DEPARTMENT OF THE INTERIOR
CANADA
Hon. ARTHUR MEIGHEN, Minister; W. W. CORY, C.M.G., Deputy Minister.

PUBLICATIONS

OF THE

Dominion Astrophysical Observatory

Victoria, B.C.

J. S. PLASKETT, Director

Vol. I, No. 1

DESCRIPTION OF BUILDING AND EQUIPMENT

BY
J. S. PLASKETT

OTTAWA
J. de LABROQUERIE TACHÉ
PRINTER TO THE KING'S MOST EXCELLENT MAJESTY
1920

Frontispiece—Observatory from South.

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By J. S. PLASKETT, DIRECTOR

CHAPTER I—INTRODUCTION

It has seemed desirable before describing the installation, to give some account of the initiation and development of the undertaking, as only when the methods of development are brought out will the account be complete and the description thoroughly understood.

In the development of the radial velocity work by the writer at the Dominion Astronomical Observatory, Ottawa, a stage was reached where it was recognized that the field of useful work with so comparatively small an aperture as 15 inches would soon be seriously limited. Even with single prism dispersion, 33 A per millimetre at $H\gamma$, stars fainter than 5·5 photographic magnitude required impracticable exposure times and furthermore it was deemed inadvisable to observe, with such low dispersion, stars with good lines, when much more accurate values could be obtained with greater dispersion. Thus the field was limited to spectroscopic binaries of early type, brighter than 5.5 magnitude and it was evident that, with a telescope of 15-inch aperture, the available stars for observation would soon be exhausted.

Hence, when the need for larger telescopic aperture made itself felt, it was natural to be on the lookout for opportunity to secure it. Plans for such additional equipment began to take more concrete shape at the Mt. Wilson meeting of the International Union for Co-operation in Solar Research in 1910, which I had the good fortune and honour to attend as representative of the Dominion Astronomical Observatory.

At the meeting a committee on Co-operation in the Determination of Stellar Radial Velocities of which Professor W. W. Campbell, Director of the Lick Observatory, was chairman met and discussed the needs in radial velocity work and the resources available for meeting these needs. It was evident that only the 36-inch telescope at the Lick Observatory and part of the time of the 60-inch at Mt. Wilson could be devoted to this work and further equipment was urgently needed if substantial progress in this important work was to be obtained.

At the same time, the great success of the 60-inch reflector at Mt. Wilson, made it practically certain that a large reflecting telescope could successfully carry on radial velocity observations at least equally as well as a refractor of the same aperture and at one-fourth the initial cost, leaving out of consideration the impossibility of obtaining suitable material for the objective of a very large refractor.

As a consequence of these two considerations, I determined to use every possible effort towards obtaining a large reflecting telescope for the Dominion Astronomical Observatory, at least of 60-inch aperture, and if possible larger. Upon returning to Ottawa, I brought the matter to the attention of the Chief Astronomer, Dr. W. F. King, and, as in all attempts to increase the scope and usefulness of the work of the observatory, I found him most sympathetic and eager to advance the project by all means in his power. I can not refrain in this connection from paying a sincere tribute to his memory. No man could have a chief more considerate, more encouraging, more helpful in every way, and more willing and eager to see his staff make progress than I and all the observatory staff had in Dr. King, and his death was a great loss to the Astronomical Branch, to Canada and to the scientific world.

Nothing definite, however, was attempted at that time and it was not until the meeting of the Astronomical and Astrophysical Society of America, which was held in Ottawa in August, 1911, that the first step towards the initiation of the undertaking was made. When the report of the Committee on Co-operation in Radial Velocities was presented by me at the chairman's request, the question of further equipment for the carrying on of the work was introduced, and the President of the Society, Prof. E. C. Pickering, expressed a hope that the Government could be persuaded to provide a large telescope. Later a resolution was passed expressing the admiration of the society for the radial velocity work accomplished with the 15-inch telescope and expressing the hope that the Government would soon provide a larger telescope.

