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The Astrophysical Observatory of the California Institute of Technology

The 200-inch Reflector

By Dr. George E. Hale, For.Mem.R.S.

THE choice of the best aperture for a very large telescope is less simple than it seems. The greater the generosity of a prospective donor the greater the care one should take not to overstep reasonable bounds, which are fixed by many technical considerations. Thus, when the point-blank question was put by Dr. Wickliffe Rose in 1928: "Do you want a 200-inch or a 300-inch ?", careful thought was necessary, though a doubt whether one should attempt to surpass 200 inches was immediately expressed.

Beginning with general considerations, the opinions obtained at once from two eminent engineers were certainly significant. General J. J. Carty, pioneer in telephone development, had covered the North American continent with a perfect telephone service. Gano Dunn, inventor and far-seeing constructor, had built vast engineering projects in many parts of the world. Their response was made without hesitation: a sudden advance from 100 inches to 300 inches would be too uncertain for safety. Walter S. Adams, director of the Mount Wilson Observatory, and many others afterwards consulted, independently expressed the same view. Experience has proved its clear validity.

Several conversations with Dr. Rose, then president of the Rockefeller International and General Education Boards, were held in New York, in response to his invitation to discuss large telescopes. After a visit by Dr. Rose and Mr. Thorkelson (then secretary of the Education Boards) to Pasadena and Mount Wilson, a grant was made to the California Institute of Technology in Pasadena for the construction of an Astrophysical Observatory and Laboratory, provided with a 200-inch reflecting telescope and all necessary equipment. This was conditional on the cordial co-operation of the Carnegie Institution of Washington, which was promptly offered by its president and executive committee. Dr. Adams and the staff of the Mount Wilson Observatory were also in full agreement.

In my initial suggestion to Dr. Rose, made after long acquaintance with the work of the 100-inch Hooker telescope on Mount Wilson, I had no intention of inaugurating a new observatory. The California Institute, which for years had co-operated as closely as possible with the Carnegie Institution of Washington in physical research, also did not plan to establish an observatory. But it could not be denied that the rapidly increasing possibilities of still more intimate co-operation between astronomers, physicists and chemists, the needs of the strong graduate school of the Institute, and the probability that a site even more favourable than Mount Wilson for the study of the most distant attainable nebulæ of the mysterious 'expanding universe' could be found, seemed to call for a new observatory. The rapid multiplication of lights and of manufacturing plants in Los Angeles and its vicinity since 1904 had slightly affected the purity of the sky above Mount Wilson, and while this is appreciable only under certain conditions in the photography of the faintest nebulæ with long exposures, it would be more serious with the desired focal ratio of $f/3\cdot3$ of the 200-inch telescope than with the $f/5$ ratio of the

