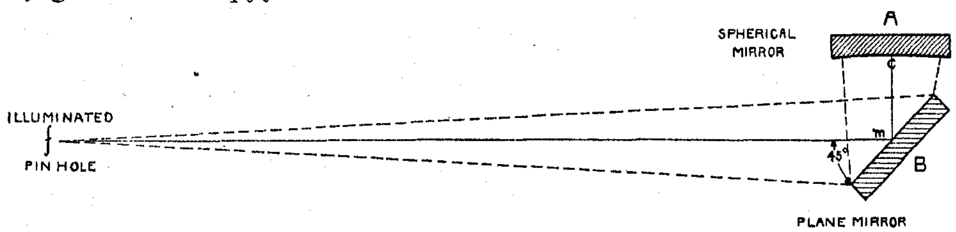


FIG. 2. DIAGRAM ILLUSTRATING TESTING OF A PLANE MIRROR.

A spherical mirror A (Fig. 2), which should not be smaller in diameter than the plane mirror B to be tested, is figured with the utmost accuracy, special care being taken that no astigmatism, however slight, exists in it. The mirror A is silvered; B is polished and unsilvered. The mirrors may be set up as shown *in plan* in Fig. 2, the distance $cm + mf$ being equal to the radius of curvature of A; both mirrors hang on edge in steel bands as already described. The light proceeding from the illuminated pinhole strikes B, is reflected to A, thence back to . thence to a focus close beside the illuminated pinhole.

When using the knife-edge test the optician sees the mirror B brilliantly il minated, and in elliptical outline, the horizontal diameter appearing foreshorten by an amount depending upon the angle at which the mirror is viewed. With t knife-edge test the surface of B is seen in relief, as a whole ; any zonal errors appe enormously exaggerated, and their character and position are readily determine just as when a spherical mirror is tested at its center of curvature; these zon errors, of course, appear elliptical, on account of their foreshortening ; their effect doubled in intensity on account of the two reflections from B (assuming that t illumination is as brilliant as the eye requires).

The test, as already described, is all that is necessary for the detection and loc tion of zonal errors. But something more is necessary in order to detect gene curvature, *i. e.*, convexity or concavity, in B. Let us assume that the mirror, wh fine-ground and polished, is so nearly flat that no curvature can be detected with Brown and Sharpe steel straight-edge of the finest quality; and for convenience description let us also assume that the surface is free from zonal errors. Let t knife-edge be moved across the reflected cone from the left; a focal point is fou at which the right and left sides of the mirror darken simultaneously; this foc point we will call f_1. Now let the knife-edge be moved across the cone fro above, instead of from the left; a focal point will be found at which the upper ar lower parts of the mirror darken simultaneously; this focal point we will call f It is only when the mirror B is a perfect plane that f_1 and f_2 coincide with ea other and with the point f (see figure). If B is slightly convex, f_1 and f_2 are ou side of f (*i. e.*, farther from the mirror than f) and f_1 is outside of f_2. If B slightly concave both f_1 and f_2 are inside of f, and f_1 is inside of f_2. In practic the exact position of f is not found (except incidentally when the plane mirror finished), for this would involve the very accurate measurement of the large di tance $cm + mf$. The determination of the positions of f_1 and f_2 with reference each other is all that is needed.

That f_1 and f_2 do not coincide when B is convex or concave is due to the fa that the curvation of B is apparently increased or exaggerated in the direction the horizontal diameter of the mirror, on account of its foreshortening in this dire tion, as seen from f; while the curvature in the direction of its vertical diameter not thus exaggerated. The effect is precisely as if the spherical mirror A were asti matic, the parts of the surface adjacent to the horizontal diameter having a differe radius of curvature from those adjacent to the vertical diameter. This effect is s marked that an extremely small deviation of B from a true plane can be detecte For example, if A and B are each two feet in diameter, the radius of curvature c A being fifty feet as before, and if the angle which the line fm subtends with th surface of B is 45°, a deviation from a true plane of $\frac{1}{350,000}$ inch in the surface c B is readily detected. If the angle of the mirror B be changed to 30°, as show in Fig. 3, the accuracy of the test for general curvature is about doubled; the latte position, however, is not usually so convenient for determining the positions of zon errors; for the greatest refinement, therefore, the stand on which A and B are supported is so designed that the positions of the mirrors can be quickly changed so as to give the greatest accuracy in each part of the test.

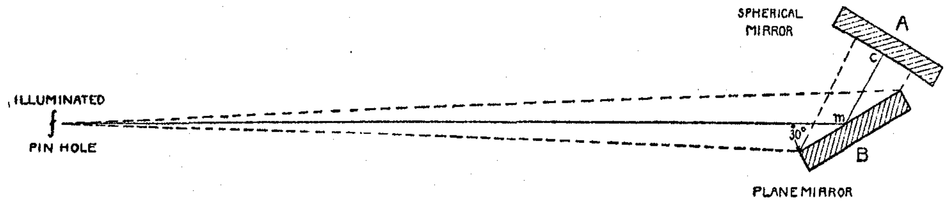


FIG. 3. DIAGRAM ILLUSTRATING TESTING OF A PLANE MIRROR.

The use of an eyepiece in this test is important because it shows how fatal to good definition is even a very slight convexity or concavity of a plane mirror when used in oblique positions. If f_1 and f_2 coincide as closely as can be detected with the knife-edge test (B being free from zonal irregularities also) the reflected image of the pinhole, as seen in an eyepiece at f, is as exquisitely sharp and perfect as if it were formed by the spherical mirror A alone. But if B is slightly convex or concave the appearance of the eyepiece image is similar to that which has already been described in connection with astigmatic concave mirrors; the image is not sharp even at the best focus; if B is convex, the image becomes elongated in a vertical direction outside, and in a horizontal direction inside, of the best focus; if B is concave the directions of elongation are the reverse of these.

The preparation of grinding tools for plane mirrors is similar to that of tools for concave mirrors. Three full-size, flat iron tools are usually made, however, all of which are grooved. These are ground together with carborundum of finer and finer grades, until all appear flat when tested with a carefully kept Brown and Sharpe steel straight-edge of best quality.

The plane mirror is fine-ground in the manner described for concave mirrors. It is of course a rare occurrence to find a large plane mirror nearly optically flat when it is first tested after grinding and polishing. My large mirrors almost invariably come out slightly convex when first polished; this may be due in part to the fact that the flat grinding tool becomes very slightly concave during the fine-grinding of the glass, from being worked on top (see page 7). Slight convexity of the mirror at this stage of the work is much better than slight concavity, for it is much better and easier to remove a high center than a high edge, during the process of figuring with polishing tools.

Manual polishing with full-size tools should be employed when the mirror is not too large to allow this. The polishing is begun with the *normal* tool shown in Fig. 4, in which the grooves are of uniform width throughout. After an hour's polishing the mirror is tested; if it is found to be convex, polishing is continued with the *concaving* tool shown in Fig. 5, in which all of the grooves are gradually widened toward the edges of the tool, so that there is a progressive decrease of action toward the edges of the glass; the amount of this widening must be

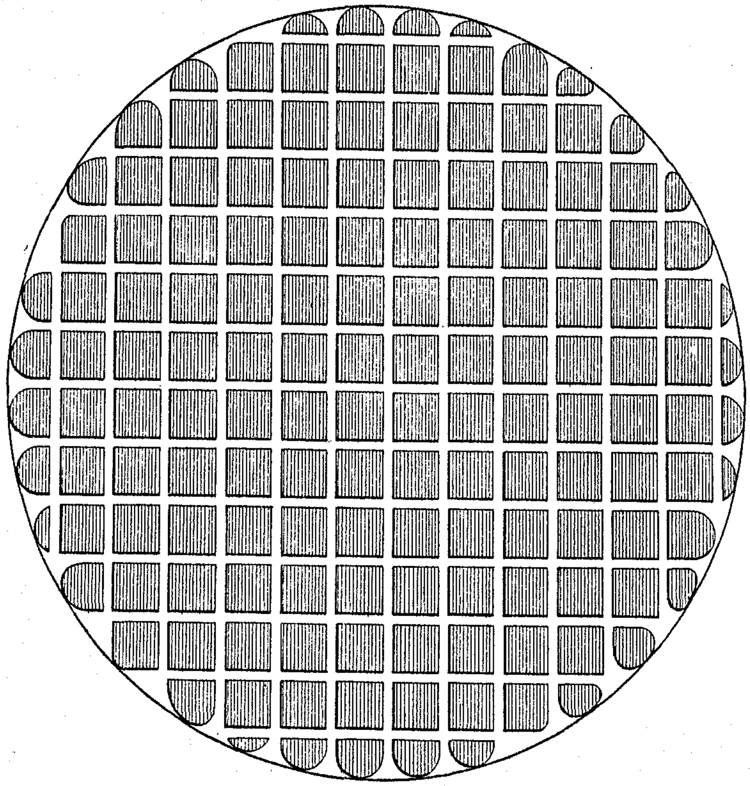


Fig. 4. Normal Polishing Tool.

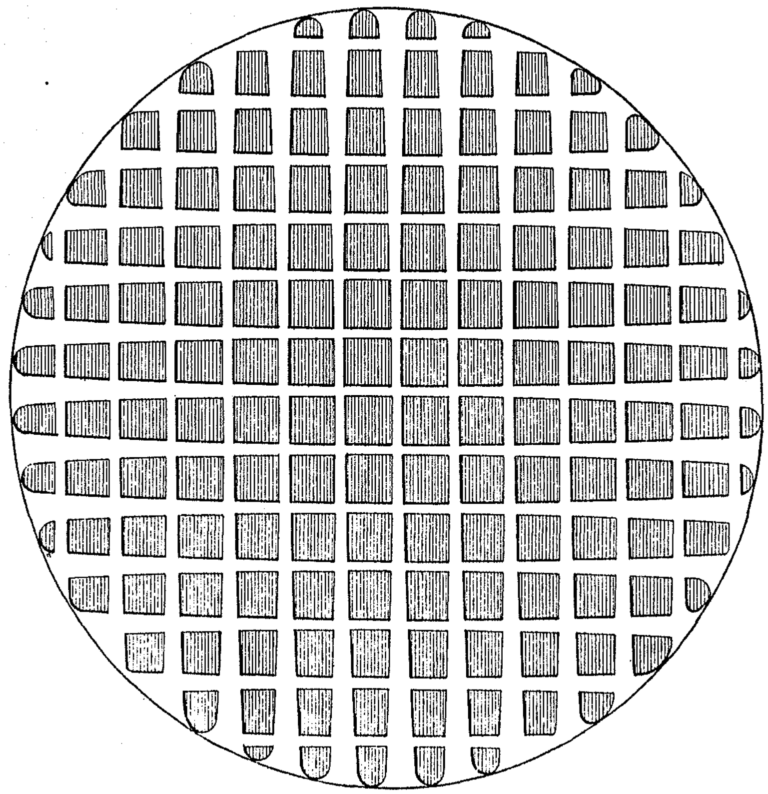


Fig. 5. Concaving Polishing Tool for Figuring Plane Mirror.

determined by experiment; it should be such that the convexity of the mirror is slowly and uniformly decreased.

If the mirror, when first tested, is found to be concave, the *convexing* tool shown in Fig. 6 is used to continue the polishing.

The concaving and convexing tools often tend to introduce broad slight zonal errors; hence recourse must be had repeatedly to the normal tool. When all trace of *general curvature* has disappeared, any remaining zonal errors are eliminated by the use of the normal tool, and, if necessary, of the small local or figuring tools, (see page 24).

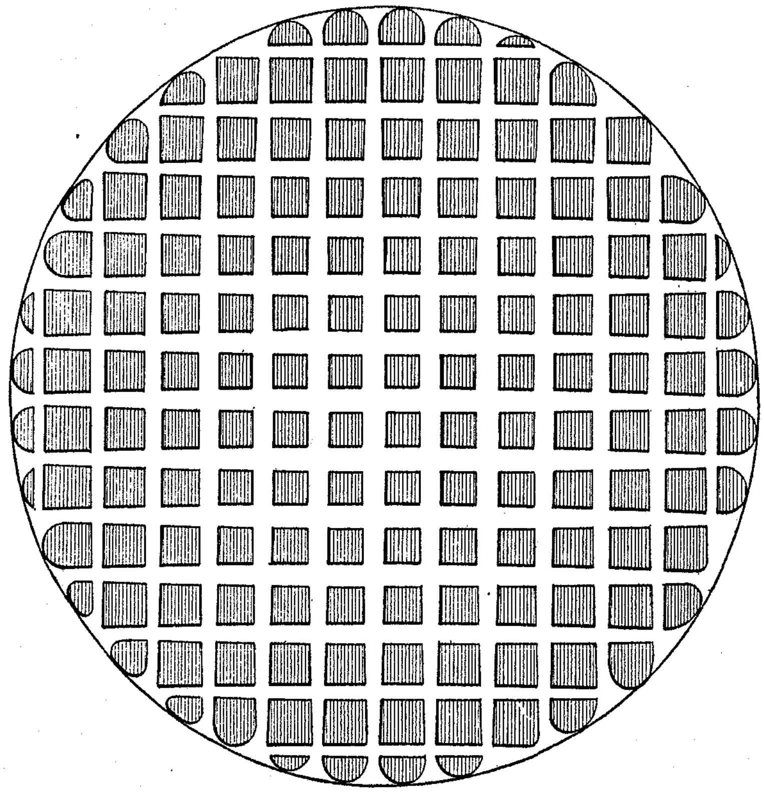


FIG. 6. CONVEXING POLISHING TOOL FOR FIGURING PLANE MIRROR.

If a finished plane mirror is available which is not smaller than the one being figured, the work is very greatly facilitated by continually cold-pressing the polishing tools on the finished mirror; every precaution must be taken, however, to prevent injury to the figure of the finished mirror by such cold-pressing.