This resolution was transmitted to the then Minister of the Interior, the Hon. Frank Oliver, but, as this was just previous to the election of 1911, naturally no action was taken at that time. Further, owing to the change of Government and to further change of ministers in the Department of the Interior, from the Hon. Robert Rogers to the Hon. Dr. Roche, the resolution had become pigeon-holed and I felt that if anything was to be accomplished, the matter would have to be brought anew to the attention of the Government.

A suitable occasion arose at the meeting of the Royal Society of Canada in May, 1912, when a resolution was introduced in Section III (Mathematical, Physical and Chemical Sciences) and was passed at a general meeting of the society, instructing the council to prepare a memorial to the Government urging the providing of a large reflecting telescope for the extension of the radial velocity work of the observatory.

This memorial, accompanied by strong letters of commendation of the project from the most eminent astronomers of Europe and America, was presented to the Premier in July, 1912, on the eve of his departure for England, was very sympathetically received by him, and was presumably transmitted to the Hon. Dr. Roche, Minister of the Interior.

However, no action was taken at the time and it almost looked as if it would again be allowed to lapse. I am convinced from the support he gave later that the minister was favourably inclined towards the project, but did not wish to commit himself without feeling sure of definite support from his colleagues and fellow members. It seemed necessary, therefore, if the telescope was to be obtained, to interest members of Parliament and members of the Cabinet in the project sufficiently to have them urge its authorization on the minister. This work, I, with the help of Dr. King, undertook and finally a voluntary committee of several members of Parliament, headed by Sir Edmund Osler, with F. H. Shepherd as organizer, interviewed the Hon. Dr. Roche on Feb. 12, 1913, and obtained his consent to make enquiries and obtain tenders for the construction of the telescope. My thanks and those of all interested in the advance of astronomy are due to Sir Edmund Osler, Mr. Shepherd, Mr. Arthur Meighen, and the other members of the committee for their active interest and help in this matter. I have also pleasure in expressing my appreciation of the sympathy and active help of members of the Cabinet and especially of the Hon. Martin Burrell in bringing this matter to a successful conclusion. Without such support, it is unlikely the construction would have been authorized, and this considerable accession to the existing resources for astronomical research of the world would have been indefinitely postponed.

Chapter II—Enquiries, Specifications and Tenders.

The first authorization of the minister was to make enquiries, prepare specifications and call for tenders for the telescope and the proposal was to get tenders for two sizes of instrument with apertures 60-inch and 72-inch.

Pursuant to this authority, I was deputed by Dr. King to visit the larger observatories, especially those where reflecting telescopes had been or were used, and the principal manufacturers of the optical parts and mountings of large telescopes in the United States. Afterwards, as the International Union for Co-operation in Solar Research was to hold a meeting at Bonn in August, 1913, and, as the Dominion Observatory, Ottawa, had taken part in the programme for the spectroscopic determination of the solar rotation as well as in other features of the work of the union, it was proposed to attend this important conference and at the same time to obtain further information in regard to the design of the telescope and to consult with some of the manufacturers in Europe.

Consequently, early in March, 1913, I departed from Ottawa to visit the Pacific Coast observatories at Mt. Hamilton and Mt. Wilson, and at the same time to make preliminary enquiries at Medicine Hat, Okanagan and Victoria in regard to the most suitable location for the telescope. Visiting the Lick Observatory in the first place I was most kindly received by Director Campbell and the members of his staff and every facility was offered me and all information, that might be of service, given. Their experience with the 36-inch reflectors at Mt. Hamilton and at Santiago de Chile was most valuable and many very useful ideas were obtained and noted for the design of the proposed telescope. So far as the design of the mounting was concerned, they favoured the long polar axis between separate piers with the declination axis crossing it in an intermediate position. The 36-inch Crossley is mounted in a modification of this form and gives good satisfaction.