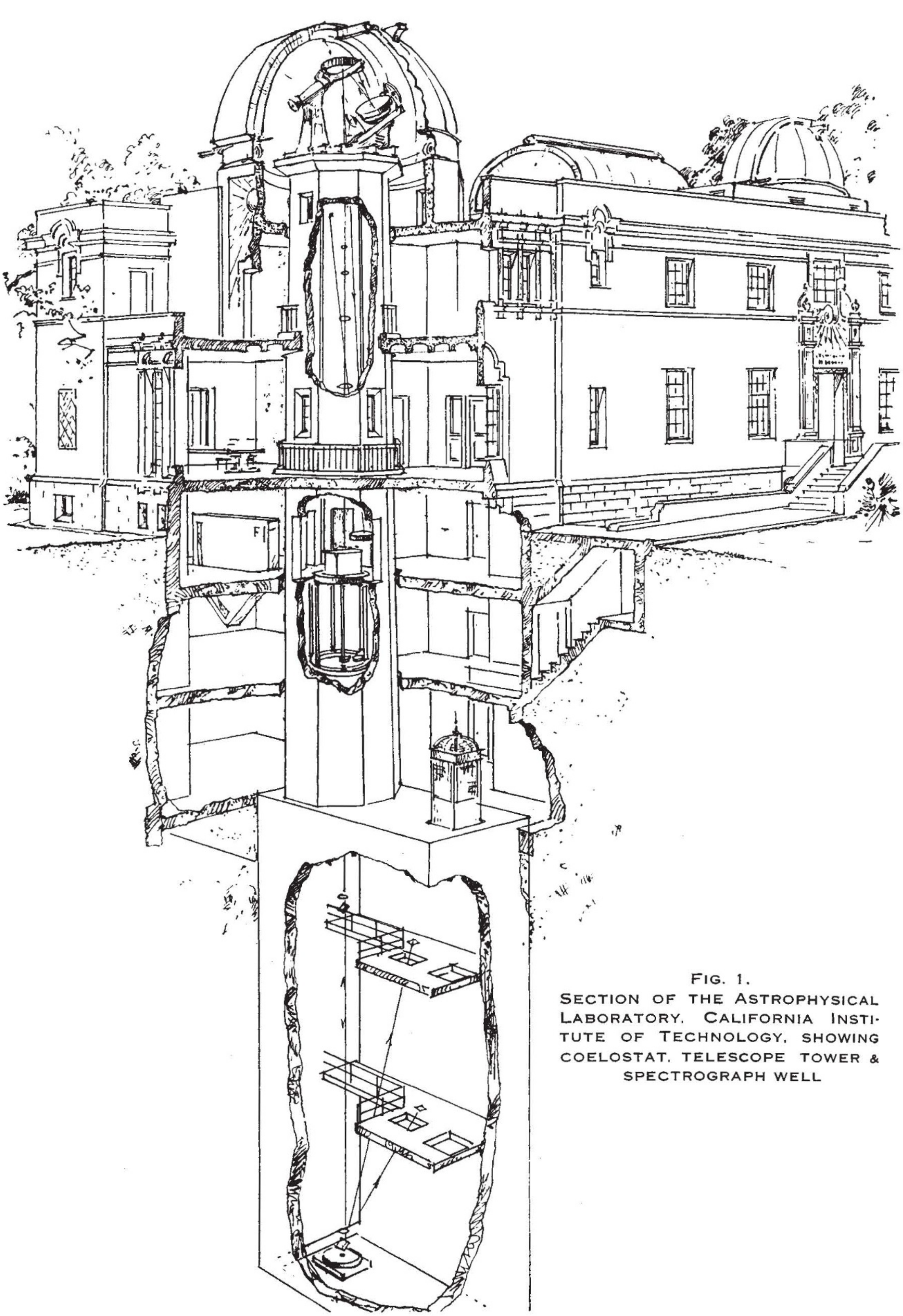

FIG. 1.
SECTION OF THE ASTROPHYSICAL LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, SHOWING COELOSTAT, TELESCOPE TOWER & SPECTROGRAPH WELL

100-inch Hooker telescope. As 95 per cent of the work of the Mount Wilson Observatory is unaffected by this change of conditions, a plan of co-operative research could be developed which would be highly advantageous to both institutions. This conclusion, which is shared by all members of the Mount Wilson staff, called for the selection of the best site now available within working distance of Pasadena, the common focus of the joint project.

construction of a very complete astrophysical laboratory, a well-equipped instrument shop and an optical shop large enough for the grinding, figuring and testing of the 200-inch mirror, all on the grounds of the California Institute in Pasadena, in close touch with the various laboratories of the Institute and the Pasadena headquarters of the Mount Wilson Observatory. More broadly, it also meant any effective co-operation advisable with individuals and institutions elsewhere.

