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THE 60-INCH REFLECTOR OF THE MOUNT WILSON SOLAR OBSERVATORY

By G. W. RITCHEY

The 60-inch reflector of the Mount Wilson Solar Observatory was first tested visually on the stars on the night of December 13, 1908, and the first celestial photograph was secured with it on December 19. A number of accessories of the telescope and its steel dome and building still remain to be completed; the most important of these

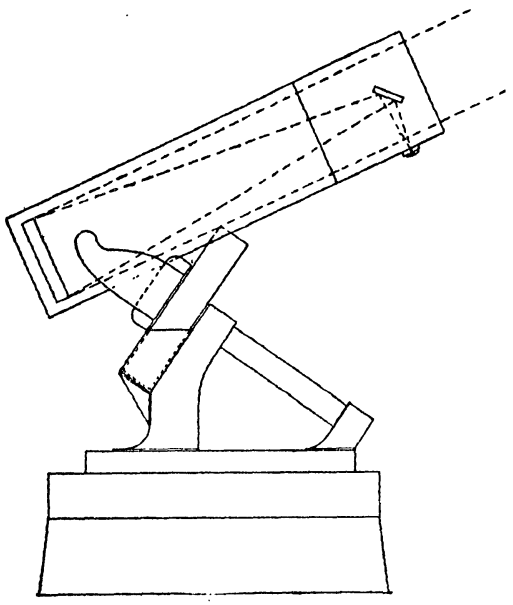

FIG. 1

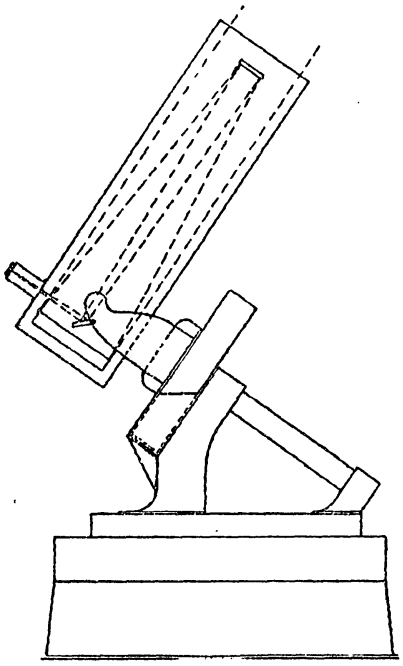

FIG. 2

are the three spectrographs, and the small refrigerating apparatus for holding the large mirror throughout the day at the expected night temperature.

The 60-inch (152 cm) reflector is designed to be used in four principal ways, as follows: First, as a Newtonian, for direct photography with the double-slide plate-carrier, and for spectroscopic work with a spectrograph carried at the Newtonian focus; in this use the focal length is 299 inches (7.6 m) (see Fig. 1). Second, as a Cassegrainian, for direct photography with the double-slide plate-carrier;

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in this use the equivalent focal length is approximately 100 feet (30.5 m), and the enlarged image is formed at the north side of the tube, near its lower end (see Fig. 2). Third, as a Cassegrainian for spectroscopic work with a large spectrograph, of the type of the Bruce spectrograph of the Yerkes Observatory, attached to the north side of the strong cast-iron part of the tube, near its lower end; in

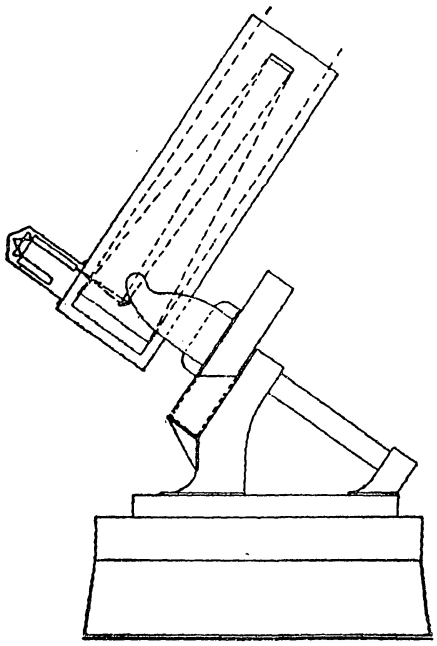

FIG. 3

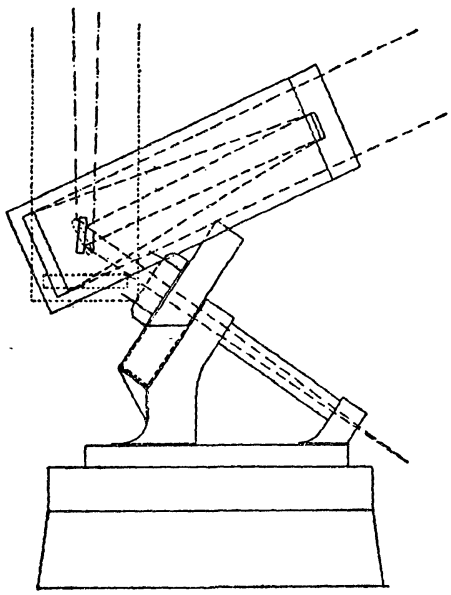

FIG. 4

this use the equivalent focal length is approximately 80 feet (24.4 m) (see Fig. 3). And fourth, as a Cassegrainian-*Coudé* for spectroscopic work with a very large spectrograph mounted on stationary piers in an underground constant-temperature pit; in this use the equivalent focal length is approximately 150 feet (45.5 m) (see Fig. 4.)