In some of the writer's early work, in which the thickness of mirrors was made only one-twelfth of their diameter, it was found that a *normal* polishing tool, as described above, tended to change the mirror very gradually toward a concave. This was undoubtedly due to the fact that the friction of polishing warmed the surface very slightly, thus expanding it and making it convex with reference to the polishing tool; the tool did not follow this change of form readily, hence the central parts of the glass were acted upon in excess. Furthermore, such thin mirrors, when unsilvered, were so sensitive to slight changes of temperature that the presence of the optician's body for a period of two or three minutes, at a distance of three feet from a mirror which was set up for testing, would throw a previously plane mirror convex by an amount many times greater than the smallest amount which can be detected by the knife-edge test. When the thickness of mirrors is made equal to about one-seventh of their diameter, their sensitiveness to all such temperature effects is very greatly decreased. Furthermore, in the case of silvered glass mirrors which are used for solar work, the writer has found that thick mirrors suffer very much less change of figure from exposure to the sun's heat than thin mirrors do. Silvering affords a great protection from changes of temperature, since the silver film furnishes an almost totally reflecting surface for heat radiations.

CHAPTER XIII.

TESTING AND FIGURING PARABOLOIDAL MIRRORS.

THE work of changing a spherical mirror to a paraboloidal one is accomplished entirely by the use of polishing tools, by shortening the radii of curvature of the inner zones, instead of by increasing or lengthening those of the outer zones. The methods of effecting this change of curvature will be described after the methods of testing a paraboloid have been discussed.

Such testing can be done at the center of curvature, by determining there the foci or the radii of curvature of successive zones of the mirror; it may be done at the *focus* of the paraboloid, by the aid of a finished plane mirror which should be at least as large as the paraboloidal one; and it may be done directly on a star. The first two methods named have the very great advantage that they may be conducted without interruption, under the practically perfect atmospheric and temperature conditions of the optical laboratory.

Testing a Paraboloid at the Center of Curvature. A knowledge of the properties of the parabola enables the optician to compute the positions of the centers of curvature of successive, definite, narrow zones of the mirror, and the surface must be so figured that the radius of curvature of each zone agrees with the computed value. In testing, each zone in succession is exposed by means of a suitable diaphragm, all of the rest of the surface being covered. In practice, two entirely different formulæ may be used, depending upon the position of the illuminated pinhole.

Let F be the focal length of a finished paraboloidal mirror, and R the semi-diameter of any extremely narrow zone or ring of its surface, concentric with the vertex or center of the mirror; the normals to this zone cross the axis at a point whose distance from the vertex is $2\,F + \frac{R^2}{4F}$; hence, if the illuminated pinhole be placed very close to the axis, and at a distance of $2\,F + \frac{R^2}{4\,F}$ from the vertex, the rays of light reflected from the narrow zone will form a focus or image in the same plane (at right angles to the axis) in which the pinhole itself lies. This is the simplest formula which can be used, but it is not the most useful in practice.

In testing paraboloids at the center of curvature the writer has always used the following method and formula: The illuminated pinhole remains fixed at the center of curvature of the central parts of the mirror, *i. e.*, at a distance 2 F from the vertex, where F is the focal length. The intervals, measured along the axis, between the reflected foci of the various zones, are now twice as great as those given by the method described in the preceding paragraph; consequently these foci can now be determined with twice the accuracy which can be attained by that method. Only the rays reflected from the parts of the paraboloid very near to the vertex are now brought to a focus in the plane of the pinhole. If the paraboloidal figure is perfect, the rays reflected from any very narrow zone whose semi-diameter is R are now brought to a focus at a distance $\frac{R^2}{2\,F} + \frac{R^4}{16\,F^3}$ back of the plane the pinhole, *i. e.*, at a distance $2\,F + \frac{R^2}{2\,F} + \frac{R^4}{16\,F^3}$ from the vertex of the paraboloid. The quantity $\frac{R^4}{16\,F^3}$ is so small in the case of mirrors of moderate size and of ordinary ratios of aperture to focal length that it can be neglected; even in testing the outermost zones of the 5-foot mirror of 25 feet focal length, this quantity is less than 0.002 inch, while the quantity $\frac{R^2}{2\,F}$ amounts to $1\frac{1}{2}$ inches.

Now let us consider what is the best method of determining the planes of the reflected foci. Draper, Common, and other workers used an eyepiece for this purpose; this serves well for mirrors of moderate angular aperture, but for mirrors in which the ratio of aperture to focal length is as great as 1 to 5 or 1 to 6 this method presents serious difficulties; if narrow zones are used the image in the eyepiece is blurred and indistinct on account of the diffraction effect produced by the edges of the zonal openings in the diaphragm, while if wide zones are used the difference of focus of the inner and outer parts of a zone is so great that the image shows evidence of marked aberration; with neither narrow nor wide zones can the position of the focus be determined with very great accuracy.

In *Publications of the A. S. P.*, vol. xiv., No. 87, Hussey gives a formula for the position of the "circle of least confusion" when a zone of *given width* is used; if Hussey's formula were employed and the pinhole were made very small and round, with smooth edges, it is probable that much greater accuracy could be attained than by the use of an eyepiece in the ordinary way.

The method of locating the reflected foci which is used by the writer is as follows; it is capable of surprising accuracy when the optician has become experienced in its use. The reflected focus of a zone is found with the knife-edge, precisely as the focus of a spherical mirror is found. The knife-edge is moved across the reflected cone from the left; if the left side of the zone is seen to darken first, the knife-edge is inside of the focus; if the right side darkens first, the knife-edge is outside of the focus; when the right and left sides of the zone darken simultaneously, the knife-edge is at the focus of the zone. One advantage of this method is that it is independent of changes of focus of the eye itself; but the great advantage is that very narrow zones or arcs can be used. Diaphragms with zonal openings $\frac{1}{4}$ of an inch wide serve admirably for mirrors of 10 or 15 feet focal length; indeed the width of the zones which are actually used is considerably less than this; for, on account of diffraction, the edges of the openings in the diaphragms always appear as brilliant lines, even while the illumination near the center of the openings is being cut off by the knife-edge; it is therefore only the illumination near the center that is used in making the comparison.

The diaphragms which I use in this method of testing do not expose entire zones, but only pairs of arcs on the right and left sides of the mirror. Fig. 7 shows the diaphragm which was used in testing in this way the mirror of the two-foot reflector of the Yerkes Observatory. The arcs are cut in a long and narrow strip of thin metal; this is attached to the inner edges of two wooden strips, *a;* these

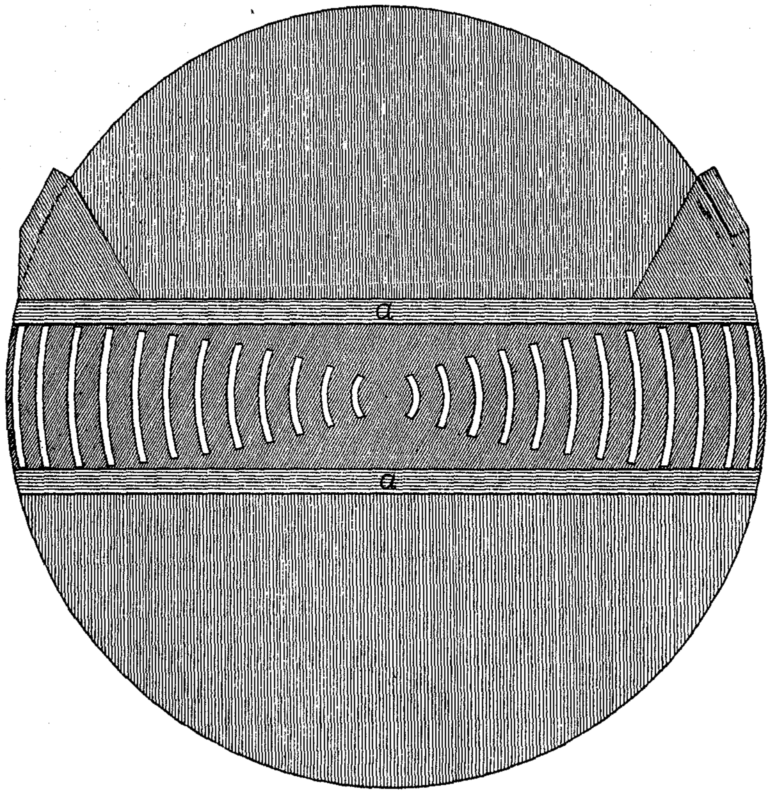


FIG. 7. DIAPHRAGM USED IN TESTING A PARABOLOIDAL MIRROR AT ITS CENTER OF CURVATURE.

edges are curved so that all parts of the thin metal diaphragm are nearly in contact with the curved surface of the mirror. The edges of the openings are bevelled so as to be extremely thin, and are finished dead-black. Twelve pairs of arcs were used, with mean radii of 1, 2, 3, ... 10, 11, and $11\frac{7}{8}$ inches. The openings of these arcs are $\frac{1}{4}$ inch in width. The foci of the successive zones (except those near the center) can be readily determined by this means to within

$\frac{1}{500}$ inch along the axis, for a mirror of two feet aperture and of ten or fifteen feet focal length.

Care must be taken when testing in this way that the entire mirror surface is *uniformly illuminated* by the cone of light proceeding from the illuminated pinhole; this condition, once secured, is easily maintained, since the illuminated pinhole remains immovable.

I have described at considerable length the methods of testing paraboloids at the center of curvature, because of the importance of the subject, and because this will probably continue to be a favorite method, especially among amateurs. But when testing is done at the center of curvature, even with the extremely accurate method just described, the making of a large paraboloidal mirror of great angular aperture and really fine figure is an exceedingly difficult task. This is due in part to the necessity of very frequent tests, in each of which the foci of a large number of zones must be determined; it is due far more to the uncertainty in determining the exact nature of errors of surface (considering the surface as a whole) corresponding to focal readings which do not agree with the computed values. In the case of mirrors of small or moderate angular aperture, much important information can be gained by viewing the surface as a whole, from the (mean) center of curvature, by means of the knife-edge test; a finished paraboloid, when thus seen, appears to stand out in relief, in strong light and shade, as a surface of revolution whose sec-

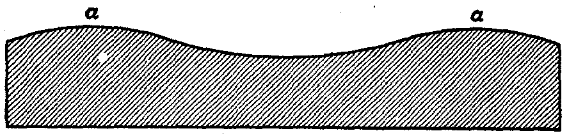


FIG. 8.

tion is that shown in Fig. 8; knife-edge and pinhole are both at the center of curvature of the zone a; the apparent curve of the surface should be a smooth one. But in the case of a mirror of large angular aperture the change of curvature is so rapid that only a narrow zone can be seen well at one time, *i. e.*, with a given focal setting of the knife-edge.

Testing a Paraboloid at its Focus. This method was briefly described by the writer in the *Astrophysical Journal*, November, 1901. It is incomparably more simple, direct, and rigorous than the test at the center of curvature. A well-figured plane mirror, which should not be smaller than the paraboloidal one, is necessary in order that the testing may be done in the optical laboratory. In practice a small diagonal plane mirror is also used, to avoid the necessity of a central hole through the large plane mirror. Both of the plane mirrors are silvered. The arrangement of mirrors is shown in Fig. 9. The diagonal prism is placed at f, with the illuminated pinhole very near the axis; pinhole and knife-edge are in the same plane, at a distance from the vertex equal to $cm + mf$, which is equal to the focal length of the mirror. The paraboloid is now tested as a whole, without the use of zones, precisely as a spherical mirror is tested at its center of curvature.

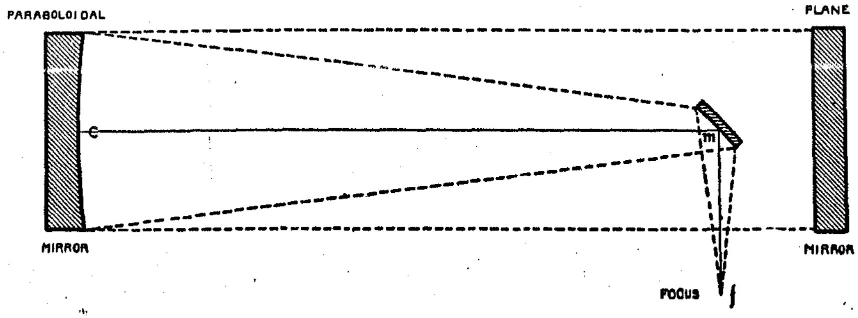


FIG. 9. TESTING A PARABOLOIDAL MIRROR AT ITS FOCUS.

If F be the desired focal length of the paraboloidal mirror whose semi-diameter is R, then the spherical surface which is fine-ground and fully polished preparatory to parabolizing should have a radius of curvature of $2F + \frac{R^2}{4F}$. This is because parabolizing is done by shortening the radii of curvature of all the inner zones of a mirror, leaving the outermost zone unchanged, as shown in Fig. 10; this is a far easier and better method in practice than to leave the central parts of the mirror

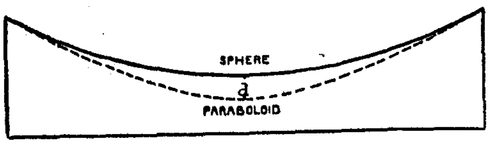


FIG. 10.

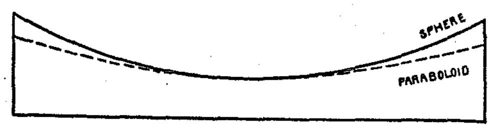


FIG. 11.

unchanged, and to lengthen the radii of curvature of all of the outer zones, as shown in Fig. 11.

Let us now suppose that the concave mirror shown in Fig. 9 is a *spherical* one with radius of curvature $2F + \frac{R^2}{4F}$, where R is the semi-diameter, and F is the distance $cm + mf$, from the center of the mirror surface to the plane of the pin-hole and knife-edge. If the spherical surface be now viewed from the point f with the knife-edge test, it will appear to stand out in relief, in strong light and shade,

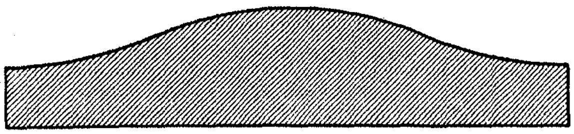


FIG. 12.

as a surface of revolution whose section is that shown in Fig. 12, the height of the protuberant center depending upon the angular aperture of the mirror. The reason for this appearance is readily seen by reference to Fig. 10. To change the spherical surface to a paraboloid, the protuberant center must be removed by the use of suitable polishing tools, until the surface, as seen with the knife-edge test from the point f, appears perfectly flat, *i. e.*, the illuminated surface darkens with perfect uniformity all over. As the paraboloidal surface nears completion, an elevated or depressed center, a "turned up" or "turned down" edge, or protuberant or depressed zones, can be seen and their character and exact position determined, with precisely the same ease and certainty with which similar irregularities are seen when a spherical mirror is examined at its center of curvation with the knife-edge test.