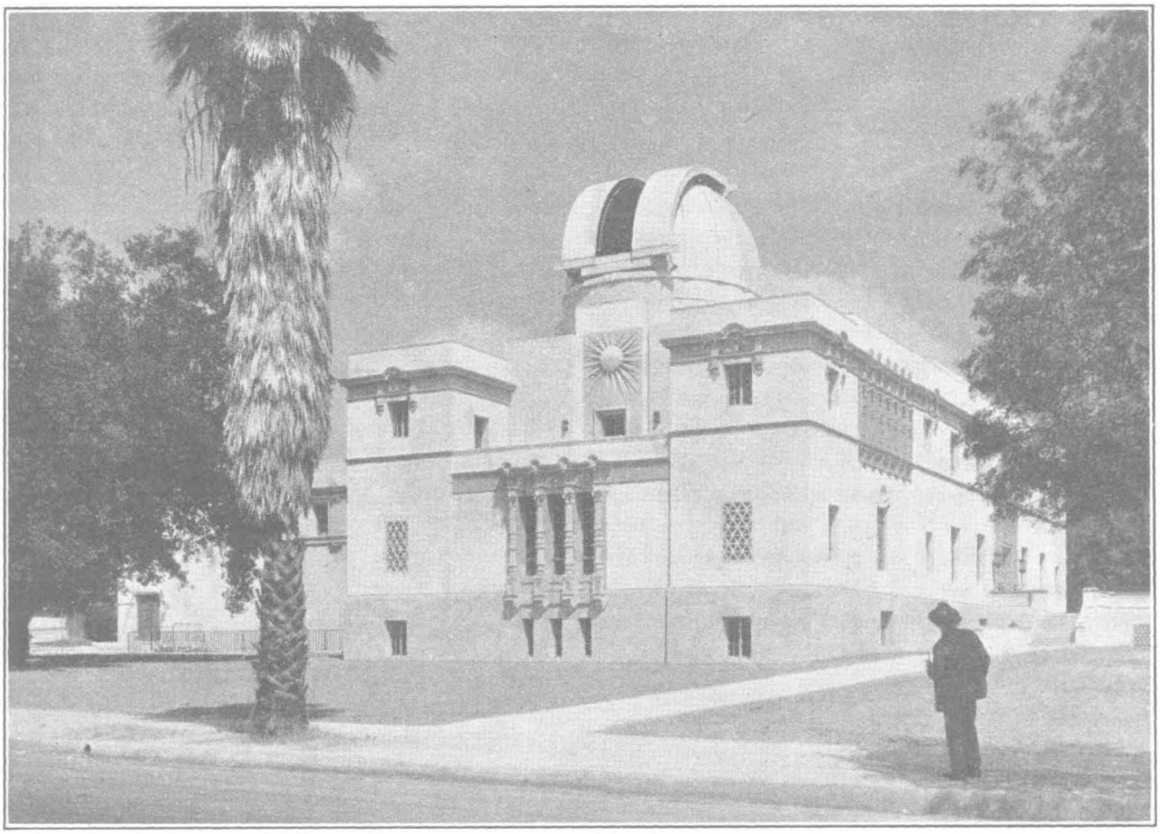

FIG. 2. THE ASTROPHYSICAL LABORATORY OF THE CALIFORNIA INSTITUTE OF TECHNOLOGY.

As soon as the attitude of the authorities of the Carnegie Institution and the California Institute could be learned, a plan was prepared in New York for Dr. Rose, embodying the following features: (1) Close co-operation between these institutions in the design and operation of the new observatory; (2) the laboratory, instruments and shops to supplement those of the Mount Wilson Observatory, thus providing new and very desirable facilities for joint research; (3) special stress to be laid on the development of new auxiliary instruments, so as to increase the efficiency of the 200-inch and other telescopes. This meant the

Everyone familiar with the limitations of large refractors, such as chromatic aberration, absorption of light by the objective, and the insuperable difficulty of obtaining satisfactory optical glass disks more than 40 inches in diameter, will recognise that the 200-inch telescope must be a reflector. But there remains a number of obstacles to be overcome. The first of these is to obtain a suitable disk for the large mirror.

We had experienced much trouble in securing the 100-inch disk for the Hooker telescope, which weighs four and a half tons. The first disk received was so filled with irregularities, such as apparent

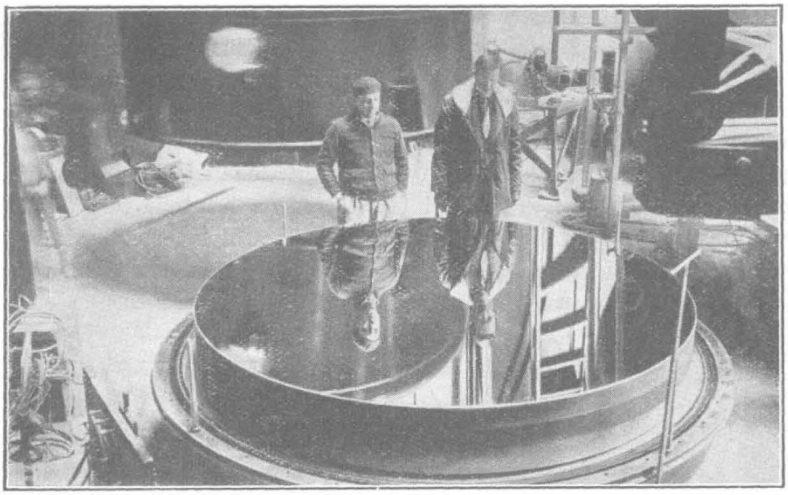

FIG. 3. 100-INCH MIRROR, ALUMINISED, WITH DR. STRONG (RIGHT) AND DR. GAVIOLA (LEFT).

surfaces of discontinuity, liberally besprinkled with air-bubbles, that its use appeared hopeless. After years of experimenting, however, nothing better could be furnished by the glass-makers. It was, therefore, decided to give one surface a spherical figure and rigorously apply the Foucault test under temperature conditions equalling the maximum annual range on Mount Wilson. The results showed that the disk was well annealed and that its internal structure should do no harm, especially as only a few small bubbles were near the surface to be figured. The insistence of the optician that it had a 'strong' and a 'weak' diameter nearly at right angles to one another was overcome by showing that the change of figure observed in these positions was due to an unsuitable edge-support, producing a component causing deflection normal to the mirror face. This having been corrected, the observed differences disappeared, and the disk was then figured to a paraboloidal form. It has served very well in the 100-inch telescope for eighteen years, showing only such variations in figure as occasional rapid temperature changes, and a somewhat defective support system (recently improved), might lead one to expect in the case of ordinary plate glass.