From the Lick Observatory I travelled to Pasadena and here at the offices and on Mt. Wilson at the Solar Observatory I found every one most willing to help in any possible way, and many valuable ideas for the design of the reflector were obtained here. The great success of the 60-inch reflector, and their experience in the operation of this large instrument, naturally made their suggestions most valuable both as to what should be incorporated and what avoided in the design of large reflecting telescopes. As is well known, in the 60-inch mounting the tube swings in a huge fork on the north end of the polar axis and in the 100-inch centrally between the two sides of a long bifurcated polar axis. In the case of the 60-inch, owing to interference of the tube with the mercury float, low declinations cannot be reached, while with the 100-inch the forked polar axis prevents the telescope tube from reaching a circle of about 30° radius around the pole. While such limitations are not very serious, especially where as in this case there are two large telescopes which supplement one another, yet in the design of the Canadian telescope it was deemed desirable, other things being equal, to have it mounted so as to reach the whole of the sky available at this latitude. As this is readily obtained by a type similar to the Crossley, Ann Arbor or Melbourne mountings, the Mt. Wilson forms were not seriously considered, although they have advantages in their symmetrical form, in the fact that the axis of the tube intersecting the polar axis lightens considerably the weight of the moving parts and requires a somewhat smaller dome than when the tube is mounted eccentrically. At the Detroit Observatory, Ann Arbor, where is a 37½-inch reflector of quite recent construction, I also obtained useful assistance in many details of construction, and am indebted to Dr. Curtiss for his willingness to assist in every possible way.

The Harvard Observatory was visited and I was much interested in the novel and original way the mounting of the 60-inch Common telescope was being carried out and in their method of synchronized electrical driving in the place of the regular governor type employed in most telescope driving clocks. Director Pickering was most kind and eager to give assistance in preparing specifications to give the best results.

Finally the works of the Warner & Swasey Co. of Cleveland and of the J. A. Brashear Co. of Pittsburgh were visited and further information of a very valuable character in regard to the mechanical and optical details of the proposed telescope were obtained.

This mass of information, much of it of course contradictory, was then arranged and tabulated and I set myself the task of preparing specifications from which competitive tenders could be obtained. In these specifications the purpose was to set forth the general form of the mounting and optical parts, the essential operations to be performed with suggestions as to the means, and the character of the workmanship required, but at the same time to leave the makers of the instrument full scope for the exercise of their ingenuity and experience in working out the details of the mechanism.

In deciding between opposing opinions in regard to the best practice optically or mechanically, especially in the latter, I was possibly better equipped than most astronomers owing to my mechanical training and knowledge and I venture to think that owing to this training the telescope is a better instrument than would have otherwise been the case.

It has seemed desirable to insert here the specifications sent to the competing firms, as indicating what I considered the best practice before the telescope was designed and in the hope that they may possibly be of use to others. As will be noticed when the description is given, these specifications were altered in a few details but generally speaking were fairly closely adhered to, and were sufficiently definite to enable tenderers to closely calculate the cost of the completed instrument and hence give an equal chance to all.

It will be noticed that these specifications contain little radical or different from the conventional form of telescope. It did not seem to be wise in a large instrument like this to introduce any untried features unless with a surety of improvement, and although I was urged to adopt some rather startling modifications, such as the use of a synchronized electric motor instead of the usual governor drive, I did not think it advisable to depart from the entirely satisfactory present methods to one which did not offer any striking advantages and did not seem to me so certain and reliable. There is one feature, however, in the design for which I am responsible, and that is the substitution of plain ball or roller bearings in the bearings of polar and declination axes, in the place of using cylindrical bearings to maintain collimation and relieving part of the friction on these by rollers or by mercury flotation. The ball or roller races in modern anti-friction bearings are of the highest quality, are hardened and ground by the best machinery and are finished to such a high degree of accuracy and polish as to excel the best of the old type cylindrical bearings so far as maintaining accuracy of collimation is concerned. At the same time the friction is very much reduced, probably to about one-fifth of the old type roller relieved cylindrical bearing, and also, I believe, below that given by mercury flotation methods, which have the disadvantage of being cumbrous, expensive and messy. Results of the tests on the bearings of the 72-inch telescope will be given in the description of the mounting.

SPECIFICATIONS FOR LARGE REFLECTING TELESCOPE FOR DOMINION ASTROPHYSICAL OBSERVATORY

PRELIMINARY

1. Estimates shall be given to cover complete telescopes of apertures 60 and 72 inches The division of the cost between optical parts and mounting shall be indicated.