THE OPTICAL PARTS

For the above uses of the telescope six optical mirrors are required, all of which have been completed in our shop: the 60-inch paraboloidal mirror of 299 (7.6 m) inches focal length, which in its finished condition is $7\frac{5}{8}$ inches (19.4 cm) thick at the edge, $6\frac{7}{8}$ inches (17.5 cm) thick at the center, and weighs 1900 lbs. (865 kilos); the Newtonian plane mirror, which is of elliptical outline, is $19\frac{3}{4}$ inches (50.2 cm) long, $14\frac{1}{2}$ inches (36.8 cm) wide, and $3\frac{1}{8}$ inches (7.9 cm) thick; the *Coudé* plane mirror, which is also elliptical in

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outline, is $22\frac{1}{4}$ inches (56.5 cm) long, $12\frac{1}{2}$ inches (31.8 cm) wide, and $3\frac{5}{8}$ inches (9.2 cm) thick; and three convex hyperboloidal mirrors, with diameters respectively of 16 inches (40.6 cm), $16\frac{3}{4}$ inches (42.6 cm), and $17\frac{1}{2}$ inches (44.5 cm), and giving equivalent focal lengths, as before stated, of approximately 80 feet (24.4 m), 100 feet (30.5 m), and 150 feet (45.7 m) respectively; each of these mirrors is about 3 inches (7.6 cm) thick. All of these mirrors are polished approximately flat on the back, and when in use in the telescope are silvered on the back as well as on the face, in order that the effect of temperature change may be symmetrical on front and back.

The methods used in grinding, polishing, and testing the mirrors are practically the same as those described in my paper on "The Modern Reflecting Telescope," published by the Smithsonian Institution in 1904. The methods used in testing the optical surfaces are also described in the *Astrophysical Journal*, **19**, 53, 1904. As these methods have now been applied and thoroughly tested in the case of a reflecting telescope of the largest size with satisfactory results, the following remarks upon the optical work may be of interest.

Of much practical importance in its bearing upon the making of very large optical surfaces is the fact that, in the case of the 60-inch glass, grinding and polishing tools of only about one-fourth the area of the glass were used with entire success in excavating the large concave and in fine grinding and polishing; a full-size, flat grinding tool was used only in the preliminary work of securing a perfect surface of revolution. A circular grinding tool of cast-iron, $31\frac{1}{2}$ inches (80 cm) in diameter, was used in all of the fine grinding of the large concave surface. In polishing this concave, and in bringing it to an optically perfect spherical surface preparatory to parabolizing, a 90° sector-shaped polishing tool of exactly one-fourth the area of the large glass was used with the best results. In parabolizing, a circular polishing tool 20 inches (50.8 cm) in diameter was exclusively used in securing the necessary change of curvature from center to edge of the glass; in addition to this the 90° sector tool, used with long diametrical and chordal strokes, was found to be of great value in smoothing out the paraboloidal surface. With these two figuring tools alone, used with the machine, a very close approximation to a true paraboloid was secured. The figuring was

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completed with much smaller tools used by hand to soften down several slight high zones.

In figuring the large paraboloid, one modification only was found desirable in the polishing machine described in my Smithsonian paper. The two cranks which give the motion to the polishing tools were remade in such a way that their throw or stroke can now be altered at will while the machine is running. The optician is thus enabled to change the position and stroke of the tool with a perfectly smooth progression while parabolizing; these changes are actually made at the end of each revolution of the glass, and a very great improvement in the smoothness of curvature of the paraboloid is at once apparent.

In the early stages of figuring the large paraboloid, testing was done at the center of curvature, by measuring the radius of curvature of the successive zones; in the final stages, however, all tests were made at the focus of the paraboloid, with the aid of a 36-inch (91.4 cm) collimating plane mirror of the finest figure, which was made in our optical shop expressly for the purpose of testing the large paraboloid and the three smaller hyperboloidal mirrors described above. This 36-inch plane mirror was mounted on edge on an iron carriage sliding on massive iron ways carefully finished straight, and could be moved horizontally by means of a long screw; in this manner it could be readily placed so as to show, at the testing knife-edge at the focus of the 60-inch paraboloid, any 36-inch circle of this paraboloid. This test is a most rigorous and satisfactory one, enabling the optician to see, and to determine the character of slight zonal errors which cannot be detected by the test at the center of curvature. The three hyperboloidal mirrors were tested in a similar manner, in conjunction with the 36-inch plane mirror.

While a collimating plane mirror of the full size of the paraboloid would be desirable and convenient, my experience has shown that a plane mirror with a diameter three-fifths that of the paraboloid, used as above described, gives excellent results. A rough disk of glass has accordingly been ordered for a 60-inch plane mirror for testing the 100-inch (254 cm) Hooker glass.