Such variations in form with temperature, however, would not be permissible in a 200-inch mirror, of far greater weight and thickness. After considering various alternatives, the Observatory Council* and its Advisory Committee† decided that a serious attempt should be made to produce a 200-inch disk of fused silica. Through the co-operation of the General Electric Company, Dr. Elihu Thomson, who had previously made several fused silica mirror disks of small aperture, undertook the very heavy task with the assistance of Mr. Ellis. After overcoming various difficulties, they succeeded in producing excellent disks of 25 inches aperture, but beyond this point a completely new procedure was needed. The method devised, which is briefly described in a recent article‡, finally yielded a disk 66 inches in diameter;

* Robert A. Millikan, Arthur A. Noyes, Henry M. Robinson and George E. Hale (chairman), members of the Executive Council of the California Institute of Technology, and Walter S. Adams, director of the Mount Wilson Observatory of the Carnegie Institution of Washington. J. A. Anderson of the Mount Wilson Observatory is the executive officer of the Observatory Council. George E. Hale has remained a member of the Mount Wilson Observatory of the Carnegie Institution since his resignation of the directorship of the Observatory in 1923.

† Walter S. Adams (chairman), Charles G. Abbot, Ira S. Bowen, J. P. Buwalda, W. H. Clapp, P. S. Epstein, Edwin Hubble, T. von Karman, R. R. Martel, H. N. Russell, F. H. Seares, R. W. Sorenson, and Richard C. Tolman.

‡ Hale, "The Astrophysical Observatory of the California Institute of Technology", *Astrophys. J.*, September 1935, pp. 111-139.

FIG. 4. MOULD FOR 120-INCH DISK SHOWING CORES FOR CIRCULAR HOLES AND TRIANGULAR OPENINGS BETWEEN RIBS.

but this and another disk of the same size proved to be unsuitable, and the long series of experiments was accordingly abandoned in 1931.

The next material chosen was Pyrex glass, so widely and successfully used for chemical and cooking utensils subject to rapid changes of temperature. Here we had the advantage of the long experience of Dr. Arthur L. Day and the Geophysical Laboratory of the Carnegie Institution of Washington, added to that of the able research staff of the Corning Glass Works. Beginning with smaller disks, Dr. J. C. Hostetter and Dr. G. V. McCauley developed a special procedure of casting, preliminary cooling and annealing, which led to the production of a 60-inch disk with ribbed back. At this stage a greatly improved type of Pyrex glass was devised, which was then used in the casting of a 120-inch disk (for testing the 200-inch), now partially ground and figured in our optical shop.

FIG. 6. THE FIRST 200-INCH DISK AT THE CORNING GLASS WORKS.

The first 200-inch mirror disk made at Corning was injured by defects in the mould, but a second one was successfully cast in an improved mould on December 2, 1934. After nearly a year of careful annealing, during which the temperature was gradually decreased from day to day by means of electrical controls, the disk has now been taken from the oven and examined.

As the tests appear to be satisfactory, the 200-inch disk will soon be shipped by rail to Pasadena in 'a well-hole' car. It has safely survived a river flood which rose nearly to the level of the annealing oven and a heavy earthquake which passed through New York State. We trust its transit across the United States, where it will clear the railway tunnels by only a few inches, will be equally fortunate.

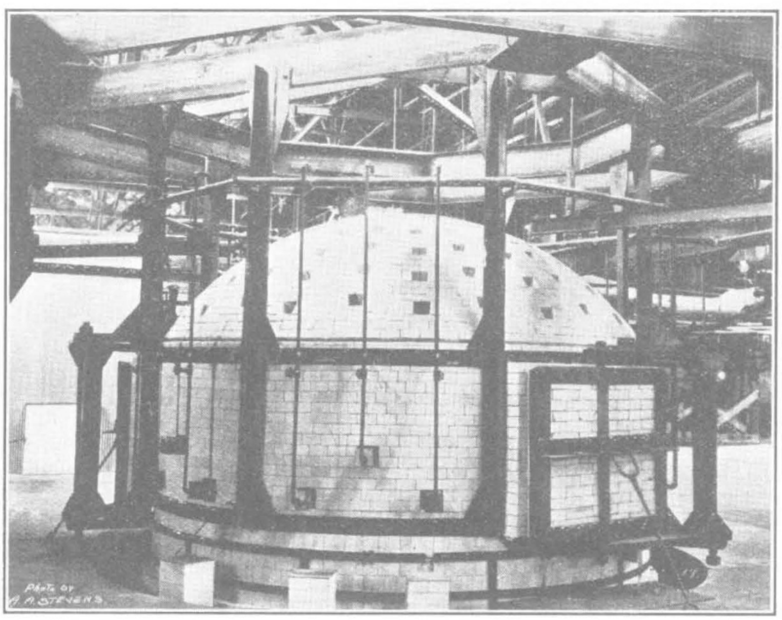

FIG. 5. BEEHIVE OVEN USED TO HEAT THE 120-INCH DISK AND MOULD DURING THE CASTING OPERATION.