2. It shall be distinctly understood that material and workmanship are to be strictly first class.

3. The specifications following are intended to cover only the general features of the instrument. Any modification of the form proposed herein will be carefully considered and if deemed of advantage adopted. When the contract is awarded all matters of detail, design and construction are to be submitted to the representative of the Government for approval, and a copy of the final drawings to be furnished.

4. It is desirable that any estimates submitted be accompanied by preliminary drawings or sketches approximately to scale showing the proposed form and principal features of the mounting accompanied by any description and specification that may be necessary to explain the design.

GENERAL SPECIFICATIONS

1. The main principle to be borne in mind in designing this telescope is to have an instrument convenient in operation, smooth and satisfactory in running without unnecessary complications.

2. The telescope is primarily intended to be used for spectrographic observations in the Cassegrain form. For this purpose a hole is required in the mirror, the spectrograph being attached below the cell.

3. The telescope in addition must be capable of being used for direct photography at the focus of the principal mirror, both at the side of the tube by the use of a Newtonian flat and directly in the prime focus.

4. A third possible use of the reflector would be with a small and comparatively light spectrograph in the prime focus.

5. Further it may be desirable to obtain direct photographs at the Cassegrain focus. If the hole in the principal mirror can be made 10 or 12 inches in diameter no additional attachment will be necessary, but if it is not considered desirable to attempt a hole of larger diameter than two or three inches then provision shall be made, in the lower section of the tube, for attaching webs to hold a diagonal mirror to reflect the light to a 10-inch square plate at the side, though such an attachment is not to be furnished at present.

OPTICAL PARTS

1. The principal and secondary mirrors shall be cast of the material, hard crown, found most suitable and generally used for large mirrors. All the mirrors must be of material free from large visible defects and must be thoroughly and carefully annealed so as to be as free as possible from internal strains.

2. The ratio of thickness to diameter in the principal mirror shall be not less than one to eight, in the smaller mirrors not less than one to six. The principal mirror shall have a central hole cast in it whose diameter is dependent upon conditions. If the diameter can be safely made about one-sixth the whole diameter, a third reflection for direct photography in the Cassegrain focus will be avoided. But if it is considered that a large hole would entail greater danger of non-uniformity of internal structure or would considerably weaken the mirror then the size of the hole to be cast may be diminished to about two inches which may be later enlarged by grinding to three inches, which is sufficient for spectrographic work.

3. The ratio of aperture to focal length for the parabolic mirror shall be one to five; for the Cassegrain combination one to eighteen. The diameter of the Cassegrain secondary shall be about 19 inches and its radius of curvature about 19·5 feet, while it shall be placed about 7 feet from the principal focus of a 72-inch mirror. For a 60-inch mirror the dimensions will be proportionately reduced. The Newtonian flat for a 72-inch mirror should be elliptical in shape with the apertures of major and minor axes about 20 and 14 inches respectively.

4. All the mirrors shall be ground smooth and true on the periphery, also around the central hole in the main mirror, and shall be ground and polished approximately flat on the back.

5. After the main mirror has been ground approximately to shape it would be desirable for it to stand for some time before figuring and if possible without delaying the completion of the telescope this should be arranged for.

6. All the optical surfaces shall be of the highest quality both as respects figure and polish. They shall be free from zonal errors and from astigmatism and when tested by the Foucault or knife edge method shall show perfectly smooth and uniform figures.

7. The main paraboloidal surface is to be tested both at the centre of curvature and at the principal focus. In the former case, with the artificial star fixed in position

the centre of focus for zones of different radii shall not vary from the theoretically computed value to a greater extent than $\frac{1}{200}$ inch for the outer zones and $\frac{1}{100}$ for the inner zones. When tested at the principal focus by means of an accurate auxiliary plane the extreme difference in focus with a fixed artificial star for zones a foot from the edge shall not exceed $\frac{1}{400}$ inch and for the inner zones $\frac{1}{200}$ inch. The same conditions shall be true when the Newtonian is tested in conjunction with the main mirror.