THE MOUNTING

In all essential features the design for a 60-inch mounting described in my Smithsonian paper has been carried out. The general

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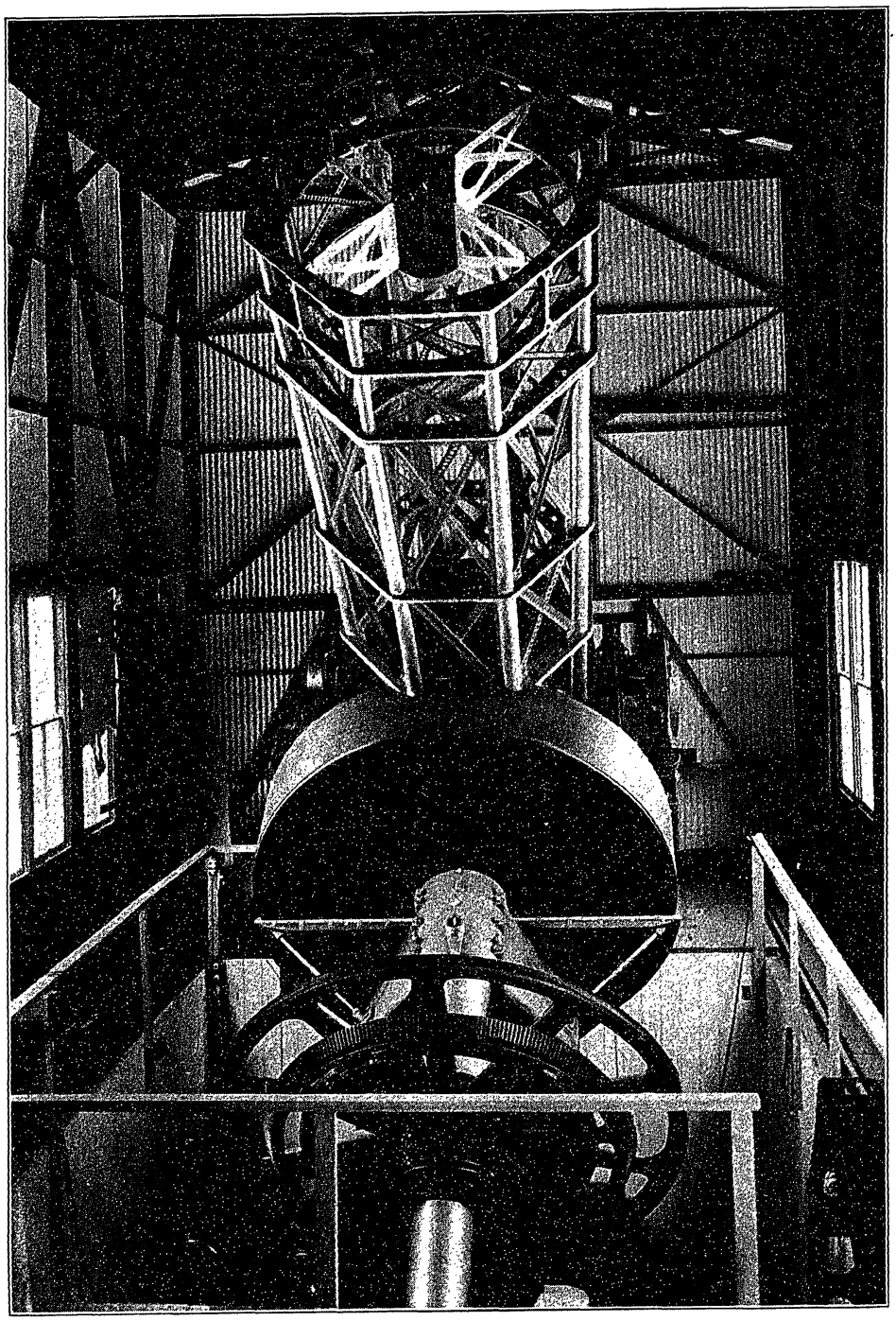
PLATE IV