After all of this experimental work, it is now possible that a successful 300-inch Pyrex disk could be made. But even if ample funds were available, it might be unwise to undertake it, as both experimental and theoretical studies made here render it doubtful whether a 300-inch telescope would photograph the faintest and most remote nebulæ more effectively than a 200-inch reflector may be expected to do.

The photographic efficiency of a telescope is closely related to its focal ratio. The question as it arises in connexion with a large reflecting telescope is much too complicated to be discussed

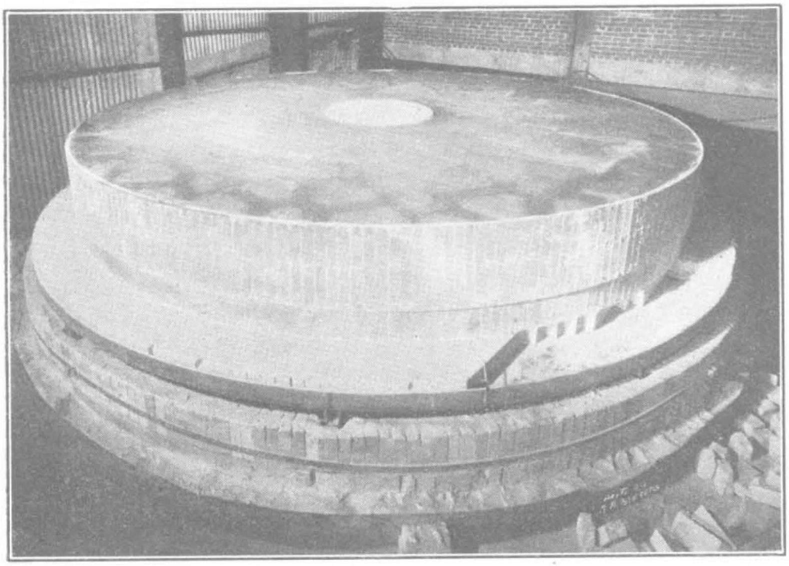

FIG. 7. THE NEW 200-INCH DISK AS IT WAS REMOVED FROM THE ANNEALER AT THE CORNING GLASS WORKS ON DECEMBER 8, 1935.

in detail in this place. The choice of $f/3{\cdot}3$ for the 200-inch mirror was made some years ago. A recent examination of the matter in the light of much additional experience and special test observations obtained with the 60-inch and 100-inch telescopes on Mount Wilson confirms the original choice.

The design of the most suitable form of equatorial telescope mounting for a 200-inch mirror has occupied our attention from the outset. After preparing many alternative designs, one due chiefly to Anderson, Serrurier and Edgar has been adopted. This will permit the telescope to be used on all parts of the visible heavens, extending from the horizon to the north pole. The observer, in one arrangement, will be carried in a cartridge-shaped house at the principal focus, where the comparatively short focal length of 55 ft. will give very bright images and permit the faintest objects to be photographed with relatively short exposures. The field at this point would be very small, were it not for the zero correcting lens devised for us by Dr. F. E. Ross, which will be mounted in front of the photographic plate. Such lenses have been tested with great success in the 60-inch and 100-inch reflectors on Mount Wilson. Photo-electric amplifiers, short-focus spectrographs, thermocouples, etc., can also be used in the principal focus.

By means of an electric motor, a convex mirror can be instantly turned into position in front of the principal focus, thereby converting the telescope into the Cassegrain form, with a focal ratio of $f/16$, giving a large and sharply defined star field below the central hole in the 200-inch mirror. Here much work will be done, both by direct photography and with suitable spectrographs. A third arrangement will involve the use of an additional plane mirror, sending the converging beam through the hollow declination axis to a totally reflecting prism, mounted before the slit of a long-focus grating or prism spectrograph. This spectrograph will hang parallel to the polar axis within a large hollow cylinder, forming part of the telescope mounting, and will be so geared that the slit will always remain vertical. Another similar arrangement, on the opposite side of the telescope tube, will carry radiometers or such other auxiliary instruments as must always remain vertical. Finally, a fourth optical arrangement will form the star image below the hollow bearing at the south end of the polar axis, where fixed spectrographs or other apparatus of any desired dimensions will be rigidly mounted within a large constant-temperature chamber.