8. The Cassegrain secondary shall be tested in conjunction with the paraboloid and auxiliary plane and the differences of focus allowable, in the images from different zones shall not exceed $\frac{1}{100}$ inch. If found desirable after the instrument is installed the secondary may be further figured to improve average conditions. The optician shall be ready to do this work without additional charge although his travelling and living expenses will be paid.

9. The diameter of the auxiliary plane used in testing the principal mirror shall be at least three-quarters the diameter of the latter and shall be corrected with the highest possible precision. It and the sphere with which it is tested shall be required to be free from zonal errors and from differences of focus for different zones of any measurable or observable amount.

10. The optician shall provide an approved knife edge apparatus for making these tests. The artificial star shall be formed by condensing the light of a powerful source, the electric arc if necessary, on a small hole not exceeding ·002 inch in diameter. This star shall be capable of adjustment but shall remain stationary during any tests, the measuring being done by the movement of the knife edge which shall be effected by micrometer screws working in slides parallel to the optical axis and transversely in any position angle. The whole apparatus to be fixed on a solid stand also possessing all necessary adjustments.

11. Adequate arrangements for maintaining the temperature of the testing room constant and for the easy and safe handling, adjusting and collimating of the mirrors during testing shall be provided. Provision for the Hartmann test shall be made if required.

12. All the mirrors including the auxiliary plane shall fulfil the above requirements and shall be tested by the representative of the Government and any other person or persons who may be asked to act. The maker shall provide all necessary facilities for these tests.

13. Five ordinary and one wide field eyepieces of suitable foci for visual observations at both the Newtonian and the Cassegrainian focus shall be provided, with the necessary adapters for holding, as well as the necessary guiding eyepieces for the double slide plate holder.

14. Two finders of four inches aperture shall be attached in convenient positions at the lower end of the tube. One long focus finder of seven inches aperture and of focal length about that of the main tube shall be attached to the latter and shall be provided with eyepiece with illuminated cross wires. Lateral adjustment of the eyepiece by means of rectangular slides allowing movement of about 15 minutes of arc in any direction, with means of clamping when adjusted, shall be provided.

MOUNTING

1. The general form of mounting is that having a long polar axis supported on separate columns with the declination axis passing through the polar axis between the bearings. The tube is mounted on one end of this declination axis as close to the polar axis as possible, balance being restored by a system of counterweights on the far end of the declination bush. Reflectors mounted in a somewhat similar manner are the 4-foot Melbourne, the 4-foot Paris and the 37½-inch Ann Arbor.

2. A spectrograph which may extend as much as eight feet below the mirror cell is to be attached to the lower end of the tube. With the type of mounting described no difficulties are introduced when the tube is on the meridian or above the polar axis. But as it is frequently convenient to work with the tube under the axis, the length of the polar axis, the form of the columns and other conditions shall be so arranged as to allow this method of working so far as is possible without making the instrument out of proportion or affecting the stability and cost of the mounting. If it is not possible under these conditions to swing eight feet then the design shall be arranged to allow as long an extension as possible. The diameter of the upper end of the spectrograph will not exceed three feet, while the lower end will be only about half that size.

3. The north and south piers shall be of cast iron provided with means of adjustment in altitude and azimuth and shall carry the bearings of the polar axis in spherically shaped seats to allow of this adjustment without introducing constraint on axis or bearings. Only so much of these piers as may be considered necessary to provide ample means of adjustment and to allow of proper driving and working of the instrument need be of iron construction and part of the telescope.

4. The polar axis shall be constructed in the best manner of the materials most suitable for the purposes it has to fulfil. If of built-up construction especial care must be taken to ensure its remaining in alignment when finished. All the bearing surfaces on this axis, as those for the main bearings, for the driving worm wheel, for the main driving gear, for the R.A. circle or any others must be truly concentric with one another and should if possible be finished by grinding at one swinging in the lathe. The greatest care must be taken in boring the bearings or bush for the declination axis to ensure that it is exactly at right angles to the polar axis. If this condition is not fulfilled it is impossible to properly adjust the telescope.

5. The declination axis shall be forged in one piece of steel of the best quality for the work it has to do and all bearing parts as well as those carrying gears or other attachments shall be turned and ground perfectly concentric with one another.

