

5. THE 200-INCH HALE TELESCOPE

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One of the first problems investigated at the start of the 200-inch telescope project was that of a suitable site. Extensive tests of climatic and 'seeing' conditions at some dozens of sites in the semi-arid south-western part of the United States led to the selection of Palomar Mountain. This is a flat-topped mountain some 10×20 km. in extent located 150 km. south-east of Los Angeles. The altitude of the telescope is 1700 m. Temperature conditions are very stable with a diurnal range of about 6° C. and observing conditions during the past two years have proved to be at least as satisfactory as those at Mount Wilson.

The optical systems of the 200-inch telescope are of the conventional type, the main 200-inch mirror being a paraboloid of focal length 16.5 m. and focal ratio 3.3. The main new feature arises from the size of the telescope. Thus instead of a Newtonian mirror, an observing cage, 180 cm. in diameter, is located in the centre of the beam at the prime focus of the main mirror. Such a cage provides ample room for the observer and obstructs no more light than a Newtonian mirror. The secondary mirrors for the other foci are mounted in the lower part of this cage. These include a Cassegrain mirror which forms an image just back of the centre of the main mirror with an effective focal length of 80 m. and two coudé secondaries each of which provides a focal length of 150 m. One of the coudé mirrors is for use at declinations below $+43^\circ$ for which the light is reflected down the polar axis with one flat mirror at the intersection of the optic and polar axes. The second coudé mirror is for use at higher declinations for which three flat mirrors are required to reflect the beam around the main mirror.

A paraboloid reflector of focal ratio $F/D = 3.3$ has so much coma that the field of good definition is only $1-1\frac{1}{2}$ cm. in diameter. To eliminate this coma Dr F. E. Ross has designed several corrector lenses to be mounted in front of the photographic plate. These yield well-corrected fields of 9-15 cm. in diameter and also provide for a variety of focal ratios in the range from $F/D = 3.6$ to 6.0.

The use of the Ross lenses, however, placed very stringent requirements on the design of the telescope tube because of the necessity of maintaining accurate collimation between the main mirror and the Ross lens at the other end of the tube. While flexure of a structure of this size cannot be completely eliminated, the tube was designed in such a way that, as the telescope is turned from the zenith to the horizon, the mirror and the cage deflect parallel to each other and by the same amount. Extensive tests have shown that in no orientation does the intersection of the axis of the main mirror with the corrector lens depart by more than $\frac{1}{4}$ mm. from its mean position.

The telescope tube including the mirror and its mounting weighs 140 tons. It is mounted in a yoke with a large horseshoe bearing 14 m. in diameter at the upper end to permit the telescope to reach the pole. The yoke and tube weigh over 500 tons. The bearings at both the north and south ends are of the oil-pad type into which oil is pumped at high pressure, so that the telescope is floated on a film of oil about $\frac{1}{16}$ mm. thick. Friction is so low that a force of 1 kg. applied at the large horseshoe bearing will turn the instrument about the polar axis.

The tracking drive is controlled by a vibrating string with a 60-cycle frequency. The current induced by this string is amplified and used to drive a small synchronous motor connected with suitable gearing to the main worm-wheel of the telescope. The rate of drive may be modified to correct for atmospheric refraction by sending a current through a coil which reacts on a magnet attached to the string, thereby changing the tension.

Selsyn motors transfer the position angles of the telescope to dials located at the main control desk and at all observing positions. These include computing mechanism which provides direct reading of the right ascension rather than of the hour angle.

The dome is double, the outside dome being of sheet steel, while the inside dome consists of 10 cm. of aluminium foil heat insulation in metal boxes. A 1 m. space is provided between domes to permit air circulation. The rotating dome weighs 1000 tons and is actuated by a mechanism which automatically holds the shutter opening in front of the telescope.

The main mirror is cast of Pyrex glass and has a diameter of 5 m. and a thickness of 60 cm. To provide maximum stiffness with minimum weight and to permit the mirror to reach thermal equilibrium with its surroundings more rapidly it was cast with a ribbed structure rather than as a solid disk. All ribs and the mirror surface are 10–12 cm. thick. However, the flexure of a mirror increases very rapidly with size and in spite of the use of a ribbed structure the mirror is very flexible. Indeed, its flexure under its own weight is equivalent to that of a 1 m. diameter solid disk, 1.5 cm. thick. Obviously a very elaborate and precise support system had to be provided if a good figure was to be maintained in all orientations. A balance-type support is installed at each of the 36 circles to which the ribs converge. These supports are designed to provide forces both perpendicular and parallel to the mirror surface equal to the corresponding components of the pull of gravity on the section of the mirror assigned to each support, with an accuracy of 0.1–0.2%.

It was obvious from this that the support system must be considered as an integral part of the mirror and that the only significant tests of the mirror are those made with the mirror resting on its supports in the range of orientations that will eventually be used. For this reason the final figuring of the mirror was done in the dome on Palomar Mountain on the basis of tests made with the mirror in the telescope using a star as the source.