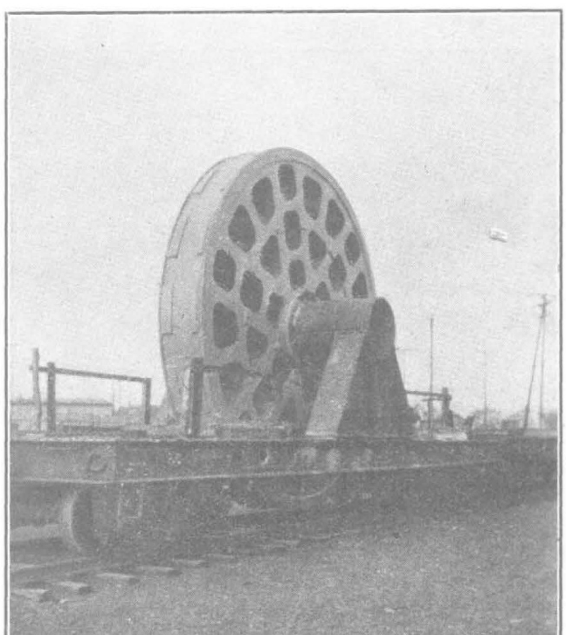

FIG. 8. BASE OF TUBE FOR 200-INCH TELESCOPE. THIS WILL ALSO SERVE TO SUPPORT THE MIRROR DISK ON THE GRINDING MACHINE.

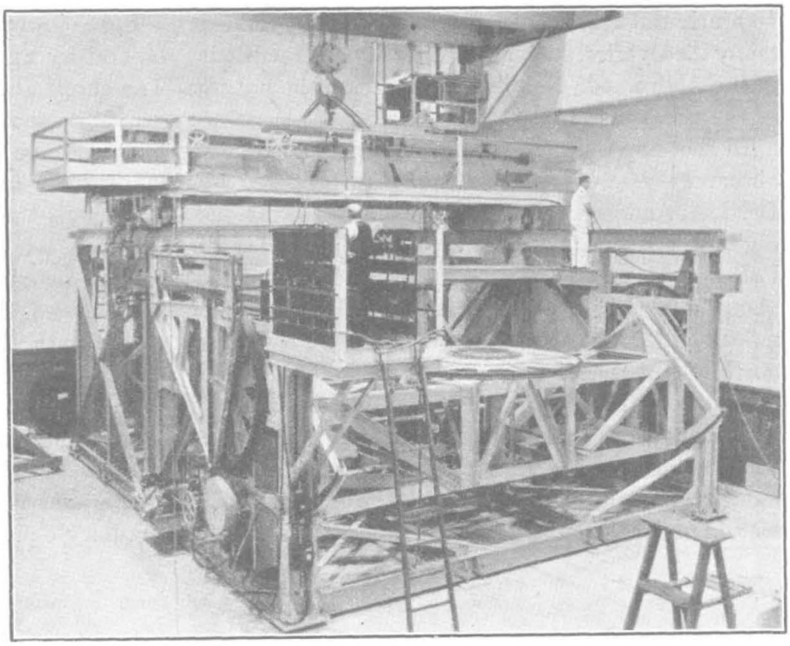

FIG. 10. 200-INCH GRINDING MACHINE READY TO RECEIVE TURN-TABLE, WHICH WILL ULTIMATELY BE USED AS THE BASE OF THE 200-INCH TELESCOPE TUBE.

The very short-focus spectrograph objective ($f/0 \cdot 59$) developed for the new observatory by Dr. W. B. Rayton was at once put into use on Mount Wilson with the 100-inch telescope, in accordance with our co-operative scheme. It is with this objective that Mr. Humason has measured the extraordinarily high apparent velocities of the extra-galactic nebulæ, from which Dr. Hubble has deduced their apparent increase of velocity with distance. Dr. Hubble is not yet fully convinced, however, that these apparent velocities are real, and it is hoped that the 200-inch telescope will ultimately throw additional light on the problem of the 'expanding universe'.