60-INCH REFLECTOR MOUNTING IN ERECTING SHOP

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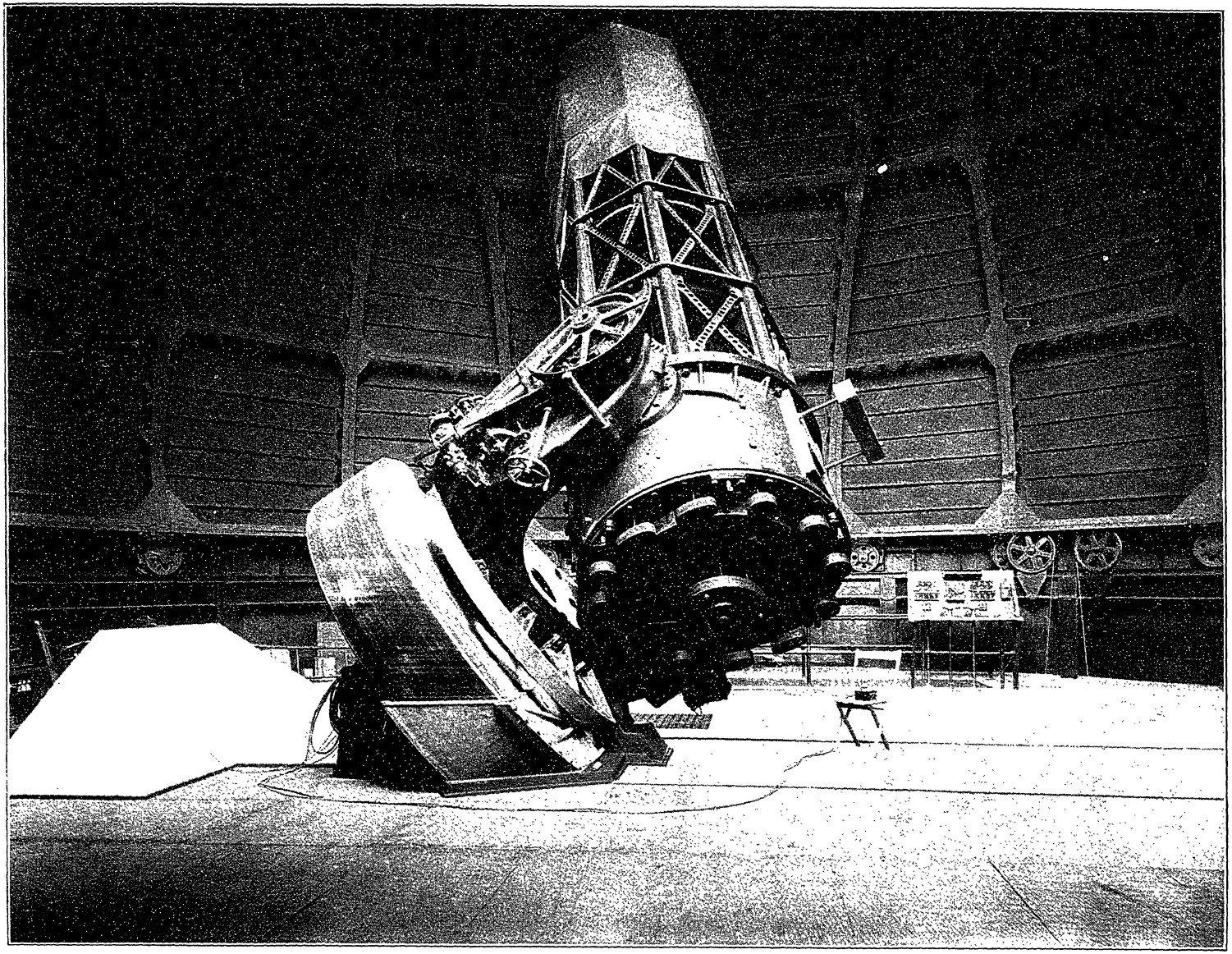
PLATE V



60-Inch Reflector Mounting in Dome

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character of the mounting will be seen by reference to Plates IV and V; the first of these shows the mounting as it appeared in our erecting shop in Pasadena, the second as it appears when finally set up in its dome on Mount Wilson.

The very large parts of the mounting, including the base, the polar axis, the mercury float and trough, and the tube, were made by the Union Iron Works Company of San Francisco; a large amount of final machining and finishing of these parts was done by us after their arrival at Pasadena. In addition, the construction of all of the smaller and more refined parts of the mounting, including the driving-clock and its connections, the electric quick- and slow-motion mechanism, the lever-support system of the large mirror, the cells and their supports for the five small mirrors, the automatic-rotation mechanism for the *Coudé*-plane mirror, the large double-slide plate-carrier, the graduated circles, and the cutting and grinding of the 10-foot (3.5 m) worm-gear on the polar axis, was done at our shop in Pasadena.

The cast-iron base is 15 feet (4.57 m) long, 7 feet (2.13 m) wide, 18½ inches (47 cm) deep, and weighs 14,000 lbs. (6350 kilos). The north and south columns, forming the bearings of the polar axis, weigh respectively 9500 lbs. (4275 kilos), and 2000 lbs. (907 kilos). The polar axis is a hollow forging of nickel-steel, hydraulic-forged by the Bethlehem Steel Company, and is turned and ground all over; it is 15 feet (4.6 m) long, varies from 15 to 18 inches (38.1 to 45.7 cm) in diameter, and weighs 9200 lbs. (4140 kilos). At its upper end is a head or flange 4½ feet (1.37 m) in diameter and 6 inches (15.2 cm) thick. To the lower side of this flange is bolted the float, which is a very rigid hollow disk of steel boiler plate, 10 feet (3.05 m) in diameter and 2 feet (61 cm) deep or thick, weighing 8600 lbs. (3900 kilos). To the upper side of the flange of the polar axis is bolted the fork, between the great arms of which the tube swings in declination on nickel-steel trunnions 7 inches (17.8 cm) in diameter. The fork is of cast-iron, of hollow box-section, is 9 feet (2.7 m) across in extreme width, and weighs 10,400 lbs. (4711 kilos). Twelve nickel-steel bolts, 2½ inches (6.4 cm) in diameter and 3 feet (91.4 cm) long, pass through reamed holes through the base of the fork, through the flange of the polar axis, and through the cast-iron center or hub of the float, thus clamping these massive parts together with

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extreme strength and rigidity at a region of the mounting where the greatest tendency to flexure occurs.