Both knife-edge and Hartmann tests were used. It was found possible to eliminate the effects of seeing by using photographic recording for all tests, and exposing for from 20 to 80 sec. to average out turbulence effects. The final tests showed the Hartmann constant and the fraction of light entering a 25, 50 and 100 μ circle given in Table I.

Table 1
Final optical tests of the 200-inch mirror

Date	Hartmann constant	Percentage of light within circle of diameter		
		25 μ	50 μ	100 μ
28 Dec. 1949	0.18	53	83	99
30 Dec. 1949	0.17	57	87	100
26 Jan. 1950	0.34	27	49	88
27 Jan. 1950	0.19	46	80	99
23 Feb. 1950	0.21	40	74	98
24 Feb. 1950	0.19	53	82	96

Since 25, 50 and 100 μ correspond to 0.3, 0.6 and 1.2 seconds of arc at the prime focus while the average seeing image at Palomar is from 1 to 1.5 sec. it is evident that very little definition is lost due to mirror imperfections.

Most of the direct photography is carried out at the prime focus position using one of the Ross lenses. Photometric measurements with photo-multiplier tubes are also made at this observing position. Since these photo-multiplier tubes are now capable of measuring stars fainter than can be observed visually elaborate mountings for the tubes have been provided for accurately off-setting from a bright star in the area, and for guiding on this star if extended readings are required.

The design of spectrographs to take advantage of the great light-gathering power of the 200-inch mirror posed many difficult problems. Thus when the seeing image has its average angular diameter of 1–1½ sec. of arc the linear image diameter is about 1 mm. at

the coudé focus of the 200-inch telescope and $\frac{1}{2}$ mm. at the 100-inch telescope. The surface brightness of the two images is the same, however. This means that if the coudé spectrograph of the 100-inch telescope, which normally uses slit widths of 0.02–0.10 mm., had been duplicated at the 200-inch we would have obtained spectra twice as wide but would have attained no gain in speed or limiting magnitudes. Obviously drastic new designs had to be attempted if the hoped-for gains in speed were to be achieved with the 200-inch telescope.

If a larger fraction of the light is to be made to pass the slit and therefore a higher efficiency is to be attained it can easily be shown that the focal ratio of the spectrograph camera must be reduced. This can be done either by increasing the aperture of the spectrograph system or by increasing the angular dispersion of the dispersing system thereby permitting a decrease in focal length while maintaining the same linear dispersion. The Mount Wilson spectrographs already use the third order of a 400-line/mm. grating or the second order of a 600-line/mm. grating. This represents the highest angular dispersion for which it has thus far been possible to rule gratings with an efficient blaze that throws most of the light into one order. The use of a larger aperture collimator beam therefore seemed to be the only available method for increasing efficiency.

As the 100-inch coudé was already equipped with as large a single grating as it has proved feasible to rule recourse was made to a composite of four matched gratings each with a ruled surface 14×18 cm. This permitted the use of a collimator focal length of 9 m. and an aperture of 300 cm. The longest camera planned for this instrument has a focal length of 3.6 m. The individual gratings therefore operate at a maximum focal ratio of about $F/D=22$ and consequently have a resolving power considerably greater than that of the fast photographic emulsions used with these spectrographs. Since the composite grating is used solely to increase intensity and not resolving power it is not necessary to bring the individual gratings into phase with each other. Instead the much easier condition has to be satisfied that the spectra thrown by the four gratings must coincide within the resolving power of the plate.

The gratings are mounted on a steel casting 5 cm. thick at the centre, tapering off to 2.5 cm. at the ends. Adjustments of the gratings are made with screws bearing upon them. The final fine adjustments of the gratings for rotation about an axis parallel to the ruled lines is made by deforming the casting on which they are mounted by turning a screw connecting the casting with a spring whose force constant is about $1/500$ of that of the casting. One turn of the screw deforms the casting by 2 or 3 μ . The mounting has been in use for two years and experience has shown that adjustments are satisfactorily maintained. In general a slight readjustment requiring possibly one or two hours of time seems to be necessary every two or three months. The four matched gratings were ruled with 400 lines per millimetre by H. W. Babcock on the ruling engine constructed by his father. They are blazed for the third order violet and second order red, from 60 to 70% of the incident light being thrown into one order.

As mentioned above, one camera has a focal length of 3.6 m. It makes use of the Schmidt principle by having a spherical mirror placed with its centre of curvature at the grating. Since this camera operates at about $f/11$ the spherical aberration may be neglected and no corrector plate is used. Other cameras of 180, 90, 45 and 21 cm. focal length are provided. The first three of these are Schmidt cameras and have their axes normal to the gratings while the collimator beam is incident at an angle of 30° . The Schmidt cameras are designed to cover the third order from about 3300 to 5000 Å. or the second order from 5000 to 7500 Å. in one exposure. This requires a field of view equal to one-fifth of the focal length. If the conventional Schmidt corrector plate had been used in the camera beam it would therefore have been necessary to place it about 90 cm. from the grating to avoid interference with the collimator beam. To avoid vignetting this requires that both corrector plate and mirror be 18 cm. larger in diameter than that necessary if the corrector plate were located near the grating. This not only greatly increases the cost but also the size of the aberrations present. Thus it can easily be shown that both the chromatic aberrations of a non-achromatic corrector plate and the off-axis