It should be noticed that even when the pinhole and reflected image are very near each other, as they should be, yet both may be far out of the axis of the paraboloid, if the mirrors are not properly adjusted or collimated; when this is the case the mirror surface, when seen with the knife-edge test, does not appear as a surface of revolution, and cannot be properly tested. The mirrors may be collimated by the following method, thus insuring that the pinhole and reflected image are both extremely near the optical axis.

The mirrors are set up approximately right by measurement. A ring about an inch in diameter, with two fine threads stretched diametrically across it, one vertical, one horizontal, is set up near the plane of the illuminated pinhole, the intersection of the threads marking the desired position of the optical axis. A light, stiff ring is made, which fits closely over the edge of the paraboloidal mirror, at the front; this ring can be slipped on and taken off as required. Two very fine bright wires are stretched diametrically across this ring, one vertical, one horizontal; these wires should be as close as possible to the face of the mirror; their intersection marks the position of the center or vertex of the paraboloid. Two fine short lines, one vertical, one horizontal, are scratched with a fine needle-point at the center of the silvered face of the small diagonal plane mirror. The eye is now placed about 3 feet outside of the plane of the crossed threads, and an assistant changes the inclination of the small plane mirror, by means of three adjusting-screws at its back, until the intersections of the threads, of the scratches, and of the wires are all seen in exact coincidence. The assistant next changes the inclination of the paraboloidal mirror (by means of three adjusting-screws at its back) until, with the eye in the same position as before, the intersection of the threads, the intersection of the wires, and the *reflection* of the intersection of the threads seen in the paraboloidal mirror, all appear in exact coincidence; the position of the axis of the paraboloid has now been defined. No attention is paid to the large plane mirror in this part of the work. The illuminated pinhole is now placed in position, and the large plane mirror is adjusted (by means of three adjusting-screws at its back) until the reflected image falls in the right position with reference to the axis and pinhole.

The frame which carries the paraboloidal mirror can easily be so designed that this mirror can be removed and replaced repeatedly, while figuring it, without sensibly disturbing the adjustments.

The difficulties of making short-focus paraboloidal mirrors of fine figure are so greatly reduced when this method of testing is used that I believe that the general adoption of this method by opticians would lead to such improvements in results as to bring about a marked advance in the usefulness of reflecting telescopes. The making of the large plane mirror which is necessary in this test becomes so simple and certain when the methods of testing and figuring described in the preceding chapter are used, that I have no hesitation in saying that when a large paraboloidal mirror of short focus and of the finest attainable figure is to be made, it is economical to make a plane mirror of the same size, with which to test it, if one is not already available. The concave mirror is first figured spherical and is used thus for testing the plane mirror while the latter is being figured; the plane mirror is then used in testing the concave one during the parabolizing of the latter. Both the plane and paraboloidal mirrors are then used in testing the small (convex) hyperboloidal mirror while the latter is being figured.

Testing a Paraboloid on a Star. With this method the mirror surface, as seen with the knife-edge test, presents the same general appearance as in testing in conjunction with a large plane mirror; in the latter test, however, errors of surface are

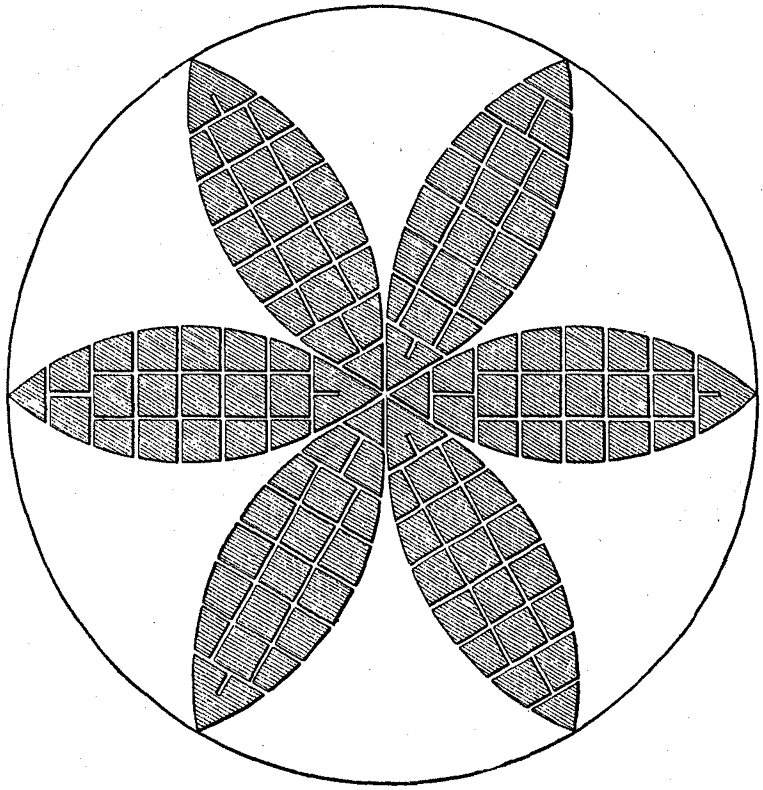


FIG. 13. FULL-SIZE POLISHING TOOL FOR PARABOLIZING.

seen in greater relief, because the effect of such errors is doubled on account of the two reflections from the paraboloid. In addition, it is impossible to overestimate the advantage of being able to test as often as is desired, in the optical laboratory, where atmospheric and temperature conditions can be controlled perfectly, and where the mirror does not have to be removed from the polishing machine in order to test it. In testing on a star it is seldom indeed that atmospheric conditions are sufficiently fine to allow any except the larger errors of surface to be seen.

Changing a Spherical Surface to a Paraboloid. As before stated, this is accomplished by shortening the radii of curvature of all of the inner zones of the surface, leaving the outermost zone unchanged (see Fig. 10). There are two distinct methods of accomplishing this: (1) by the use of full-size polishing tools, the rosin surfaces of which are cut away in such a manner as to give a large excess of polishing surface near the central parts of the tool; (2) by the use of small polishing or figuring tools worked chiefly upon the central parts of the mirror, and less and less upon the zones toward the edge.

(1) *Parabolizing with Full-Size Tools.* The rosin surface can be trimmed in a variety of ways to give a great excess of action on the central parts of the mirror. Fig. 13 shows one of the best forms of tool for this purpose, the shaded parts representing the rosin surface, coated with wax. The form of the edges of the rosin-covered areas can be altered as desired, and thus the amount of action on any zone can be in some measure controlled. Length of stroke and amount of side-throw are also very important factors in controlling the figure of the mirror. Tools of this kind serve admirably in parabolizing mirrors up to 36 or 40 inches in diameter, when the angular aperture is not very great.

(2) *Parabolizing with One-Third-Size and Smaller Tools.* In the case of very large mirrors, when full-size tools are almost unmanageably heavy, and in the case of mirrors of great angular aperture, in which the departure from a spherical surface is great and is effected with difficulty with full-size tools, one-third-size and smaller figuring tools may be used. The machine should invariably be employed in this work, the transverse slide being used to place the tool in succession upon the various zones. In order to preserve the surface of revolution the setting of the transverse slide should be changed only at the end of one or more complete revolutions of the glass. The rosin squares of the small tools should be somewhat softer than usual, so that the surfaces of the tools can accommodate themselves slowly to the slightly different curvatures of the successive zones. The squares around the edges of the tools should be trimmed, as before described, in order to soften the action of the edges. The mirror should be tested very often, and the utmost care taken to keep the apparent curve of the surface, as seen with the knife-edge test, a *smooth* one, *i. e.*, free from small zonal irregularities, at all stages of the parabolizing; this is not extremely difficult when the optician has become experienced in the use of the transverse slide.

The mirror of the 2-foot reflector of the Yerkes Observatory, which has a focal length of only 93 inches, was parabolized in this way by the writer. Two small tools were used, of 6 and 8 inches diameter respectively. The actual difference of depth, at the center or vertex of this mirror, between the paraboloid and the nearest spherical surface is almost exactly 0.0004 inch. This difference is unusually large in this case, on account of the exceptionally great ratio of aperture to focal length. This difference varies, in different mirrors, as the fourth power of the diameter of the mirrors, and inversely as the cube of the focal length. In the case of Lord Rosse's great mirror, in which the aperture is 6 feet and the focal length 54 feet (ratio 1 to 9) the corresponding difference at the center is only 0.0001 inch, very nearly. In the case of the 5-foot mirror of the Yerkes Observatory, of 25 feet focal length, the corresponding difference is about 0.0006 inch. This gives some idea of the actual amount of glass which must be removed by the figuring tools in parabolizing.

CHAPTER XIV.

TESTING AND FIGURING CONVEX HYPERBOLOIDAL MIRRORS.

THE methods of figuring and rigorously testing convex hyperboloidal mirrors are now so thoroughly developed that the reflecting telescope can be regarded as a universal photographic telescope of the highest class, capable of giving, at the focus of the paraboloidal mirror of large angular aperture, the finest photographs now attainable of large and excessively faint objects such as the nebulæ in general; while by the addition of a small convex mirror a great equivalent focal length is obtained for the photography of bright celestial objects requiring large scale, such as the moon, the planets, the dense globular star clusters, and the annular and planetary nebulæ. The convex mirror of course serves as an amplifier, and possesses the great advantages over a lens used for this purpose that the perfect achromatism and the high photographic efficiency of the reflector are retained, and that the mechanical arrangements are very compact and economical. In order to give perfect definition the convex mirror must be an hyperboloidal one.

The writer has recently made two convex mirrors of different curvature, for use with the 2-foot reflector. These give equivalent focal lengths of 27 and 38 feet respectively.

Fig. 14 shows the arrangement of mirrors employed in the 2-foot reflector when used as a Cassegrain; a small diagonal plane mirror is used at m, to avoid the necessity of a hole through the center of the large concave mirror. P is the paraboloidal mirror, with its focus at f; H is the hyperboloidal mirror, the secondary

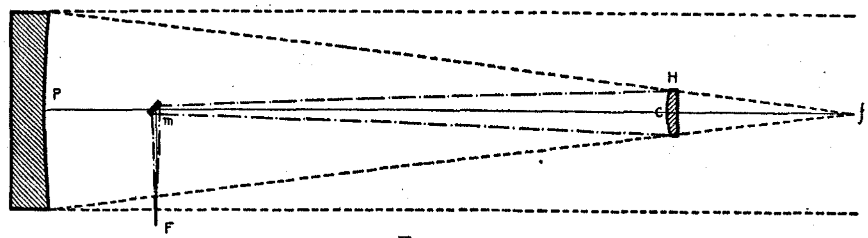


FIG. 14.

focus or magnified image produced by the combination being at F; the point c is the center of the hyperboloidal surface. Calling the distance $fc = p$ and the distance $cm + mF = p'$, then $\frac{p'}{p}$ represents the amount of amplification introduced by the convex mirror. The radius of curvature R of the spherical surface to which the convex mirror is ground and polished preparatory to hyperbolizing is found with sufficient accuracy for all practical purposes by the formula $\frac{1}{p} - \frac{1}{p'} = \frac{2}{R}$ whence $R = \frac{2pp'}{p'-p}$.

For example, let the focal length of the paraboloidal mirror P, Fig. 14, be ten feet; let $fc = p = 2$ ft. and $cm + mF = p' = 8$ ft. Here $\frac{p'}{p} = 4$; the image of the moon or other celestial object produced at F is therefore four times larger in diameter than it would be at f, the focus of the paraboloid; and $\mathrm{R} = \frac{2\,pp'}{p'-p} = 64$ inches.

The method of testing the convex mirror while hyperbolizing it is shown in Fig. 15. The illuminated pinhole is placed very near the axis at F. The diverg-

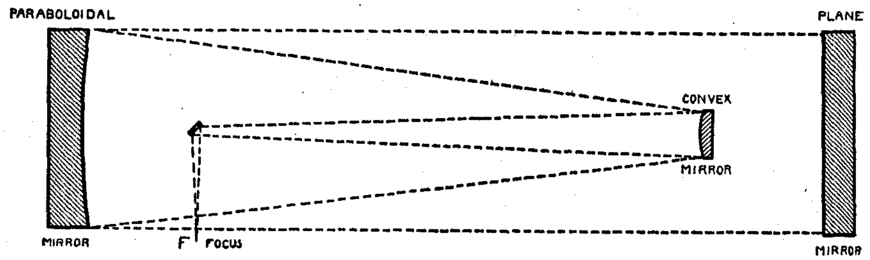


FIG. 15. DIAGRAM ILLUSTRATING TESTING OF HYPERBOLOIDAL MIRROR.

ing cone of light strikes the small plane mirror, then the convex, then the large paraboloid, whence if all of the mirrors are finished and are well adjusted or collimated, the light is reflected in a parallel beam to the large plane; returning, the rays are brought to a focus very near the axis of figure and in the plane of the illuminated pinhole. All of the mirrors except the convex one are silvered. The convex spherical surface with radius of curvature R, as above described, when viewed with the knife-edge test from the point F, presents the same general appearance of a smoothly curved surface of revolution, in strong light and shade, which a paraboloidal surface presents when similarly viewed from its center of curvature (see Fig. 8, p. 33). All that is necessary to produce the hyperboloidal surface is to soften down, with suitable polishing tools, the apparent broad protuberant zone between the center and edge, until the mirror, as seen from F, appears perfectly flat; *i. e.*, until the illuminated surface is seen to darken with absolute uniformity all over when the knife-edge is moved across the focus. This hyperbolizing may be done with small local or figuring tools, or with a full-size tool so trimmed as to give an excess of action on the broad zone a, or (what is usually best) by a combination of the use of both kinds of tools.

As in the case of the paraboloid, it is necessary in this test that all of the mirrors be lined up or collimated with care; otherwise the surface of the convex mirror will not appear as a surface of revolution, and cannot be properly tested. The axes of the paraboloid and hyperboloid must coincide, and the face of the large plane mirror must be at right angles to these axes. These adjustments are made by means of an extension of the method of collimation described in the preceding chapter, p. 35. First the paraboloidal mirror is adjusted so that its axis intersects the hyperboloid at its exact center or vertex; in making this adjustment fine threads are stretched diametrically across the cell of the convex mirror, this mirror being removed during this part of the adjustment. Next, the small diagonal plane is adjusted for inclination, care being taken that the intersection of the lines scratched in its film is placed in the axis of the paraboloid. Then the convex mirror is adjusted for inclination, by reflection. Finally, with the illuminated pinhole in place, the large plane mirror is adjusted, as previously described.