The float dips in a cast-iron trough which is machined to nearly fit the float, leaving a space of only one-eighth of an inch all around; this space is filled with 650 lbs. (295 kilos) of mercury. The immersed part of the float gives a displacement of about 50 cubic feet (1.4 cu. m) of mercury, thus carrying 21½ tons (19,479 kilos) of the moving parts of the telescope in the fluid, and relieving 95 per cent. of the weight on the large bearings of the polar axis. The mounting is so designed that the center of weight of the moving parts is vertically above the center of flotation.

The large worm-gear for the diurnal rotation of the telescope is 10 feet (3.05 m) in diameter and has 1080 teeth. While being cut, these teeth were spaced with the utmost care with the aid of a 36-inch (91.44 cm) Warner and Swasey graduated circle of the finest quality. The teeth were then hobbed (with a hob of special design by which the accuracy cannot be lost) and were then ground with hone powder of finer and finer grades, with oil, and were finally polished with rouge and oil. This treatment not only eliminates any small irregularities of spacing, but leaves the teeth exquisitely smooth.

The driving-clock is in many respects a copy of the driving-clock of the 40-inch Yerkes refractor, built by Warner and Swasey. I have introduced one important modification, however, as follows: the clock-governor is driven by a weight through a spur-gear train, as usual, but the motion of the governor is communicated to the telescope through the medium of a worm and worm-gear, which are ground with the utmost care to eliminate periodic errors. This worm-gear of 80 teeth, together with the large worm-gear of 1080 teeth on the polar axis, gives the entire reduction from the clock-governor, rotating once in a second, to the polar axis, which rotates once in 24 hours. Furthermore, the two worm-gears named are the only gears used in communicating the rotation of the clock-governor to the polar axis, the driving-clock being so placed that all spur-gears and bevel-gears are dispensed with.

To relieve friction and wear on the polished teeth of the large worm-gear, and on the clock and clock-connections, the following simple expedient is used. A small wire-rope passes over a grooved wheel keyed to the polar axis, runs over two grooved pulleys on the

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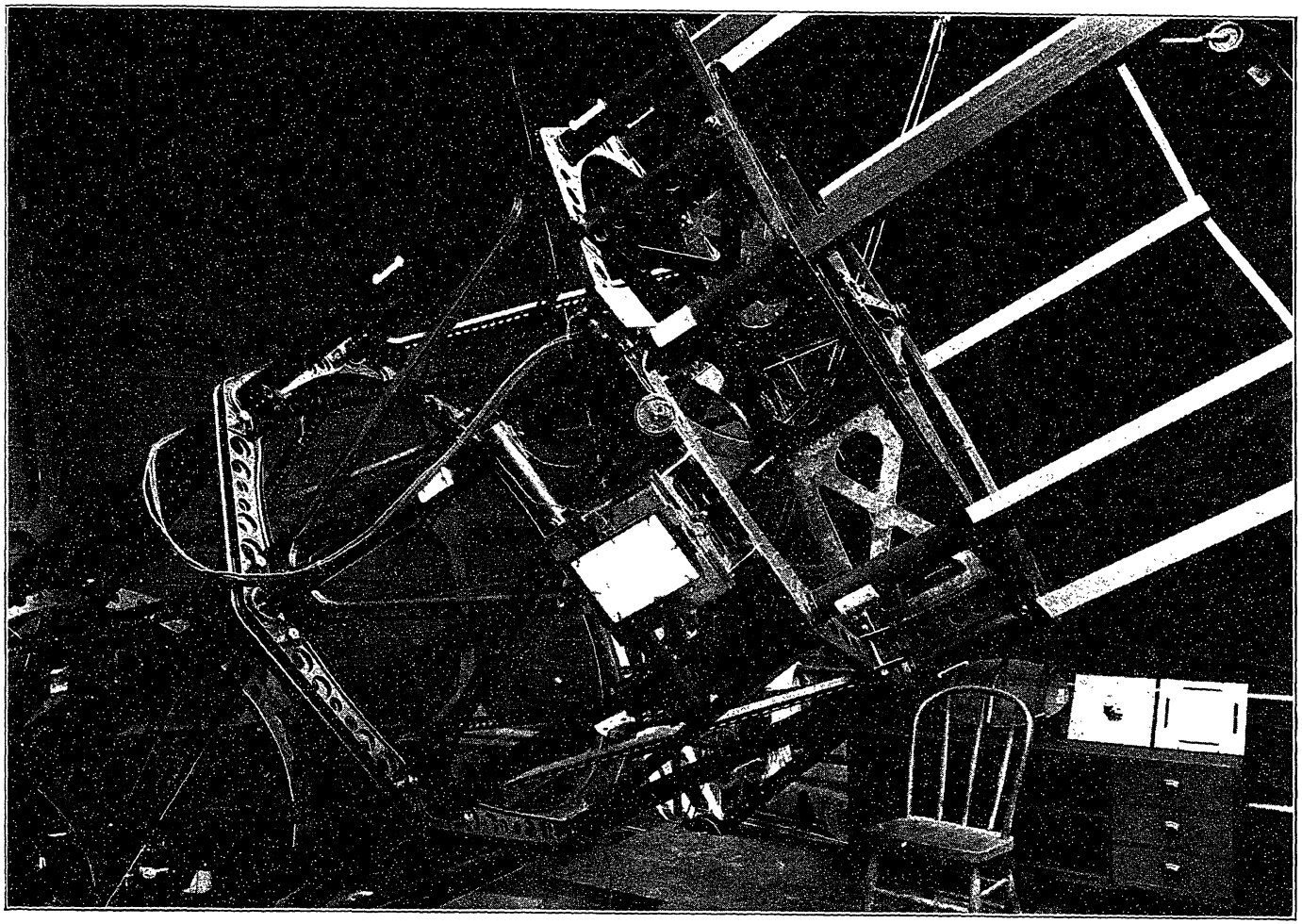
PLATE VI