As an important aid in this task, the British Scientific Instrument Research Association, through the kind collaboration of Sir Herbert Jackson, Dr. Harry Moore and Mr. R. J. Bracey, has recently completed an even more remarkable spectrograph objective, with a focal ratio of $f/0 \cdot 36$. Recent tests by Mr. Humason show that this lens has a flat field over an ample range of wave-length, and is considerably faster than the Rayton lens. The photographic plate is used with its film in immersion contact with the flat face of the rear lens of the system designed by Mr. Bracey. The lens was perfectly made for us by Messrs. R. and J. Beck, Ltd., and is employed with an excellent collimator objective and two prisms made by Messrs. Ross, Ltd. Its speed is so great that its efficiency is determined by the brightness of the sky background. Thus the darker the sky background the fainter the nebular spectra that can be recorded. It is expected that on Palomar Mountain, which is far from city lights, this lens can be used to special advantage with the 200-inch telescope.

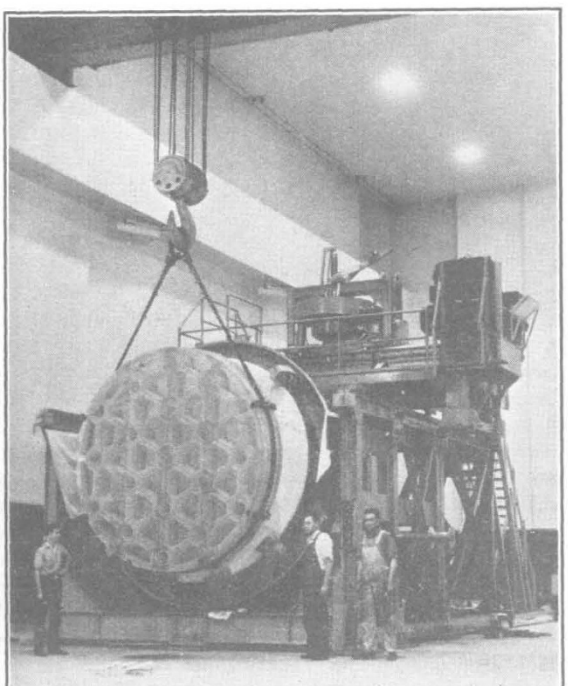

FIG. 9. 120-INCH MIRROR DISK BEING PLACED ON GRINDING MACHINE.

Another great improvement has been developed for us by Dr. John Strong, whose method of applying a coat of aluminium, instead of silver, to large telescope mirrors has been fully tested in the case of the Crossley reflector on Mount Hamilton and the 60-inch and 100-inch reflectors on Mount Wilson. The gain in reflecting power, especially in the ultra-violet, the durability of the aluminium film and its freedom from scattered light, have been amply confirmed both here and at the Lick Observatory.

Still another striking development of auxiliary apparatus effected for use with the 200-inch telescope is shown by the improvement of photo-electric amplifiers accomplished by Dr. A. E. Whitford, working in co-operation with Dr. Joel Stebbins. Already applied to various objects with the

100-inch reflector, these amplifiers have yielded many discoveries, such as the increased dimensions of the Andromeda Nebula, new light on the nature of the Galaxy, etc.

In choosing a site for the new observatory, many observers were enlisted under a plan prepared by Dr. J. A. Anderson. A long series of tests of various high-level regions has resulted in the choice of Palomar Mountain (lat. 33° 21′ 20″ N., altitude about 5,600 ft.), an isolated summit about 93 miles south-east of Pasadena and about 50 miles north of San Diego. The average seeing appears to be distinctly better than on Mount Wilson, and all other conditions are favourable. Much preliminary construction has been done there during recent months, and it is expected that the lower (fixed) section under the large dome will be erected shortly.

Space prevents a description of the astrophysical laboratory and the instrument and optical shops. The shops are very fully equipped, and the large grinding machines for the 120-inch and 200-inch mirrors have been built in them, together with many other instruments.

Perhaps the most important applications of the 200-inch telescope will be in the study of very remote nebulæ, the analysis of the nearer large spirals, and the complete spectrographic investigation with the highest dispersion of many stars in our own Galaxy. It need scarcely be said, however, that many other capital problems, both astronomical and physical, await the utilisation of the great light-gathering power of the 200-inch mirror and the advantages offered by its special auxiliary equipment.

FIG. 11. FIRST RESIDENCE ERECTED ON THE NEW OBSERVATORY SITE, PALOMAR MOUNTAIN.

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of the Fair. The largest number of foreign buyers visiting the Fair will come from Holland; Germany is second on the list and Belgium, which was second last year, is third. Large contingents of buyers will also arrive from France, Denmark, Switzerland, the United States, Norway, Sweden, Poland, Czechoslovakia and Spain. From the British Empire countries, the largest number of buyers will come from the Irish Free State, with Canada next, followed by India, South Africa and Australia in that order. Altogether sixty-four countries will be represented.