CHAPTER XV.

SILVERING.

It is not my purpose to discuss the various processes of silvering. Several methods have been admirably described by Draper (see p. 2 of his book), by Brashear, and by Common (see p. 159 of his paper *On the Construction of a Five-Foot Reflecting Telescope*). I have used almost exclusively the formula published by Brashear in 1884, in which sugar is the reducing agent. After experience with this process, and when the grades of chemicals specified below are used, silver films are invariably obtained which take a perfectly black polish, and which are so thick as to be nearly opaque even to the sun's disk. Small mirrors are usually silvered face down; films which are satisfactory in all respects are obtained when this is done.

In the case of large mirrors it is more economical of silver, as well as safer and more convenient in manipulation, to silver face up. Two difficulties occur, however, when this is done; first, minute transparent spots are liable to occur in the film; these are so small, however, that they can be seen only when looking through the film at a bright object; second, the refuse silvering solutions must be poured off the mirror, after the silver has been deposited, at exactly the right stage of the reaction; if poured off too soon the film will be thin; if too late, the muddy-brown precipitate which settles upon the film will slightly tarnish the latter in such a manner that it will not take a perfect polish; it is only by experience that the optician is able to determine the right instant for pouring off the refuse solutions. Mr. Common encountered similar difficulties in silvering face up, and resorted to the use of solutions without caustic potash, and also to the use of Draper's method of reducing with Rochelle salt; these methods, while subject to their own special difficulties, do not give the objectionable precipitate. The writer has adhered to the use of a slight modification of Brashear's formula already mentioned, in part because no opportunity has occurred for comparing thoroughly the merits of the various formulæ, and in part because the films obtained by this method give entire satisfaction in use.

The Reducing Solution. This consists of distilled water, 200 parts; loaf-sugar or pure rock-candy, 20 parts; alcohol (pure) 20 parts; nitric acid (c. p.) 1 part. The proportions given are by weight. This solution is greatly improved by keeping, a solution which has been made for several months working more surely than one newly made. A gallon of this solution is usually made at one time.

The operation of silvering a 2-foot mirror face up will now be described. It will be assumed for the present that the back of the mirror is unsilvered. A silvering table is used, which is a strong structure of oak wood having a tilting frame carried on two trunnions, so that the mirror can be quickly turned from a horizontal to a vertical position, for the purpose of pouring off the cleaning and silvering solutions; a strong narrow edge-band of flexible steel prevents the mirror from sliding off; the tilting frame is heavily weighted below so that it cannot turn down accidentally. Thus all handling of the mirror while silvering is avoided.

The old silver film, if one exists, is removed with strong nitric acid on a bunch of absorbent cotton tied to a glass rod. The face and edge of the mirror are then quickly washed with distilled water. A band of strong brown drawing paper, which has been dipped in melted paraffin, is drawn around the edge of the glass and tightly bound to it by means of a thin band of copper with tightening screws; the paper should project about three inches above the glass; the joints should all be made water-tight by means of more paraffin and a warm iron. A dish about three inches deep is thus formed, with the mirror as its bottom.

A 10 per cent solution of pure caustic potash in distilled water is now used for thoroughly washing the face of the glass and the inside of the paraffin band; this is done with a large bunch of absorbent cotton tied to a glass rod. This solution is then poured out and the glass is similarly washed several times with fresh supplies of distilled water, to get rid of all traces of potash. Enough distilled water is now poured on the glass to entirely cover it while the silvering solutions are being mixed.

All of the vessels, graduates, etc., used for mixing the silvering solutions, must be thoroughly washed, first with nitric acid, then with caustic potash, and rinsed with distilled water, just as the mirror is cleaned.

For silvering the face of a 2-foot mirror, 2 ounces of silver nitrate (Powers & Weightman) are dissolved in 20 ounces of distilled water. One and one-third ounces of caustic potash, pure by alcohol (Merck), are dissolved in 20 ounces of water in a separate vessel, and the solution is cooled. Strong aqua ammonia (pure) is added, drop by drop, to the nitrate solution, while the liquid is thoroughly stirred; the mixture turns light-brown, then dark-brown; the ammonia is slowly added until the liquid becomes clear. The caustic potash solution is now added slowly, with thorough stirring; the mixture now becomes very dark-brown or black. Ammonia is again added, with thorough stirring, until the liquid again just clears. A solution of one-fourth ounce silver nitrate in 16 ounces of distilled water having been prepared, this is added to the mixture, a few drops at a time, with thorough stirring, until the entire solution has a decided straw color, while remaining transparent. This straw color is the test for the condition of instability which is absolutely necessary in order that the metallic silver shall be thrown out of combination when the reducing solution is added later. The solution is now thoroughly filtered through absorbent cotton.

A quantity of reducing solution is taken containing an amount of sugar equal in weight to one-half that of the entire amount of silver nitrate used; this is also filtered. The silver solution and reducing solution are now both diluted with distilled water, preparatory to mixing; the quantity of the diluted solutions, together, should be sufficient to cover the glass about one inch deep.

An assistant pours off the water which has stood on the glass, while the optician quickly mixes the dilute silver and reducing solutions in a large pitcher or granite-ware bucket. The glass being horizontal, the mixed solution is immediately poured on, and the mirror is rocked slightly by means of the tilting frame. The liquid quickly changes to a transparent light-brown color, then dark brown, then black, after which the silver immediately begins to deposit. The solution gradually changes to a muddy-brown color, and in three or four minutes after the solutions are poured on the glass, begins to clear; the light muddy-brown precipitate settling upon the film. With the proportions given, the silver film should be sufficiently thick in about five minutes after the solutions are poured on the glass provided that the room, glass, and solutions are all at a temperature of sixty-eight degrees or seventy degrees Fahrenheit. When first formed the brown precipitate is so light that it moves about with the rocking of the glass; but it very soon deposits in large areas on the film. As soon as this begins to occur, the solution must be very quickly poured off the glass, an abundance of distilled water poured on, and a large bunch of absorbent cotton, held in the fingers, instantly used to displace all streaks of the precipitate which adhere to the film. The film is now washed again and again with fresh distilled water and a soft bunch of cotton; then an abundance of water is poured on and the film allowed to soak for an hour. When this is poured off, the paper band is carefully removed, with the glass horizontal so that no liquid from the edge can run upon the silver film; this must be done quickly, before the latter has time to dry. A small amount of alcohol is now flowed on the film; this is repeated several times to get rid of all water; the glass is then turned on edge, and is quickly dried with a fan.

After standing for an hour or two in a dry room the film is to be burnished. A soft pad as large as the hand is made of the softest chamois skin; this is used on the film without rouge, with light circular strokes, to condense the silver. After two hours of this work a little of the finest washed dry *jeweler's* rouge is rubbed into the chamois-skin with a piece of clean absorbent cotton; from thirty to sixty minutes use of the pad with the same stroke as before should now bring the film to a perfect polish, without scratches.

If the back of the mirror is already silvered, the face can be silvered by the method just described, without injuring the film on the back; the mirror now rests upon three curved and beveled blocks of soft wood which touch only the rounded corner or edge of the back of the glass; extra precautions are now taken to prevent any of the solution from touching the back. I regard this method as much better in the case of large mirrors than to attempt to silver both back and face at the same time in a deep tray; in the latter method the difficulties of handling and properly cleaning the mirror are almost insurmountable.

The back of the mirror does not usually need silvering oftener than once in three or four years. The face is usually silvered two or three times a year, to keep it in the finest condition for photography, in which any yellowing of the film is very objectionable.

CHAPTER XVI.

A SUPPORT-SYSTEM FOR LARGE MIRRORS.

The proper support of mirrors in their cells when in use in the telescope is a matter of vital importance. Small mirrors can be made very thick and can be supported at their edges as a lens is supported; the cell must be so designed that no sensible change of position of the mirror in its cell can occur. The necessity of supporting large mirrors in such a manner as to prevent flexure from their own weight, in all positions which can occur in use, has long been recognized, and elaborate support-systems for this purpose have been devised and used by Rosse, Grubb, Common, and others. Comparatively little attention has been given, however, to two additional requirements which are no less important; first, the position of the mirrors in their cells should be defined with the greatest attainable stability, in order to secure permanence of adjustment or collimation; second, the method of support should be such that the silvered back of the mirror is exposed to the air as freely as possible. It is assumed that a large mirror need never be turned farther than ninety degrees from the position in which it lies horizontal upon its back.

In the *Astrophysical Journal* for February, 1897, the writer described a method of supporting large mirrors which fulfills all of the requirements named in the preceding paragraph. I have employed this method in the designs for the support-system of the 5-foot mirror. These designs are described and illustrated here.

I.—*The Back-Support.*

Let us consider the mirror to be divided into twelve imaginary segments of equal weight, as shown in Fig. 16, Plate VIII. The back of the mirror rests, primarily, upon three strong bronze plates, each ten inches in diameter, represented by the double circles *a* Fig. 16 and at *a* Fig. 17, the center of each plate being exactly behind the center of weight of the corresponding segments; these are called the stationary plates. The upper surface of each plate is flat and is ground to fit the flat back of the glass; the lower surface is spherical, and is ground to fit the large spherical socket in which it rests. It will be noticed that these plates are near the edge of the mirror, in the outer ring of segments; the base of stable support is therefore large. It is evident that by properly designing these plates and their supports we can fix with very great stability the plane of the mirror which rests directly upon them; there is no building out from the three primary points of support by means of intermediate levers and triangles, as in the older systems.

The weight of the remaining nine segments of the mirror is just balanced by means of nine weighted levers, each of which is entirely independent of every other, which lie in a plane parallel to the back of the mirror. One of these levers is shown in elevation at *c*, Fig. 17, and in plan in Fig. 21. The positions of the nine levers are indicated by dotted crosses in Figs. 16 and 18. These levers are suspended between pivots screwed through lugs connected to the cell. The cone bearings, shown in Fig. 21, are finely fitted, and are ground to reduce friction. The long arms of the levers carry adjustable lead weights (*d* Figs. 17 and 21) which are made in the form of plates, in order that they may occupy as little space as possible perpendicular to the plane of the mirror; the short arms of the levers are thus made to press against the backs of the corresponding segments through the medium of light plates of bronze represented by the single circles *b* Fig. 16 and at *b* Figs. 17 and 21.

The large mirror weighs very nearly 2000 pounds, so that each segment weighs $166\frac{2}{3}$ pounds. With the cell in a horizontal position the lead weight on each arm is adjusted until it just balances a standard weight of $166\frac{2}{3}$ pounds placed upon the plate on the short arm. This adjustment being completed the mirror is laid upon the support-system; three-quarters of its weight is carried by the nine levers, leaving one quarter to be divided equally between the three heavy plates *a*. Thus each of the twelve segments is entirely supported at the back, independently of all of the other segments. Now suppose that the edge-support, which will be described below, be introduced, and the entire system, with the glass, inclined in any direction and at any angle; all of the levers and weights retain the same position as before with reference to the glass, but they do not exert the same pressure, on account of the inclination; so far as the back-support is concerned there will still be a perfect balance maintained in the case of each segment; this is true whatever point of the edge of the mirror becomes lowest—*i. e.*, in whatever direction the levers lie with respect to the vertical plane through the axis of figure of the mirror.

It should be noticed that in the case of each of the twelve 10-inch supporting plates only a ring one inch wide around the edge is in contact with the glass; the part of each plate inside of this ring consists of deep, narrow arms, which do not touch the glass, and which allows free access of air to the latter.

For very large or thin mirrors a larger number of plates and levers can of course be used. An incidental advantage which occurs when this is done is that the base of stable support afforded by the three stationary plates is still larger, compared with the size of the mirror, than when twelve plates are used.

II.—*The Edge-Support.*

The relation between the back-support and edge-support is so intimate that any inefficiency in the latter must injuriously affect the operation of the former, however perfect that may be in itself. In an equatorial reflecting telescope, different parts of the edge of the mirror become successively lowest, as the position of the telescope changes. With the flexible band and cushioned edge-support so much used in the past, the heavy mirror necessarily changes its position, laterally, with