DOUBLE-SLIDE PLATE-CARRIER IN PRINCIPAL FOCUS OF 60-INCH REFLECTOR

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west side of the telescope base, and is loaded with about 100 lbs. of iron weights hanging vertically on the west side of the pier. With this assistance, only about two pounds' pressure on the teeth of the 10-foot worm-gear is required to rotate the moving parts toward the west.

As a further means of keeping the teeth of the large worm-gear continually in the finest condition, a small motor is provided by means of which the gear and its worm can be repolished at any time. In practice this is done several times each week; the worm-shaft is disconnected from the driving-clock by simply removing two small screws, fine graphite and oil are supplied as a lubricant, and the large worm-gear and its worm are run together for an hour.

As a result of the mercury flotation and the care which has been given in finishing the driving-clock, the clock-connections, and the large worm-gear, the great telescope follows the stars with exquisite smoothness and accuracy, despite the fact that the moving parts weigh nearly 23 tons.

The telescope is provided with electric quick and slow motions. The former give a speed of 30 degrees per minute of time, in both right ascension and declination. The latter are arranged to give two speeds, one of six minutes of arc in a minute of time, for ordinary fine setting, and a slower one of one-half minute of arc in a minute of time for guiding with the spectrographs. The electric wiring is so arranged that the slow motions can be operated from several convenient points.

The octagonal skeleton tube is worthy of description because of its extraordinary rigidity. It consists of eight conical tubes of $\frac{1}{8}$ inch (3.2 mm) sheet steel, about 15 feet (4.6 m) long, tapering from 5 inches (12.7 cm) diameter at their lower ends to 3 inches (7.6 cm) diameter at their upper ends; each tube is made of two parts riveted together, with two flanges 135° apart extending their whole length; to these flanges are riveted the diagonal braces; three rigid rings connect the eight tubes together. Any one of four interchangeable extensions of the tube, called "cages," of similar construction, can be connected to the upper end of this permanent part of the skeleton tube; one of these carries the Newtonian plane mirror and its accessories; this is shown in Plate VI; each of the others carries one of the small hyperboloidal mirrors, with its cell, cell-support, and small

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electric motor for focusing. A simple and effective machine, called the "cage-lift," which is suspended from the framework of the dome, enables the observer or assistant to interchange the cages quickly and safely.

The Newtonian "cage" or tube-extension can be connected to the tube in four different positions 90° apart, that is, with the diagonal plane mirror and the double-slide plate-carrier facing either north, east, south, or west. The cage-lift is so designed that the tube-extension can be rotated to the position desired while suspended in it, before being attached to the tube.

The double-slide plate-carrier is most carefully designed, and is much more elaborate than those which I have made and used in the past. It is so planned that it will take either 5×7 inch (12.7×17.8 cm) or $6\frac{1}{2}\times 8\frac{1}{2}$ inch (16.5×21.6 cm) photographic plates. This and other features of the design allow a very large range of movement of the guiding eyepiece, for choosing the most suitable guiding-star available—a matter of the utmost importance in using this attachment. Provision is made for altering the plane of the photographic plate when desired, during the exposure, without danger of relative rotation of the field and plate.

Mention should also be made of the lever-support system of the 60-inch mirror. The system fully described in my Smithsonian paper has been used without modification. The mirror is "floated" so that no flexure occurs sufficiently large to be detected by optical tests; and, in addition, the position of the mirror is defined so perfectly with reference to its tube that no wandering or jumping of the star-images, due to the slipping of the mirror in its cell, can be detected in the guiding eyepiece.

THE STEEL BUILDING AND DOME

The building which supports the dome is entirely of light steel construction. Twenty columns, each 22 feet (6.7 m) high, form the corners of the 20-sided equilateral polygon. These columns support twenty horizontal box-girders, which carry the double track upon which the dome revolves.

The building has two sheet-metal walls; the inner one is of $\frac{1}{16}$ inch galvanized sheet steel, and is planned to be air-tight; the outer wall, two feet distant from the other, is of light galvanized sheet steel,