aberrations for the angular fields here considered become excessive if the focal length F becomes appreciably less than that given by the formula

$$F^2 = \frac{D^3}{20},$$

D being the aperture of the corrector plate and all dimensions being given in centimetres. For an aperture of 34 cm. which is the width of the camera beam coming from the gratings a focal length of 45 cm. is permissible. On the other hand for an aperture of $34 + 18 = 52$ cm. the minimum permissible focal length is 84 cm. Thus the 45 cm. focal-length Schmidt camera would have had to be omitted with the corrector plate 90 cm. in front of the grating.

A new arrangement was therefore adopted in which a corrector plate of slightly less than half strength is mounted parallel to and practically in contact with the grating. The light therefore passes through the corrector plate twice, once before and once after diffraction. Both theory and observations indicate that the performance of these 'twice through' corrector plates is equivalent to that of a single corrector plate of the same aperture.

For a still shorter focal length recourse was had to the use of a fused quartz aplanatic sphere of radius 6.3 cm. When combined with the 45 cm. Schmidt camera it reduced the focal length in the ratio of the square of the index of the quartz, i.e. to $45/n^2 = 21$ cm. By polishing a concave surface of about 13 cm. radius on the rear surface of the sphere it was found possible to correct for most of the residual spherical aberration as well as to flatten the field. By this procedure a well-corrected flat field 17 mm. in diameter was attained. This covers a range of 670 Å. in the third order blue and 1000 Å. in the second order red at one exposure.

Table 2 summarizes the data concerning the various cameras of this coude spectrograph. The lowest rows give the limiting photographic magnitudes that can be reached

Table 2
Coudé spectrograph cameras

Camera focus (cm.)	360	180	90	45	21
Focal ratio	12	6	3	1.5	0.7
Mirror diameter (cm.)	120	90	75	50	50
Usable plate length (cm.)	55	40	30	15	1.7
Dispersion:					
3rd order violet (Å./mm.)	2.3	4.6	9	18	39
2nd order red (Å./mm.)	3.4	6.8	14	27	58
Limiting magnitude (photographic):					
Widened to 0.1 mm.	7.5	9.8	11.9	13.4	15.0
Unwidened	7.5	9.8	12.0	14.3	16.6

with a one-night exposure under average seeing conditions. While these values are calculated, experience to date indicates that these limits can easily be reached.

For very low dispersion studies such as the measurement of the radial velocities of nebulae, a small spectrograph has been constructed for use at the prime focus, thus avoiding the loss of light at the two or four extra mirrors of the coude arrangement. This spectrograph has a collimator beam with an aperture of 7.5 cm. and is a grating instrument, two gratings ruled with 300 and 600 lines/mm. and blazed for use in the second order being provided. Two cameras of the thick-mirror Schmidt type with focal lengths of 3.5 and 7.2 cm. and therefore operating at focal ratios of $F/D = 0.47$ and 0.95 are available. The various combinations of cameras and gratings yield dispersions of 105, 210 and 430 Å./mm.

The 200-inch telescope was placed in operation for direct photography in November 1949. Nearly all of the auxiliary photometers and spectrographs described here have been completed during the past three years and have been in use from six months to

two years. I am very happy to state that the performance of all the equipment has come up to our expectations, and that the problems ahead are primarily concerned with planning the most effective observing programmes for the telescopes.

Dr Bowen, on a question by Dr Page, answered that the limiting magnitude of the prime focus spectrograph is about the 17th. This implies that in photographing spectra of very faint galaxies, such as were observed by Humason, the image is too faint to be seen at the eyepiece. Guiding is performed by off-setting against a brighter star.

Pour clore cette deuxième réunion, M. Couder, remerciant les orateurs montre combien les travaux récents sur les instruments astronomiques sont riches en promesses.

On peut penser que la mise en œuvre de l'effet photo-électrique est une date plus importante dans l'histoire des sciences d'observation que l'invention de la plaque photographique elle-même; cela, à cause du rendement quantique des photo-cathodes.

D'autre part, faut-il rappeler que les progrès dans la connaissance de l'univers ont été rigoureusement associés à la mise en service de chaque 'plus grand télescope du monde'. Les télescopes de Herschel ont dévoilé la structure de la Voie Lactée, à celui de Lord Rosse est due la découverte des nébuleuses spirales étrangères à la nôtre. Le miroir de 60" a déterminé pour la première fois la distance d'une autre galaxie; le 100" a mesuré les vitesses radiales des nébuleuses spirales. D'après les premiers résultats obtenus avec le 200", on peut s'attendre à voir les efforts accomplis par des découvertes aussi fondamentales que les précédentes. Et le Président précise qu'en disant cela, ce n'est pas un vœu qu'il forme, ce n'est pas un espoir qu'il exprime: il énonce une certitude rationnelle.