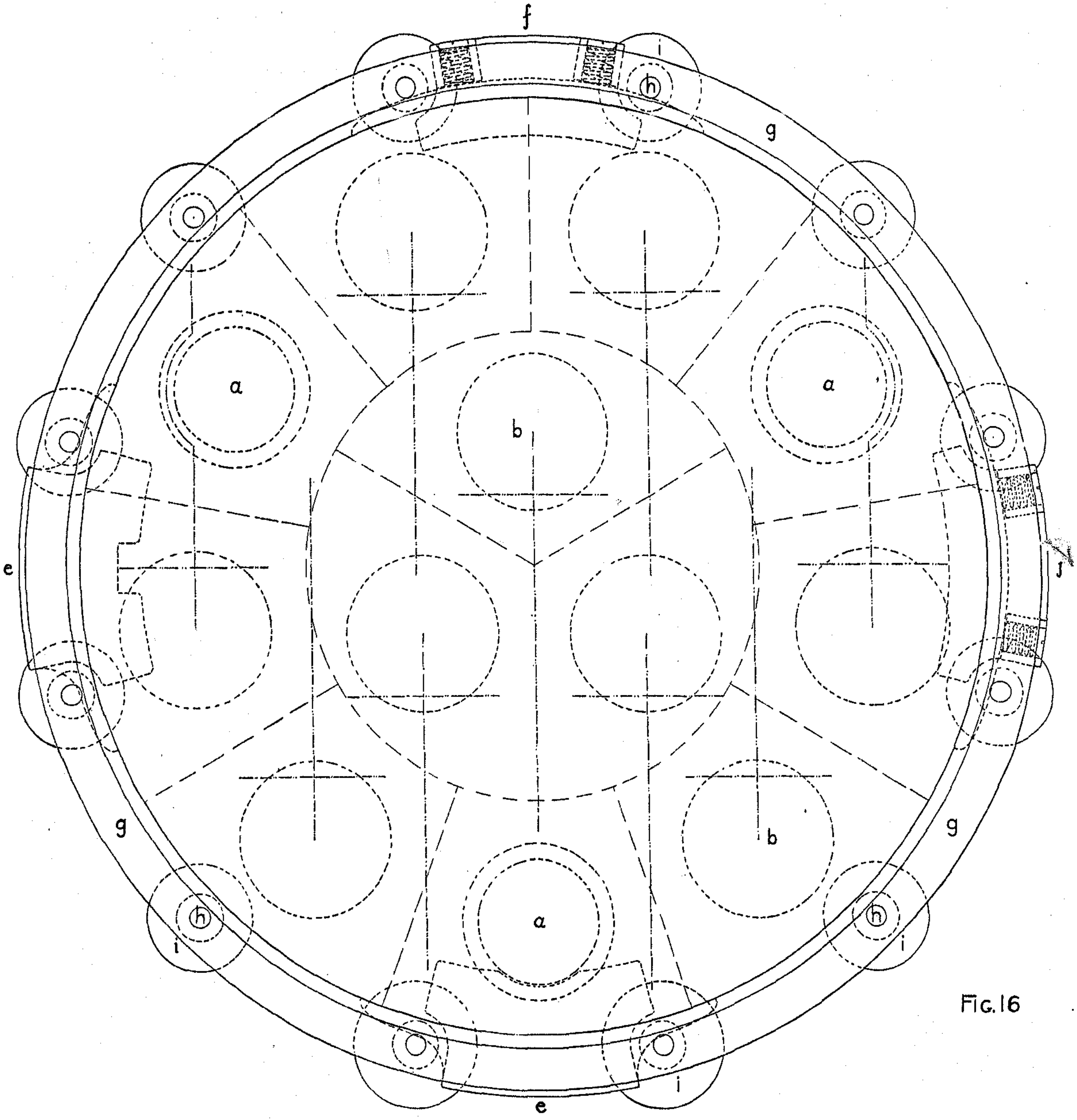


FIG. 16

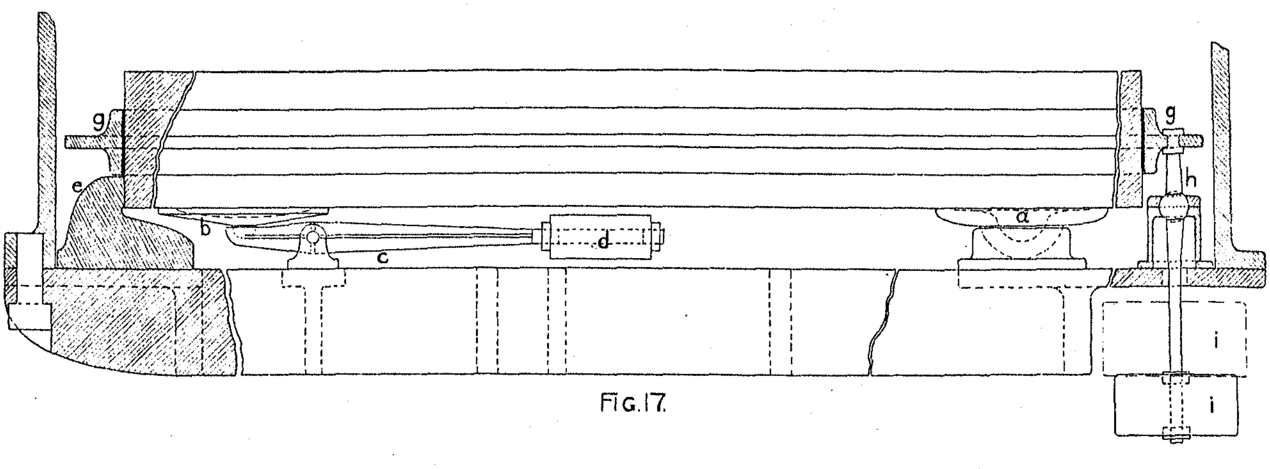


FIG. 17.

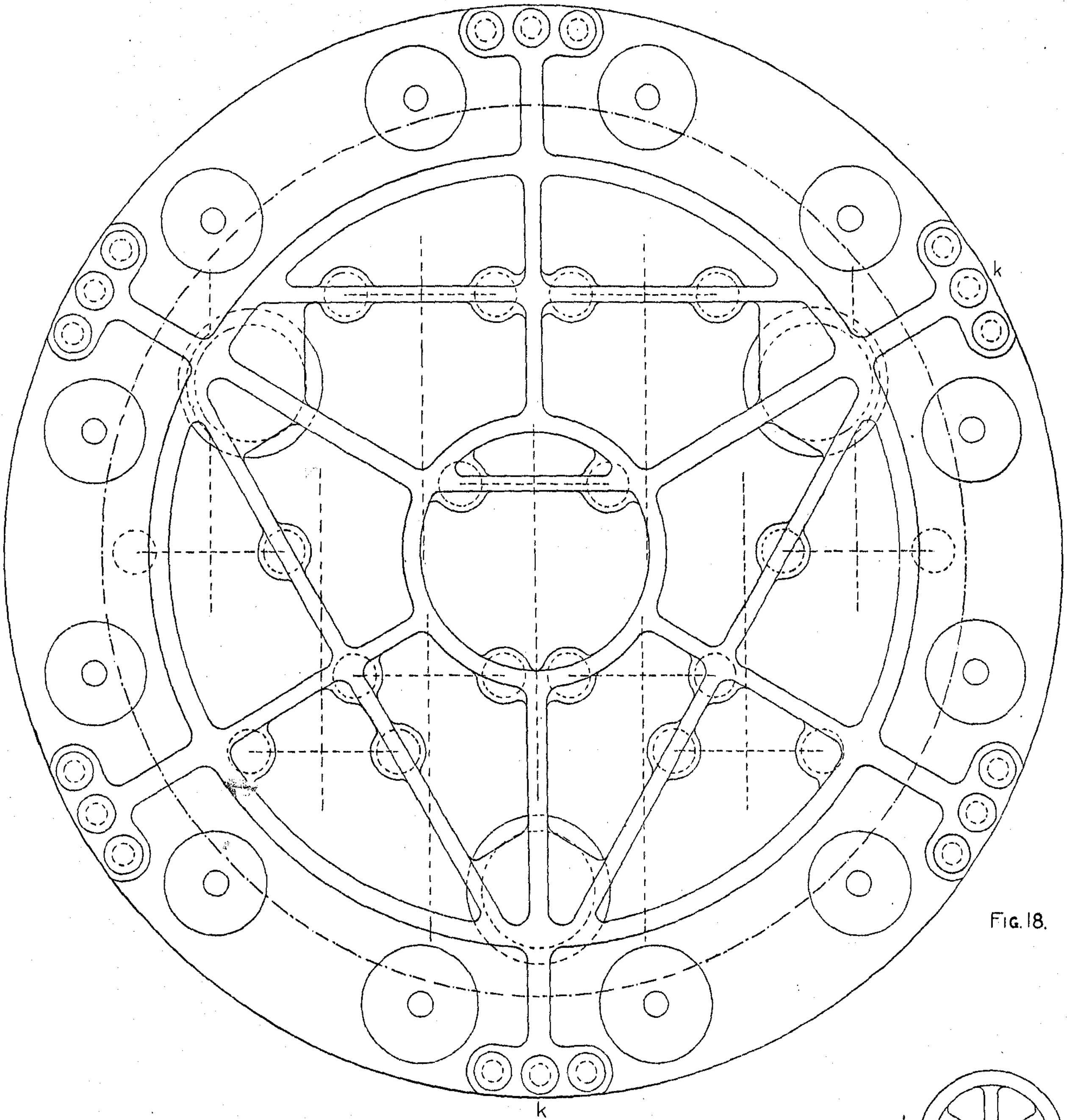


Fig. 18.

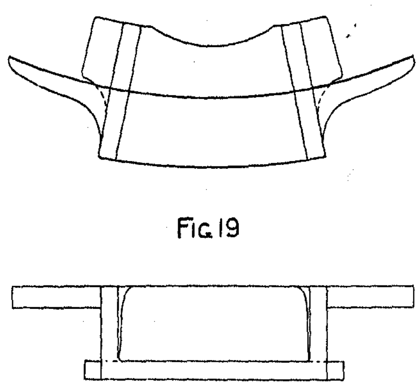


Fig. 19

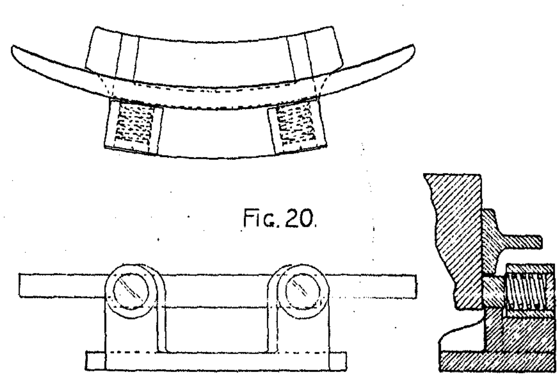


Fig. 20.

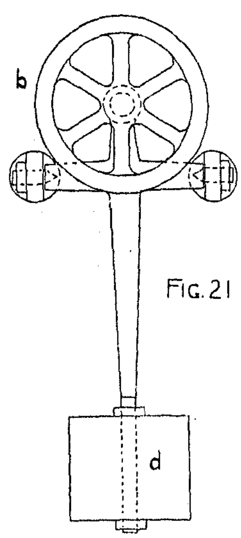


Fig. 21

SUPPORT SYSTEM FOR LARGE MIRROR.

respect to its cell, in taking its position down against the edge-support; thus not only is permanence of position lost, but this tendency to lateral shift must impair the freedom of operation of the back-support system.

In the present plan four metal arcs are used which rigorously define the position of the mirror laterally. Two of these arcs (*e* Figs. 16 and 17, and Fig. 19), adjacent to each other, are bolted down to the cell, and their inner edges are scraped to fit the ground edge of the glass; these are called the stationary arcs; the other two arcs (*f* Fig. 16 and Fig. 20), diametrically opposite the stationary ones, exert a slight pressure against the edge of the mirror, by means of springs, for the purpose of seating the mirror against the stationary arcs and holding it there; this pressure need amount to only a very small percentage of the mirror's weight, for all of the lateral pressure due to the weight of the mirror when the latter is inclined is carried by a strong metal *counterpoising ring* of T section (*g* Figs. 16 and 17); this completely encircles the edge of the mirror, and fits it loosely, a band of leather or thick felt paper being inserted between the ring and the glass. For convenience in description, imagine this ring to be suspended from the tube above, by means of three short wires, so that if the mirror were removed the ring could swing freely in its own plane. The ring is pressed up against the edge of the mirror, when the latter is inclined, by a system of twelve short weighted levers (*h* Figs. 16 and 17) which hang perpendicular to the plane of the ring. These levers are suspended from the cell-plate behind the ring, by means of ball-and-socket joints, as shown in Fig. 17, or preferably, to reduce friction, on pivoted universal or Hooke's joints. The ends of the short upper arms of these levers fit loosely into holes in the ring; the long lower arms carry lead weights (*i* Figs. 16 and 17) which are capable of slight adjustment.

Assuming that the counterpoising ring weighs 400 pounds, so that the combined weight of ring and mirror is 2400 pounds, the adjustment of the edge-support levers is effected by turning the entire cell to a vertical plane, with the mirror and ring removed, and adjusting each of the twelve lead weights until it just balances a standard weight of 200 pounds hung on the short arm of the lever at the point where this is to touch the ring.

I regard the use of a support-system which will fulfill all of the conditions mentioned at the beginning of this chapter as absolutely essential for large mirrors. Only those who have tested large mirrors and combinations of mirrors in the optical shop, and those who have actually used large reflecting telescopes, can fully appreciate the necessity of a support-system which will both support the mirrors without constraint and flexure, and define their positions permanently with respect to the tube and axes, in all positions of the telescope. These conditions can now be attained easily and economically; without them it is folly on the one hand to expect good definition and successful photographs, or, on the other hand, to complain that the reflecting telescope is subject to serious inherent difficulties which cannot be overcome. In the case of large mirrors in which the ratio of thickness to diameter is not less than as 1 to 9 or 1 to 10 the support-system just described floats the mirror so perfectly in all positions which can occur in actual use that no flexure or distortion can be detected with the most sensitive optical tests. Furthermore, with the method of edge-support described, and in the case of the 5-foot mirror weighing a ton, no lateral shift amounting to $\frac{1}{2000}$ inch can occur when the mirror is turned in extreme oblique positions.

In Figs. 17 and 18 is shown the massive cell-plate of cast-iron which carries the mirror and its support-system, and which is connected to the short cast-iron section of the tube; this connection is made by means of strong adjusting screws, by means of which the mirror and its support-system, as a whole, are adjusted for collimating the mirror; these adjusting screws are shown at *k*, Fig. 18. Additional screws are also shown at *l* in this figure; these are backed out of the way when collimating is being done; when this is finished they are brought into position, and assist in bolting the cell-plate rigidly to the tube. As is shown in Figs. 17 and 18, the central part of the cell-plate, a circle about 50 inches in diameter, consists of open ribs or arms which allow free access of air to the silvered back of the mirror.

When the face of the mirror is to be resilvered, the cell-plate, support-system, and mirror are removed as a whole, and silvering is done in the manner described in the preceding chapter, without taking the mirror from its supports or disturbing the adjustments of the latter in any way. Furthermore, the mirror can be taken out of the telescope in this way, silvered, and replaced, without sensibly disturbing its collimation or the position of the focal plane. When the back of the mirror must be resilvered, which need not be done oftener than once in three or four years, the glass must of course be removed from its support-system.