6. The diameters and sections of the polar and declination axes shall be of sufficient size to carry the required weights without undue flexure. The amount of flexure allowable shall be decided by the Government representative.

7. The bearings on both polar and declination axes shall consist of roller bearings entirely. The practice of depending on plain cylindrical bearings for the alignment and of relieving some of the friction by counterpoised rollers, mercury flotation, or other methods is to be abandoned and both alignment and friction taken care of by roller bearings only. Whether bearings like the Timken Roller Bearing (which provides means of adjustment to take up wear and lost motion) or straight cylindrical roller bearings

are to be used will be decided later. In either case the rollers must be prevented from getting out of place and from sliding against one another by some form of cage or by intermediate smaller rollers. It is essential that the rollers and the external and internal bearing sleeves shall be of steel, hardened and ground with the greatest of accuracy.

8. The end thrusts shall also be cared for by means of anti-friction bearings, preferably of the roller type and also without sliding friction. Means of adjustment on one of the end thrust bearings on the declination axis will be necessary.

9. Timken roller bearings or some equally good friction relieving device shall be applied to other bearings in the telescope where friction will be liable to affect the easy and smooth movement of the telescope. Some that may be mentioned are—the bearing of the worm wheel on the polar axis, of the slow motion arm on the declination axis, of the shafts transmitting quick motion in R.A. and Dec. and any others deemed desirable.

10. The principle to be followed in designing the quick and slow motions and the setting circles is to have the maximum of convenience in operation with the minimum of complication and expense. To this end the following general scheme is suggested though any modifications proposed will be considered.

11. Quick motion in R.A. shall be effected by means of a hand wheel on the south pier, gearing as directly as possible into a large fixed gear on the polar axis. The setting circle in R.A. shall be so arranged that it may be conveniently read from the quick motion wheel and this circle shall be driven at the sidereal rate so that one may set directly to the R.A. of the star without calculation for hour angle. No fine graduations are required but the ruling and figures shall be sufficiently distinct to be read directly without magnifier or telescope to minutes of time, and allow of estimation to fifths of a minute. An hour circle coarsely graduated to five minutes of time will also be required.

12. Taking into account accessibility and simplicity the best method of obtaining the quick motion in declination seems to be by an electric motor mounted on the declination bush and gearing into a large gear keyed to the outer end of the declination axis. This motor shall be actuated from a switch near the R.A. hand wheel, while the declination circle might be near the large gear and read directly from the switch. A moderately coarse graduation easily read without telescope and yet admitting of estimation to 5 minutes of arc and if feasible by some auxiliary device even closer is required.

13. The clamp in right ascension should be near the hand wheel and a clutch for disconnecting the latter from the axis if considered necessary. The clamp in declination must be near the quick motion switch and it is necessary to arrange an interlocking device so that the act of clamping will disconnect the motor and that the tube must be unclamped before it is possible to start the motor.

14. The foregoing specifications have shown that the intention is to have the preliminary quick setting and clamping of the telescope in R.A. and Dec. made from one position at or near the south pier as probably the most direct and convenient place.

15. The slow motions in both R.A. and Dec. shall be effected by means of electric motors, these motors being actuated from small switch contacts which may be held in the hand of the observer and of which there shall be two sets, one at the upper and one at the lower end of the tube to enable the final setting and guiding to be done at the finders and guiding eyepieces.

16. The slow motion in R.A. shall be applied by means of differential gears in the worm shaft or clock train, these gears being driven by a small motor and no arm and tangent screw motion is necessary.

17. The slow motion in declination shall also be actuated by means of an electric motor, the necessary communicating mechanism being sufficiently rigid to ensure that the tube may be started and moved in declination smoothly and without springiness or lost motion. Friction in the mechanism must be relieved by rollers or balls so that when unclamped the tube may move easily and freely.

18. The speed for the quick motions shall be about 45° to the minute and for the slow motions about 30 minutes of arc to the minute, and the motors must be provided with some kind of brake or clutch so that the telescope stops when the switch is opened.