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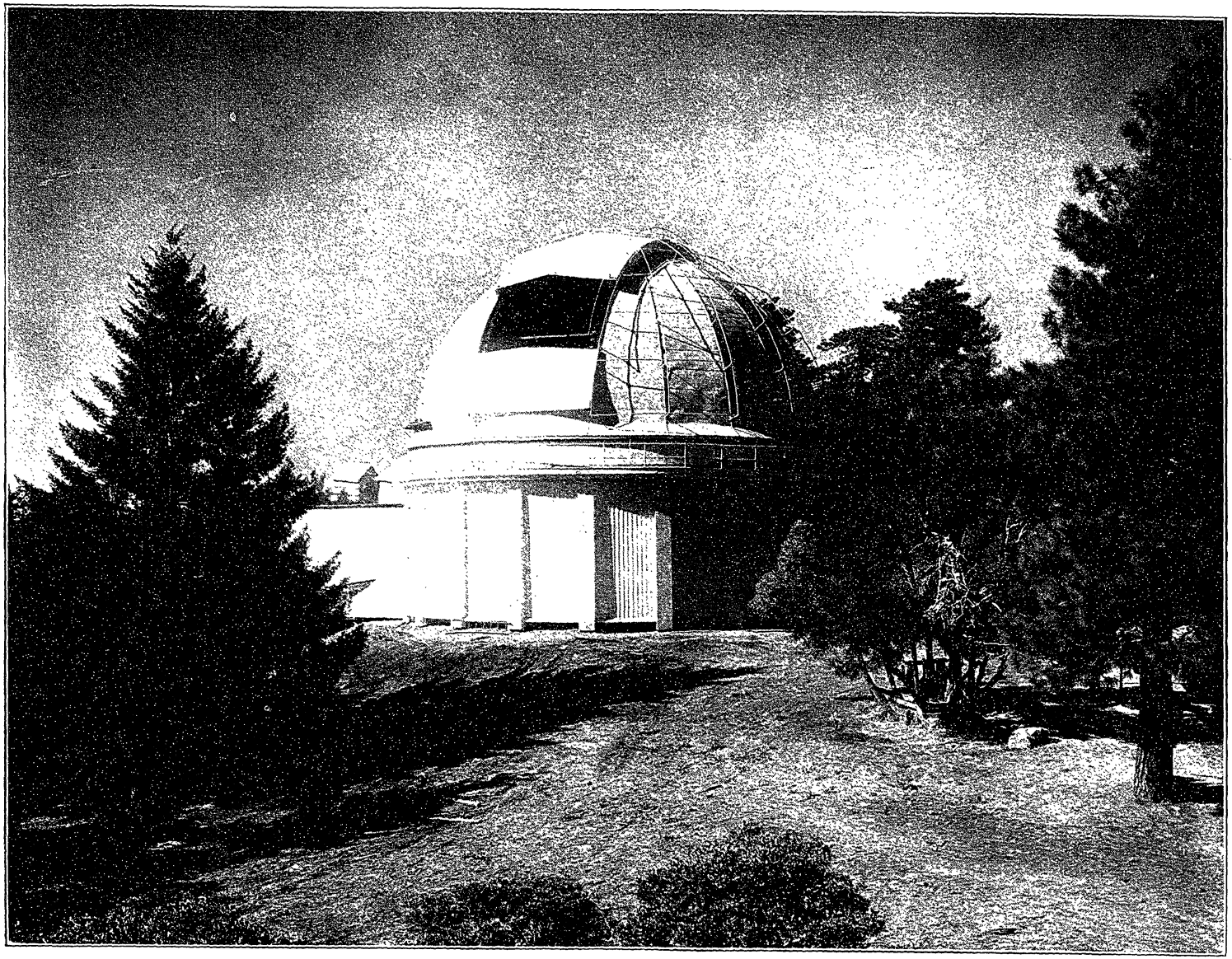
PLATE VII



STEEL BUILDING AND DOME FOR 60-INCH REFLECTOR

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and serves merely as a sun-protection. A free circulation of air is allowed between the two; both are painted white. Sixteen sheet-metal windows, closing air-tight against heavy rubber packing, are easily accessible from the lower floor, and assist in ventilating the building and dome quickly when desired.

The ground floor of the building is of cement; on this floor are the dark rooms and the electric machinery for revolving the dome. Nineteen feet above this is the operating floor, of thin checkered steel plate supported by light steel columns and I-beams. From this floor are operated the dome-drive machinery, the dome-shutter, the wind-screen, the quick and slow motions of the telescope, the right ascension and declination clamps, etc.; from this floor also the right ascension and declination circles are read. On this floor are arranged the silvering carriage (which is necessary when removing the large mirror from the tube, and when silvering it) and the interchangeable ends of the tube which are not in use on the telescope. In this floor are twelve large trap-doors, $3\times7\frac{1}{2}$ feet (0.9×2.3 m) in size, which can be quickly opened to assist in ventilating the building and dome.

The dome is 58 feet (17.7 m) in diameter, and is of light steel construction with sheet-metal covering, coated inside with granulated cork, to prevent dripping from condensation of moisture, and painted white outside. It revolves on double tracks which are machined true, the dome wheels being all double, conical, and furnished with the best Hess-Bright ball-bearings. The dome moves with great smoothness. Two motors are used in turning it: one of three horse-power, which is so geared that the dome makes one complete revolution in six minutes; and a one-horse-power motor, which drives a variable-speed machine, by which the speed of the dome can be changed at will (by simply turning a hand-wheel) to any point between one revolution in one hour and one revolution in twenty-five hours; this allows the observer, when working on the observing platform attached to the dome, to be moved with exactly the right speed to compensate for the horizontal component of the motion of the telescope.

The dome-shutter is extremely large, having a clear opening 16 feet (4.9 m) wide. Instead of opening horizontally in halves, the shutter runs back over the dome, as shown in Plate VII; it is opened

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and closed by a six-horse-power electric motor. A large metal door, below the shutter opening, 17 feet (5.2 m) long by 8 feet (2.4 m) high, turning outward on hinges at its bottom, can be opened when it is necessary to observe objects near the horizon.