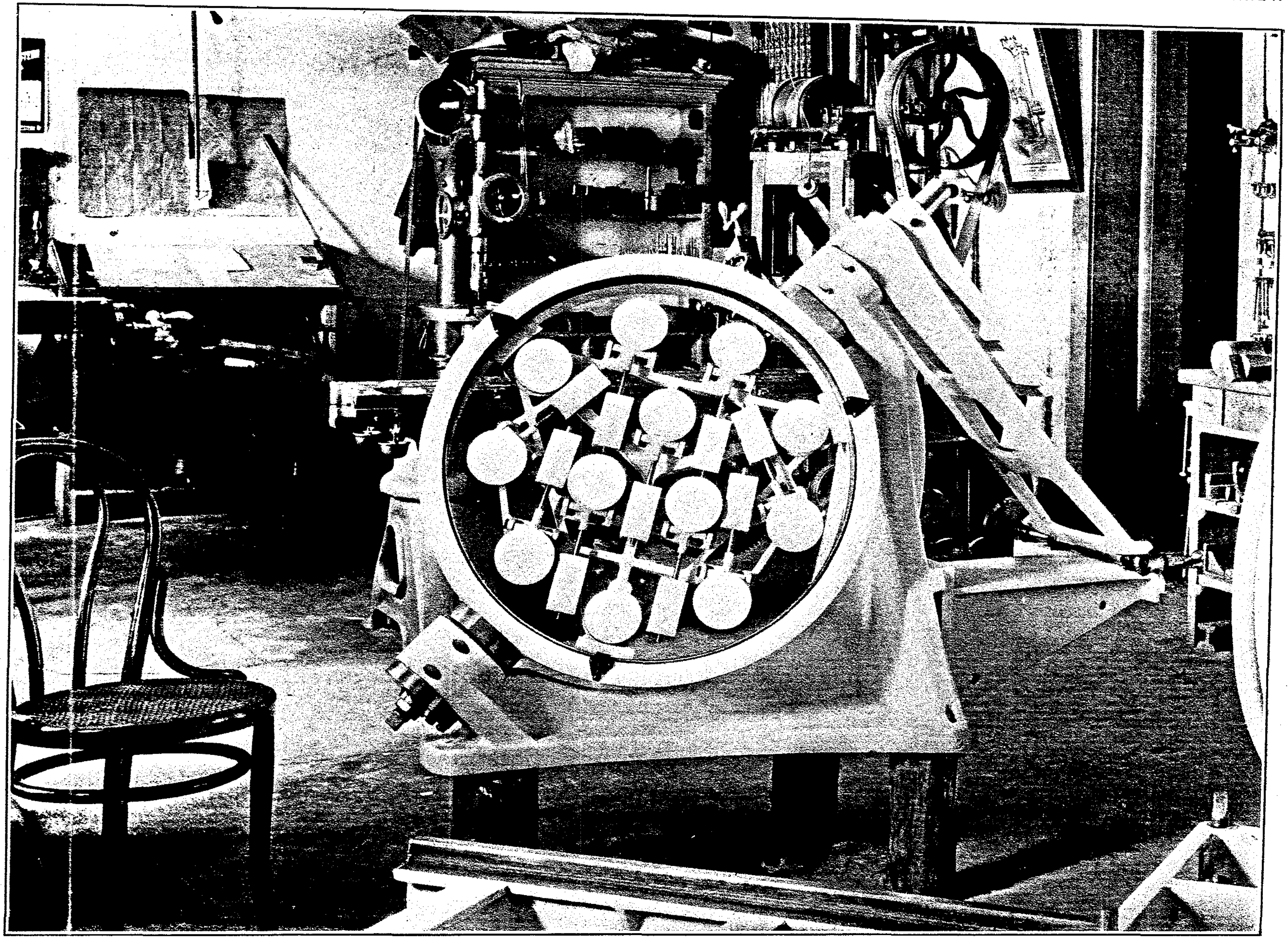
This support-system, as described, may appear complicated and expensive; in reality it is not so, for all of the levers, plates, etc., used for the back-support can be exactly alike, as can also the levers used for edge-support; even when a greater number of levers than twelve are used the construction is simple and economical.

In Plate x is shown a 30-inch plane mirror supported at the back by twelve plates and nine levers as described above; the mirror is shown unsilvered, so that the plates are seen through 4 inches of glass. This is a part of the 30-inch cœlostat recently constructed from the writer's designs in the instrument and optical shops of the Yerkes Observatory.

CHAPTER XVII.

A MOUNTING FOR A LARGE REFLECTING TELESCOPE.

In considering the requirements for a modern reflector mounting for photographic and spectroscopic work, the writer can probably not do better than to describe the designs for the proposed mounting of the 5-foot reflector. These designs are the result of experience both in optical work and in the use of the 2-foot reflector and the 40-inch refractor of the Yerkes observatory in astronomical photography.



LARGE COELOSTAT WITH 30-INCH PLANE MIRROR.
PLATES AND LEVERS FOR BACK-SUPPORT ARE SEEN THROUGH THE UNSILVERED GLASS.

With the present great improvements in the materials and methods of machine construction there is no longer any excuse for unstable and inconvenient mountings for reflectors. The focal length of modern reflectors intended for photography is short; the ratio of aperture to focal length generally used in such instruments will probably be not greater than as 1 to 4, nor less than as 1 to 6; with such ratios the mounting can be made extremely compact and rigid. By the addition of a small convex mirror the equivalent focal length can be increased from three and one-half to five times, and fine definition retained; when this is done the actual length of the tube is less than when the telescope is used at the primary focus.

The reflecting telescope defines well only at or near the optical axis; hence the mirrors must remain in perfect adjustment with reference to each other and to the eyepiece or photographic plate, in all positions of the telescope which can occur in use. Not only must the mirror supports be such as to define the position of the mirrors rigorously always, as described in the preceding chapter, but the short tube must be excessively strong and rigid so that no sensible flexure can occur. This is especially necessary when the telescope is used as a Cassegrain, or as a *coude;* for when these forms are employed it is only when the axes of the paraboloid and hyperboloid coincide that fine definition can be secured. When the necessity of these conditions is fully realized by makers and users of reflectors, a marked advance in the usefulness of reflecting telescopes will result. It was the lack of such rigidity and of such permanence of adjustments, fully as much as the lack of means of rigorously testing the optical surfaces, which made the old Cassegrain reflectors, including the great Melbourne instrument, such lamentable failures. I consider the failure of the Melbourne reflector to have been one of the greatest calamities in the history of instrumental astronomy; for by destroying confidence in the usefulness of great reflecting telescopes, it has hindered the development of this type of instrument, so wonderfully efficient in photographic and spectroscopic work, for nearly a third of a century.

When the telescope is to be used for photography, either direct or spectroscopic, it is indispensable that the mounting be so designed that reversal is not necessary when passing the meridian; for it is frequently necessary to expose for six or eight hours without reversal, on faint objects; and the best part of such an exposure is that in which the celestial object is near the meridian. Several forms of reflector mounting have been devised in which reversal is not necessary; the well-known English closed-fork mounting is one of them.

In designing the proposed mounting of the 5-foot reflector of the Yerkes Observatory, of twenty-five feet focal length, the writer has adopted the form in which a short open fork is used at the upper end of the polar axis. The tube hangs between the arms of this fork, being carried on two massive trunnions; the heavy lower end of the tube is so short that it can swing through, between the arms of the fork, for motion in declination.

The fork mounting presents several marked advantages with respect to compactness and stability, as well as convenience and economy, over all forms which are modifications of the German equatorial mounting, in which the tube is carried out at one side of the equatorial head. The tube, carrying the great weight of the mirror and its cell, is here supported at two opposite sides, instead of from one side only, as in the German forms; no heavy counterpoises are required; this form is much better adapted for the *coude* arrangement of mirrors, so essential in work with very large spectroscopes, only three reflections in all being necessary for this arrangement; furthermore, when the instrument is used at the primary focus, the upper end of the tube is more easily accessible, in all positions of the instrument, from an observing carriage attached to the inside of the dome.

The weight of the moving parts of the telescope will be about twenty tons. On account of this great weight, and also of the overhang of the fork above the bearings of the polar axis, an efficient anti-friction apparatus for the polar axis is demanded, which will at the same time relieve the effect of the overhanging weight of the upper end of the polar axis. The advantages afforded for this purpose by mercury flotation, when this is properly applied, are so great, and the mechanical details for such flotation work out so simply and economically, that this method will undoubtedly be used.

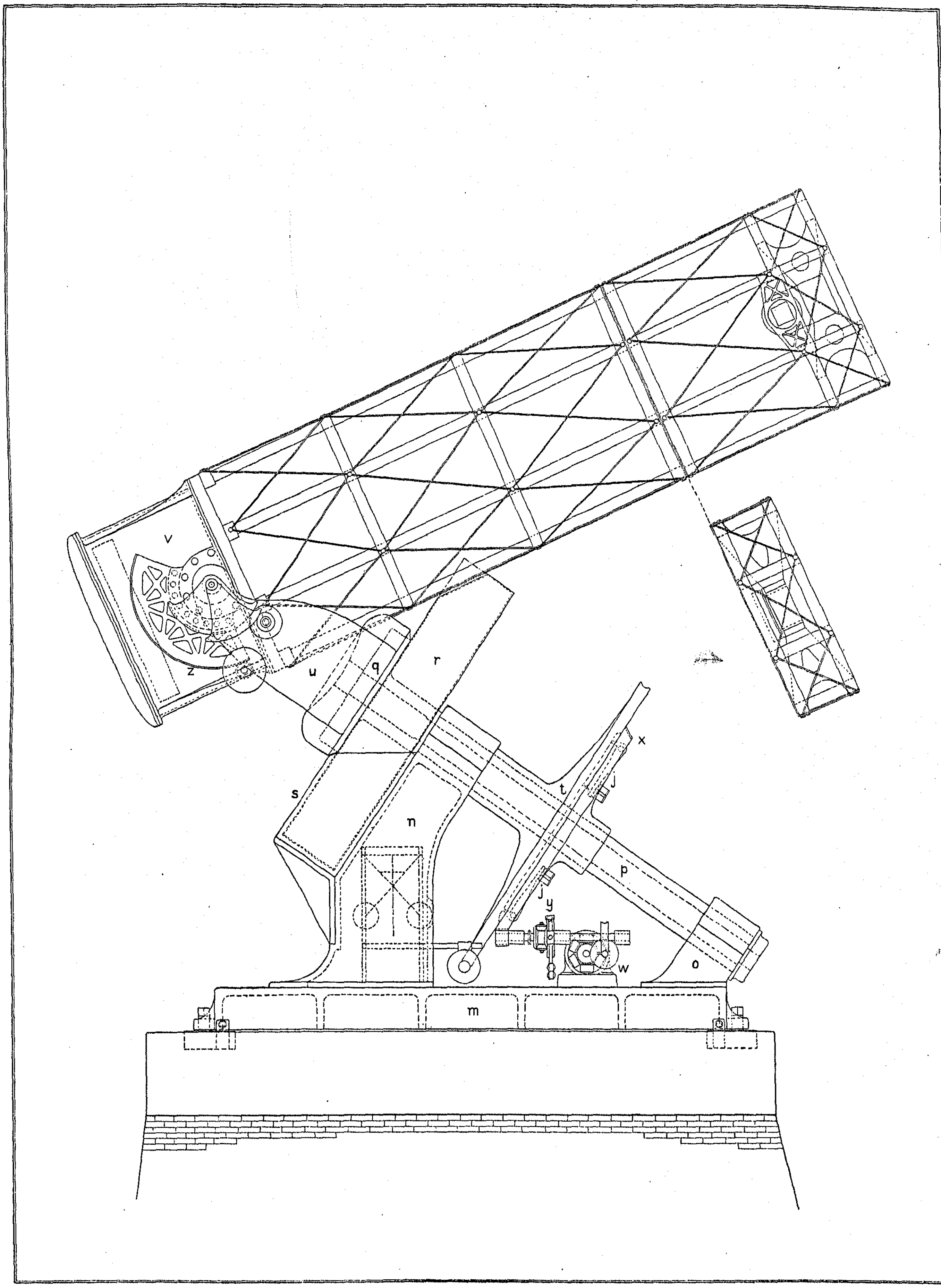
The proposed mounting will now be briefly described in detail, and attention will be called to many points which are indispensable to the success of a reflecting telescope to be used for photography.

The equatorial head consists of three iron castings, the triangular base-plate *m*, Plate XI, and the two posts *n* and *o*, which carry the bearings for the polar axis. Both posts are hollow, with walls $1\frac{3}{4}$ inch thick, and are bolted and pinned to the base casting; the post *n* contains the large driving clock.

The polar axis *p* is of hydraulic-forged steel, with a head or flange *q*, 48 inches in diameter and 7 inches thick, forged upon it; the axis is $14\frac{1}{3}$ feet long over all, is 20 inches in diameter for a distance of 2 feet below the head, and is 16 inches in diameter for the remaining $11\frac{2}{3}$ feet of its length; the axis is hollow, with walls $4\frac{1}{2}$ inches thick. The bearings of the polar axis are of hard Babbitt metal, and are halved.

Attached to the lower surface of the 4-foot head of the polar axis is the large hollow disk or float *r*, 10 feet in diameter and $22\frac{1}{2}$ inches thick or deep; this is constructed very strongly of angle steel covered with steel plates $\frac{3}{8}$ inch thick; the whole is finished smooth on the outside, and is turned true in a lathe. The corresponding trough *s* is of cast-iron and is turned true on the inside. The inner surface of the trough is separated by $\frac{1}{8}$ inch all around from the outer surface of the float; this space is filled with mercury. With the dimensions given the immersed part of the float displaces about 45 cubic feet of mercury, which thus floats about nineteen tons, or 95 per cent of the weight of the moving parts of the telescope. The center of flotation is vertically below the center of weight of the moving parts. Only three-quarters of a cubic foot of mercury is required to float nineteen tons in this manner.

The importance in astronomical photography of the smoothness of motion afforded by really efficient flotation of the moving parts cannot be overestimated. The great size of the worm-wheel *t* which rotates the polar axis, will materially



DESIGN FOR MOUNTING OF FIVE-FOOT REFLECTING TELESCOPE.

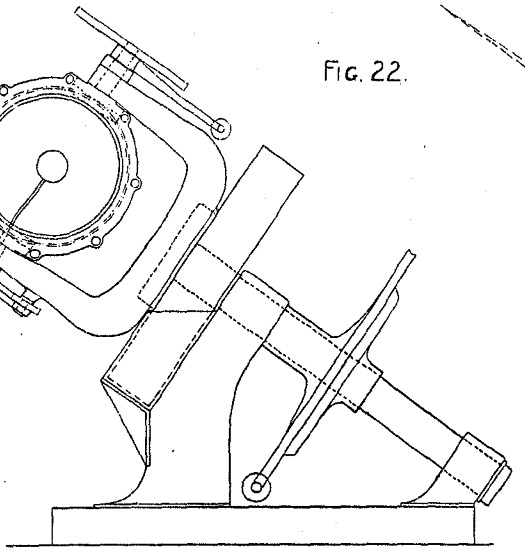


FIG. 22.