International Protection of Birds

THE recently re-organised British National Section of the International Committee for Bird Preservation met on January 15 at the British Museum (Natural History). There were present Mr. Percy R. Lowe (chairman); Dr. F. H. A. Marshall (Royal Society); Mr. Hugh Gladstone and Mr. David Seth-Smith (Zoological Society of London); Dr. G. Carmichael Low (British Ornithologists' Union); Mrs. Frank E. Lemon and Mr. A. Holte Macpherson (Royal Society for the Protection of Birds); Mr. N. B. Kinnear and Mr. Hugh Whistler (National Trust); Mr. D. A. Bannerman and Mr. G. E. Lodge (Society for the Promotion of Nature Reserves); Mr. C. W. Hobley (Society for the Preservation of the Fauna of the Empire); and Miss Phyllis Barclay-Smith (hon. secretary). The chairman made reference to the great advance made by the International Committee for Bird Preservation during the past two years, and paid tribute to the pioneer work of its chairman, Dr. Gilbert Pearson, of the United States. Among the subjects which are engaging the activities of the British Section at the present moment are a proposed International Convention for the Preservation of Birds, to take the place of the Paris Convention of 1902, the further protection of the quail from an international point of view, and an investigation as to the actual status of wild duck in the British Isles. The question as to whether there may not be a serious decrease in the numbers of wild duck is giving rise to considerable anxiety to ornithologists and sportsmen.

Modern Spectroscopy

THE three Cantor lectures on the above subject, delivered by Prof. H. Dingle to the Royal Society of Arts in November and December 1934, have now been published (London: Royal Society of Arts, 1935. 2*s*. 6*d*.). They deal with the spectra of atoms, molecular and absorption spectra, and applications of spectroscopy. The first lecture outlines the main characteristics of atomic spectra, primarily from the experimental point of view. The second deals, in a rather more detailed manner, with band spectra; some indication is given of how these arise, and of their structure. The subject of absorption spectra is also touched upon. The non-physicist, to whom the lectures were primarily addressed, will find the third lecture, on the applications of spectroscopy, of particular interest and value, since it contains a good deal of matter not readily available elsewhere. The difficulties of qualitative and quantitative spectrum analysis are clearly set forth, and the present possibilities of such methods are indicated, some interesting examples being cited. This particular application of spectroscopy is, of course, older than any other, but unexpected obstacles to its general application were encountered at an early stage, and until recently the method has been neglected to such an extent that the very meaning of the term 'spectrum analysis' is apparently unfamiliar to some of the younger physicists of the present day, with whom it connotes the analysis *of* spectra, for physical purposes, instead of analysis *by* spectra for chemical purposes. Concerning the section devoted to astronomical spectroscopy, it need only be said that in lucidity and interest it is quite representative of the author's well-known writings on this subject. The text is well illustrated throughout by diagrams and reproductions of spectrum photographs. The lectures will without doubt appeal to a wide circle of readers, that is to say, all those who have no special knowledge of spectroscopy but wish to obtain a general idea of what it is about and what is its contribution to the general body of scientific knowledge.

Rare and Standard Books on Engineering

MESSRS. HENRY SOTHERAN, LTD., have now issued part 2 of their Catalogue of Science and Technology, No. 3, an annotated and classified list of old, rare and standard works on "Exact and Applied Science". This part enumerates books on mechanical and electrical engineering, conveniently arranged in appropriate sections, and includes publications throughout the period from the beginning of the sixteenth century down to recent years. Many famous volumes are mentioned—such as Papin's "New Digester" (1681) and the quaintly bombastic "Century of the Names and Scantlings of such Inventions as at present I can call to mind to have tried and perfected" of Edward Somerset, second Marquis of Worcester, whose work, if inclined towards perpetual motion, was genuinely moving in the direction of the steam engine. Gilbert's "de Magnete" (1600) is of great interest not only as being in Lord Kelvin's view "one of the finest examples of inductive philosophy that has ever been presented to the world", but also in that it contains the rarest of all autographs of men of science, that of Gilbert himself, the father of electrical science. Napier's "Descriptio" (1614) and Newton's "Principia" (1687) are represented by first editions. As many of these books have been the possessions of outstanding men of science, their notes are of peculiar value. A copy of Silvanus Thompson's "Dynamo-Electric Machinery" (1886) is enriched "with very numerous MS. notes (often severely critical and sometimes sarcastic) by Oliver Heaviside, F.R.S.".

Botany in the University of Sydney

VOL. 2 of Botanical Reprints from the University of Sydney shows very valuable work in progress on characteristic groups of the Australian flora. A. Burges has a first paper upon the rust fungi of the Dominion, which deals most appropriately with the genus *Uromycladium*, in which six of the