A light metal observing platform, 17 feet (5.2 m) long by 9 feet (2.7 m) wide, travels up and down the curve of the shutter opening, by means of a three-horse-power electric motor. This platform can be operated either from the operating floor or from the platform itself, by simply pushing a button; it is so designed that it automatically remains horizontal in all positions. In addition to its vertical movement, and its horizontal movement with the dome, the platform can be moved about 30 inches (76.2 cm) radially with respect to the vertical axis of the dome. This combination of motions enables the observer to reach the upper end of the tube, and to work with the telescope as a Newtonian, with the utmost convenience, in most positions of the telescope.

A wind-screen 17 feet (5.2 m) wide by 35 feet (10.7 m) long is provided, which can be quickly raised and lowered in the shutter opening by suitable mechanism; it is made of heavy black canvas supported on large steel tubes with rollers at their ends. This protects the telescope from wind, and also from lights in the valley.

As will be seen in Plate VII, the exterior of the dome is covered with a strong frame-work of steel pipe. This will be covered during the spring, summer, and fall with gores of white canvas, laced on, at a distance of about two feet from the sheet-steel covering of the dome; provision is made for ample circulation of air beneath the canvas. This, together with the white outer wall of the building below, affords a complete sun-protection for the building and dome.

Furthermore, the entire building and dome are planned to close air-tight. For this purpose a frictionless water-seal is provided at the junction of the building with the dome; and all outside doors and windows close tightly against heavy rubber packing. The dome-shutter also is lined all around with air-tight cushions which can be pressed tightly in place by means of two levers operating a series of toggle-joints. In the early morning, after a night's work, the dome and building will be closed, not to be opened until after sunset, and thus a great volume of 120,000 cubic feet (3360 cu. m) of cool night air will be shut in air-tight. It is believed that this provision,

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together with the complete sun-protection of the dome and building, will reduce the rise of temperature within the structure during the day to a very few degrees. This protection from daily temperature changes should be sufficient for the telescope mounting and for the smaller mirrors. To further protect the large mirror during the day, a small refrigerating plant will be installed within a few months, which will supply constant-temperature air, at the expected night-temperature, circulating through a jacket inclosing the entire lower end of the telescope tube. The necessity for this protection of the large mirror from the daily rise and fall of temperature, to preserve the finest optical figure, was fully demonstrated by a long series of experiments in the optical shop with this mirror after its completion.

It will be seen also that a serious effort has been made in the design of the dome and building to eliminate the so-called dome- and building-effect, that is, the local effect upon atmospheric definition caused by heat-radiation from, or air currents in, the dome and building, which is often a most serious detriment to the successful performance of large telescopes. An hour after sunset the 16 ventilating windows near the lower floor of the building, the 12 trap-doors in the operating floor, and the great dome-shutter, the latter having an opening 16×45 feet (4.9×13.7 m) in size, are all opened, and the light metal columns, girders, and walls, inside and outside, quickly assume the temperature of the night air. The ventilating doors and windows are then closed, to prevent draughts. The very fine definition which we have already had on Mount Wilson with the 60-inch aperture, even on winter nights, indicates not only that the provisions just described are highly effective, but that the general atmospheric conditions at night on the mountain will prove sufficiently good for this and even larger apertures.

In this brief description of the new reflector and its accessories, I have called attention chiefly to those refinements and special features which, in designing the instrument, have appeared to me necessary. Mere bigness is no criterion of efficiency; if a great telescope is to yield a gain in results even approximately proportional to its increase in size, the utmost care must be given to meeting all those conditions which experience in the use of large telescopes has shown to militate against their successful performance. It was a most serious question whether it would be possible to give as fine a

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figure to the 60-inch mirror as was attained in the case of the 24-inch Yerkes mirror; the difficulties were of course incomparably greater, but the final figure of the 60-inch is decidedly better than that of the smaller mirror, and it is confidently expected that the temperature control will enable it to remain so while the telescope is in use. Similarly, it was a serious question whether the moving parts of the 60-inch telescope, weighing 23 tons (20,838 kilos), could be made to follow the stars as smoothly as those of the 24-inch, which weigh one ton (907 kilos); such smoothness of following is of course necessary for the finest results in photography; and it must be remembered that much greater smoothness and accuracy of motion are actually required in the large instrument, on account of its greater focal length and magnifying power. It is therefore a great satisfaction to see the star in the guiding eyepiece of the 60-inch remain perfectly bisected on the spider-lines for several minutes at a time, without perceptible tremor, and in addition, frequently to see the image of the guiding star itself, even with winter conditions, as small and sharp, and with its diffraction pattern as clearly cut, as I have ever seen in the 24-inch at Yerkes.

For the successful performance of the new reflector, special credit is due to Mr. Jacomini, foreman of the instrument shop of the Observatory; to Mr. Barnes, Mr. Schrock, and Mr. Kinney, for their great care and skill in the optical work, and to Mr. Dowd, for the installation of the complicated electrical work of the telescope mounting and dome.

I am indebted also to Director Hale for the opportunity afforded me to carry out in their entirety my plans for the great reflector and its dome, building, and accessories.

JANUARY 7, 1909

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