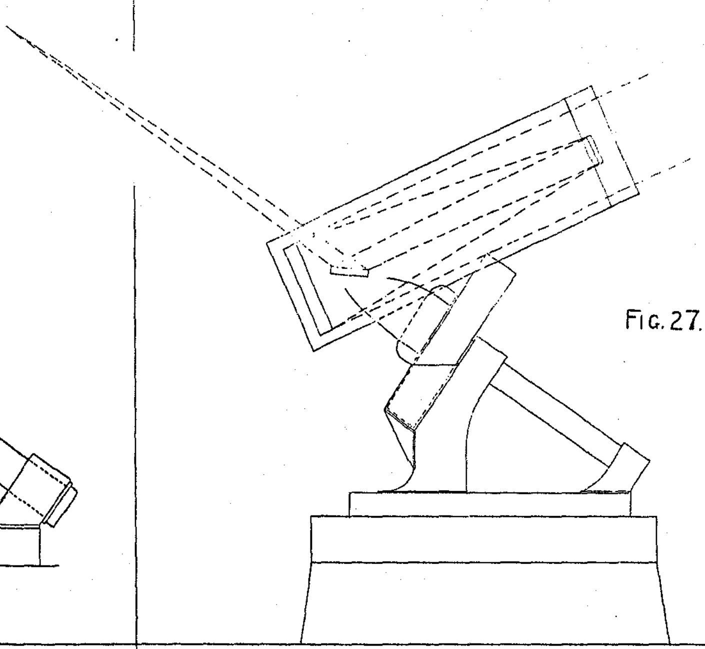


FIG. 27.

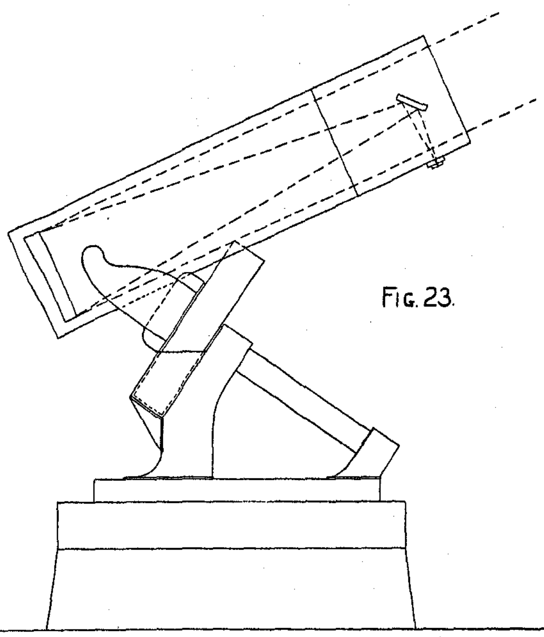


FIG. 23.

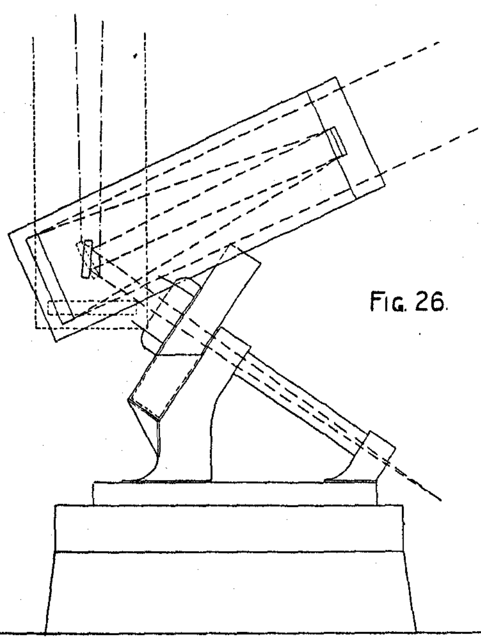


FIG. 26.

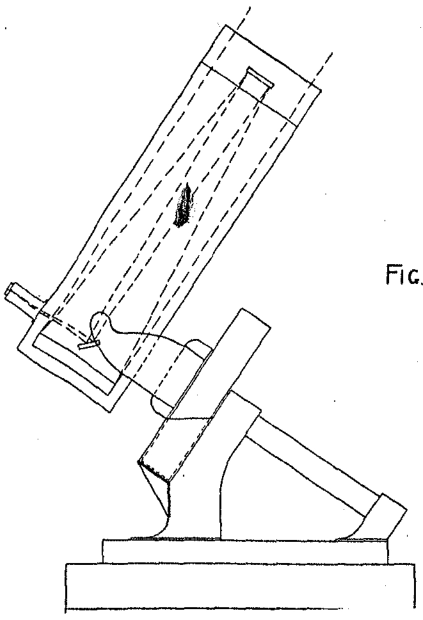


FIG. 24.

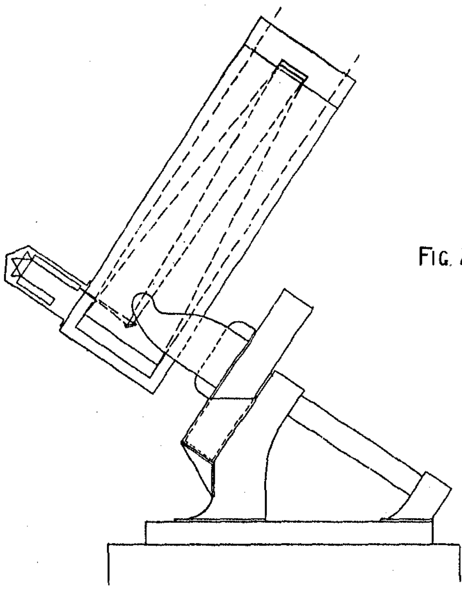


FIG. 25.

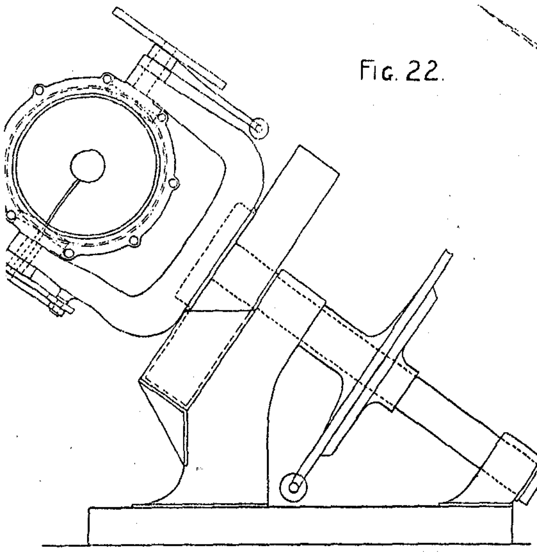


Fig. 22.

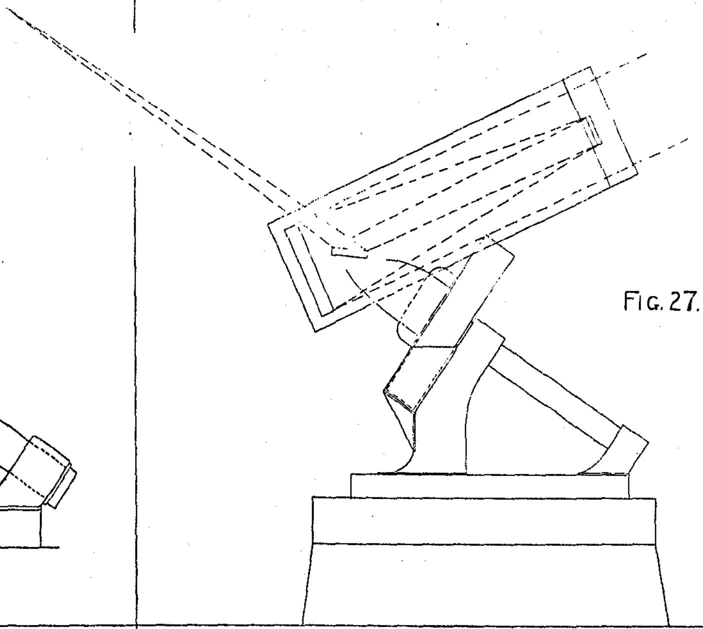


Fig. 27.

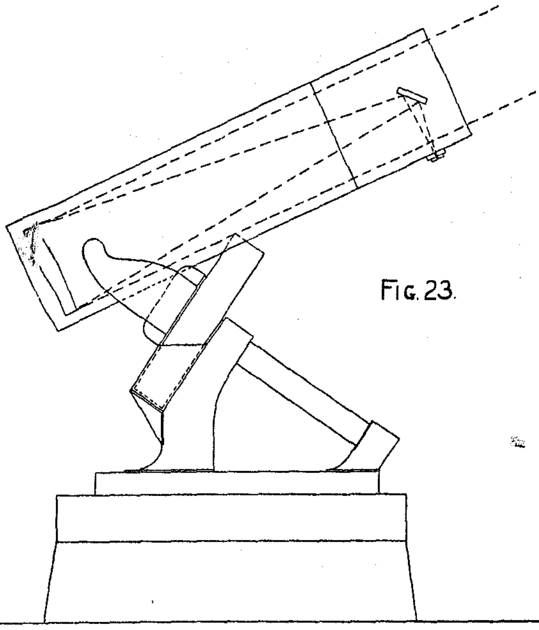


Fig. 23.

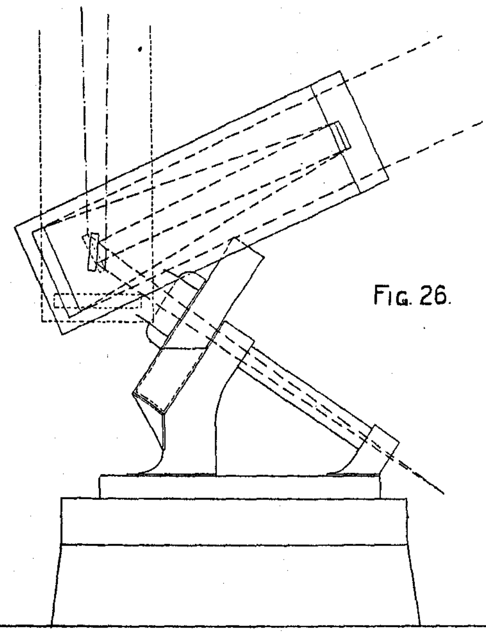


Fig. 26.

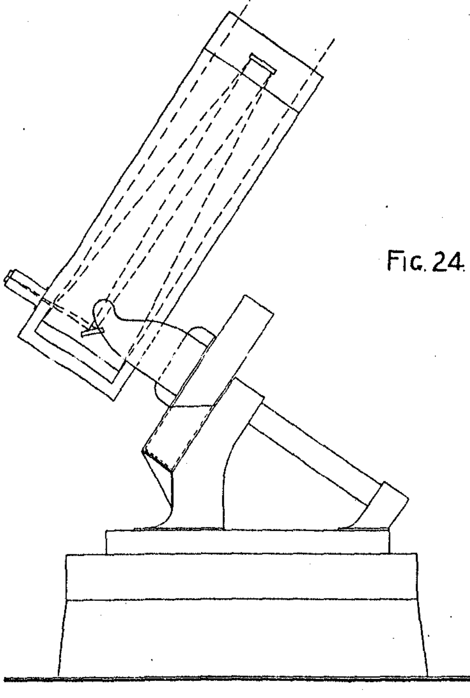


Fig. 24.

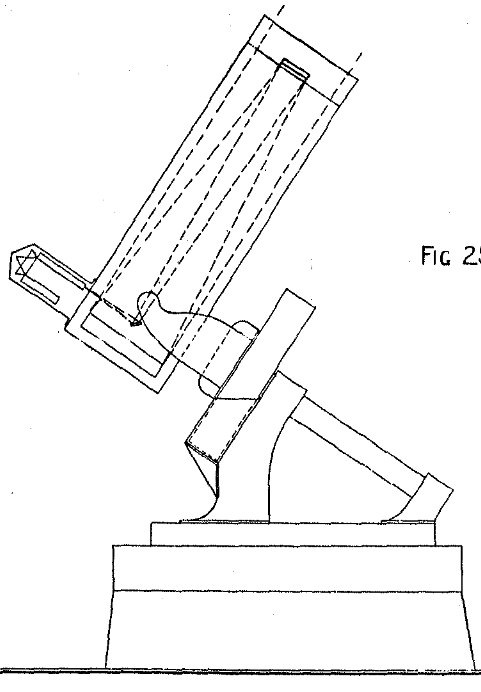
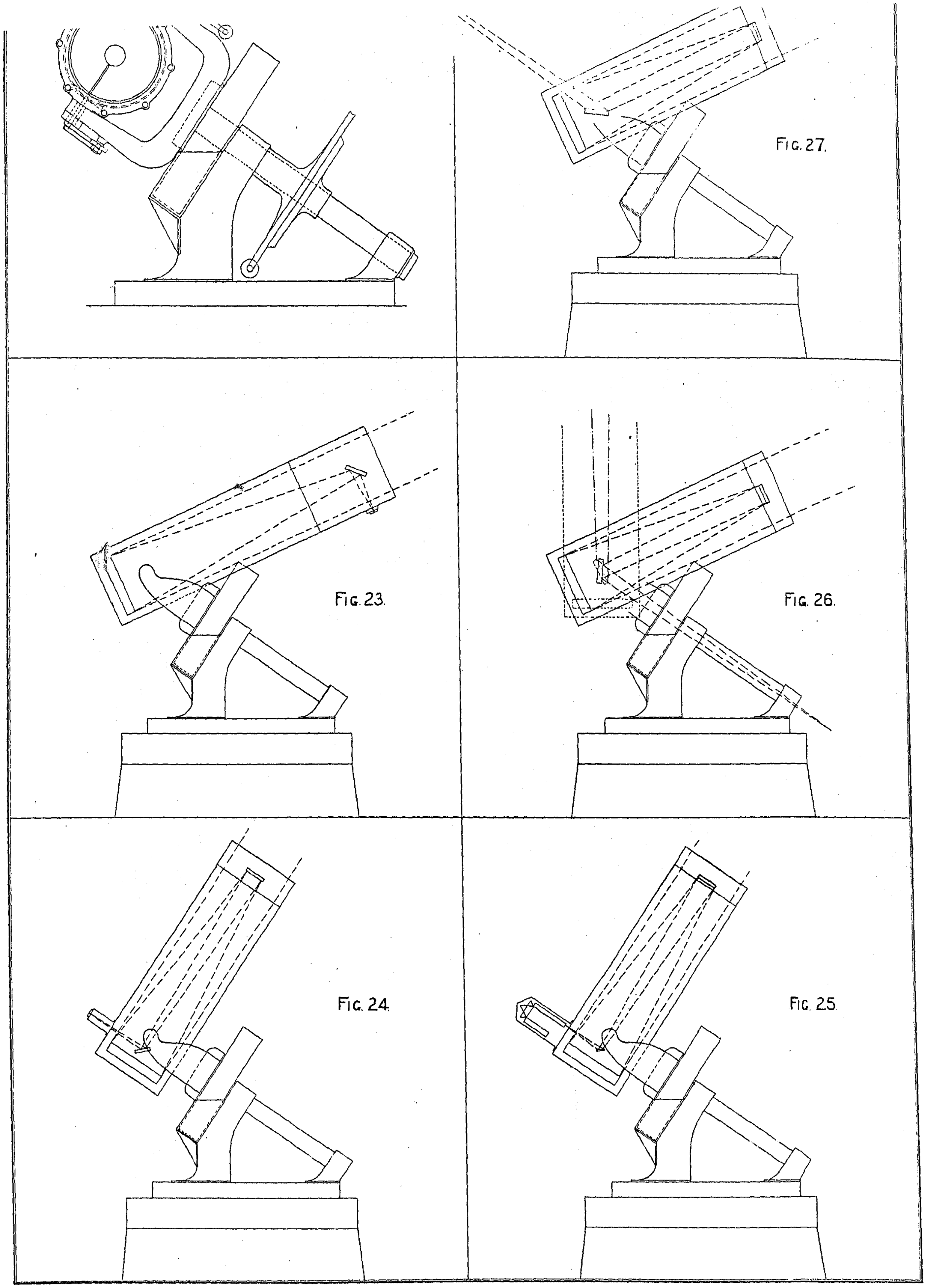


Fig 25

DESIGN FOR MOUNTING OF FIVE FOOT



DESIGN FOR MOUNTING OF FIVE-FOOT REFLECTING TELESCOPE.

assist in giving smoothness and accuracy of driving; this worm-wheel is 10 feet in diameter.

Attached to the upper surface of the 4-foot head of the polar axis, by means of a circle of 2-inch bolts, is the large cast-iron fork *u*, different views of which are shown in Plate XI and Fig. 22, Plate XII. The extreme outside width of this fork is $8\frac{1}{3}$ feet; it is of hollow or box section, with walls averaging $1\frac{1}{2}$ inches thick; it weighs about five tons.

Between the two arms of the fork hangs the short round cast-iron section *v* of the tube; two 7-inch steel trunnions, having large heads or flanges, are bolted to this casting, and turn in bronze bearings at the upper ends of the fork arms; this part of the tube is 46 inches long; its inside diameter is 70 inches; its thickness is 1 inch; it is reinforced at top and bottom by flanges. To the lower flange is connected the cell-plate (described in the preceding chapter) which carries the large mirror and its support-system.

To the upper flange of the short cast-iron section of the tube is bolted a strong cast-iron ring which forms the lower end of the main or permanent section of the octagonal skeleton tube; this section is 13 feet 11 inches long, and 6 feet 8 inches outside (diagonal) diameter. It is constructed of eight 4-inch steel tubes, connected by strong rings designed to resist compression; diagonal braces, which are connected together at all intersections, greatly increase the rigidity of the structure. This entire section is so rigid that it can be placed in a large lathe for facing the ends parallel to each other, and for turning a slight recess in the ends for the purpose of accurately centering the parts which are to be connected to them.

To the upper end of the permanent section of the skeleton tube can be attached any one of three short extension tubes or frames, as desired; two of these are shown in Plate XI. The lower end of each extension is turned true, with a projecting ring which fits into the turned recess in the upper end of the permanent section. With this arrangement the various extensions can be removed and replaced without sensibly affecting the adjustments of the mirrors and other apparatus which they carry, with reference to the optical axis of the large mirror.

The extension which is shown in place on the telescope in Plate XI and in Fig. 23, Plate XII, is the longest one; it is 6 feet 11 inches long; it is used for all work at the primary focus of the telescope; it carries the diagonal plane mirror and its supports, and the eyepiece and double-slide plate-carrier. This extension can be rotated upon the turned end of the permanent section, so that the eyepiece or photographic apparatus can be brought to the side of the tube which is most convenient for observing or photographing a given object. The diagonal plane mirror is of the finest optical glass, is elliptical in outline, is 15 x 22 inches in size, and is $3\frac{1}{2}$ inches thick; it is carried in a strong cast-iron cell, which is supported from the skeleton tube by four thin steel plates, as shown in Plate XI. The diagonal plane mirror is sufficiently large to fully illuminate a field 7 inches in diameter at the primary focus. The double-slide plate-carrier is designed for $6\frac{1}{2}$ x $8\frac{1}{2}$ inch photographic plates.

The other two extensions of the tube, which are only about 2 feet long, are employed when the telescope is used as a Cassegrain and as a *coude* respectively; each carries a convex mirror 19 inches in diameter and $3\frac{1}{6}$ inches thick, of the finest optical glass, and of the proper curvature for the purpose desired.

Figs. 24 and 25, Plate XII, show the telescope used as a Cassegrain. In these cases the amount of amplification introduced by the convex mirror is about $3\frac{1}{2}$ diameters (see p. 38); the equivalent focal length is therefore about $87\frac{1}{2}$ feet, and the ratio of aperture to focal length as 1 to $17\frac{1}{2}$. Fig. 24 shows the telescope as used for direct photography with the double-slide plate-carrier at the secondary focus. In Fig. 25 a spectrograph similar to the large Bruce spectrograph of the Yerkes Observatory is shown attached to the north side of the short cast-iron section of the tube; this affords a most stable base of support for the spectrograph, at a point where it can be easily counterpoised.

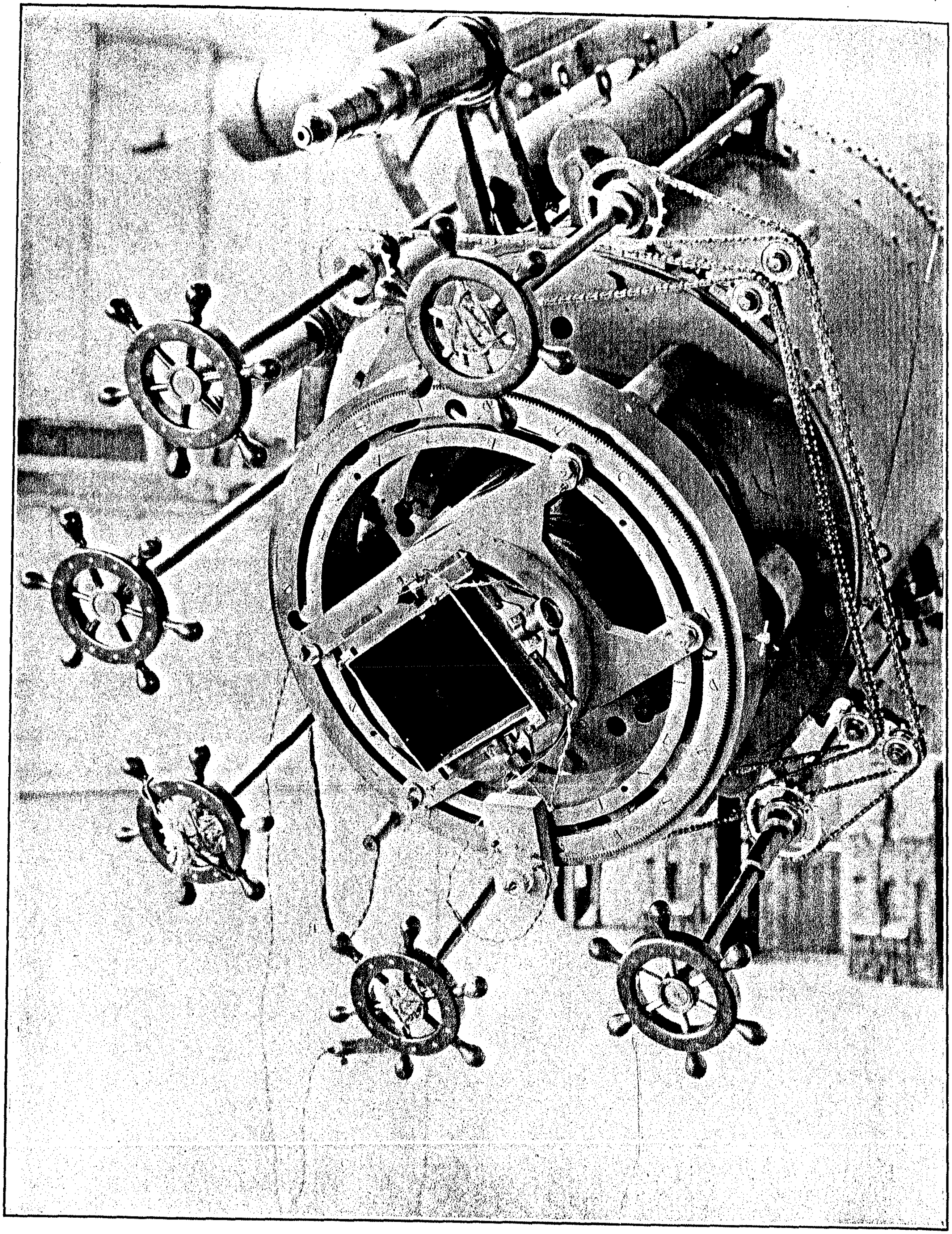
Figs. 26 and 27, Plate XII, illustrate the use of the telescope as a *coude;* the curvature of the convex mirror is now such that the equivalent focal length is about 125 feet. The cone of rays from the convex mirror strikes a diagonal plane mirror at the intersection of the polar and declination axes, and is by it reflected *in a constant direction*, which can be toward either the north or south pole of the heavens, as desired. This arrangement is almost indispensable when extremely large and powerful spectroscopes and other kinds of physical apparatus are to be used with the telescope; the focus is now in a constant position, so that such instruments need not be attached to the telescope, but can be mounted on stationary piers, in constant temperature rooms, if desired.

A brief description of the mechanism for quick-motion and slow-motion in right ascension and declination should be given. These are planned to be entirely electrical, although hand-motions are added, to be used in case of an emergency. Quick-motion in right ascension, both east and west, is given by the reversible motor *w;* this is connected by gearing to the large bevel-gear *x* through the medium of an electric clutch *y*. The bevel-gear *x* is permanently fixed to the polar axis. When the switch which starts the motor is thrown in, the electric clutch *y* acts, and a motion of rotation is communicated to the polar axis; this rotation is only at the rate of 45 degrees per minute; this is sufficient, since reversal is never necessary; hence very little power is required. The clutch is so adjusted that it will slip when even slight undue resistance is encountered. When the current is shut off from the motor the clutch is released automatically; the polar axis is then free from the motor and gear-train.

Quick-motion in declination is given in a manner entirely similar to that in right ascension, by a small reversible motor attached directly to the large cast-iron fork; this motor drives, through the media of a gear-train and an electric clutch, the toothed sector *z*, which is permanently fixed to the cast-iron section of the tube.

The driving-clock and 10-foot worm-wheel are "clamped in" to the polar axis, when desired, by the electric clamps *j* which lock the 10-foot worm-wheel to the bevel-gear *x;* the former is of course free to turn on the polar axis when not thus clamped.

Slow-motion in right ascension is given by means of a small reversible motor



LARGE DOUBLE-SLIDE PLATE-CARRIER ATTACHED TO 40-INCH REFRACTOR; YERKES OBSERVATORY.

which acts on a set of differential gears in the shafting connecting the driving-clock and the driving-worm. This device is used on the 2-foot reflector and on the 30-inch cœlostat, and is extremely simple and effective.

Slow-motion in declination is given by means of a small reversible motor which acts on the long sector attached to the upper trunnion shown in Fig. 22, Plate XII.

In concluding this necessarily brief and incomplete description of a modern reflector mounting, attention should be called to an attachment which is absolutely indispensable for the best results in direct photography of all celestial objects requiring long exposure. I refer to the double-slide plate-carrier, by means of which hand-guiding or correcting for the incessant small irregular movements of the image, which are nearly always visible in large telescopes, can be done incomparably more accurately and quickly than by any other means now known. This device is due to Dr. Common, who described it in *Monthly Notices*, Vol. 49, p. 297. In 1900 the writer designed and constructed a small attachment of this kind for use with the 40-inch refractor and the 2-foot reflector; this attachment and its use are described in the *Astrophysical Journal* for December 1900, p. 355.

The photograph of the central parts of the Andromeda Nebula (Plate I), was made by the writer with this small plate-carrier attached to the 2-foot reflector. The exposure time in this case was four hours. The images of the fainter stars on the original negative are only 2 seconds of arc in diameter; stars are shown which are more than a magnitude fainter than the faintest stars which can be detected visually with the 40-inch refractor; intricate structure and details are shown in the nebulosity, which are entirely invisible with the 40-inch refractor and all other visual instruments, and which have never been photographed before. When it is remembered that the focal length of the 2-foot reflector is only 93 inches, and that the aperture was in this case reduced to 18 inches, in order to secure a larger field than is well covered when the full aperture is used, some idea can be gained of the results which could now be obtained in celestial photography with a modern reflecting telescope which would compare in size, cost, and refinement of workmanship with the great modern refractors.

In Plate XIII is shown the large double-slide plate-carrier, taking 8 x 10 inch plates, which was constructed from the writer's designs in 1901, for use with the 40-inch refractor; the plate-carrier is here shown connected to the eye-end of the great telescope. A description of this attachment, together with some photographs obtained with it, will be found in the *Publications of the Yerkes Observatory*, Vol. II, p. 389.