19. The tube above its attachment to the declination axis shall be of skeleton construction, below of closed construction. The lower part shall be of cast iron, or steel and cast iron, or of other materials as may best answer the purpose. Such openings in the sides of the lower section near the mirror, closed by light removable covers, as may be deemed necessary for convenience in burnishing the mirror or for other purposes shall be made.

20. The mirror cell shall be of cast iron of substantial construction, rigidly attached and yet easily removable for the purpose of resilvering. The mirror shall be supported on the back in the cell by a system of counterweighted levers or by any other suitable system, such as a multiple three-point support, which will equally distribute the weight of the mirror. An edge support system like that used on the 60-inch Mount Wilson telescope shall be used to maintain collimation without undue stress on the edge of the mirror.

21. As the latest experience has shown that nothing is gained so far as temperature effects on the mirror are concerned by leaving the cell open at the back it may preferably be entirely closed in, except a central aperture as large as the hole on the mirror.

22. An attaching ring about 3 feet in diameter shall be cast on and turned up true on the bottom of the cell with convenient appliances for attaching and orienting the spectrograph and other accessories.

23. Some convenient and effective means of covering the mirror which shall at the same time act to a certain extent as a heat insulator shall be provided.

24. For the skeleton section of the tube above the declination axis, the construction shall be as light as is consistent with maintaining the mirrors in good collimation. As a first approximation the amount of flexure allowable at the Cassegrain mirror situated about 19 feet above the surface of a 60-inch and nearly 23 feet above a 72-inch mirror shall not exceed one-eighth of an inch when the tube is horizontal. The flexure when the instrument is used in the prime focus with the heavier extensions required need not be so small and a tube to carry the Cassegrain with the above flexure would be sufficiently rigid for all purposes.

25. The upper end of the tube shall be so designed as to allow the necessary changes from one form of the telescope to another (Cassegrain, Newtonian and prime focus) to be made with the minimum of risk, labour, and change of balance.

26. The Cassegrain mirror which for a 72-inch telescope is of about 19 inches aperture and situated nearly 23 feet from the surface of the principal mirror must be held firmly and yet without constraint in its cell and cell and mirror shall be capable of being easily and accurately adjusted for collimation. After collimation has been effected the system must be movable with a slow smooth motion along the optical axis for the purpose of focussing. This motion must be carried by rods and gearing to the lower end of the tube near the guiding eyepiece of the spectrograph and must not change the collimation. The mirror and system are to be held in position by four arms of thin steel plate, placed edgewise, attached firmly to the periphery of the tube.

27. When the telescope is used in the Newtonian form or at the prime focus the Cassegrain must be removed to prevent obstruction of the light and when used at the prime focus the Newtonian mirror must be removed for the same reason. One double slide plate holder attachable either at the Newtonian or prime focus with the necessary focussing and adjusting devices and guiding eyepieces shall be provided. When used at the prime focus provision must be made for carrying the plate holder movements and guiding eyepiece to the side of the tube. The plate used in this plate holder will be 4 inches square and care must be taken in the design that light from the whole mirror except that occulted at the centre shall reach every part of this plate unobstructed. The Newtonian attachment and also that in the prime focus shall be provided with convenient means of rotation and clamping in position angle to bring the plate holder or other attachments to a convenient position for guiding. The adapters or attachments in which the plate holder is held must be designed to admit of the use of a small spectrograph.

28. The tube must be attached to the declination axis at such a place that with the Cassegrain in place and no spectrograph below the mirror the tube is nearly in balance. Balance will be restored when the spectrograph is attached by weights placed north and south of the upper end of the tube. Provision for attaching weights below the cell for restoring balance when the other attachments are in use must be made.

29. The driving clock shall be of ample size to do the work and made in the best manner. Great care must be taken with the communicating gears and shafts between the governor and the worm shaft to prevent the introduction of any periodic error in driving. The clock shall be wound automatically by an electric motor.

30. The connection between clock and worm shaft shall be as direct as possible and, if differential gears are introduced in the worm shaft, care must be taken that the two parts of the shaft are exactly concentric else a period may be introduced. Provision must be made in the connection to allow the adjustment of the telescope in altitude and azimuth without affecting the driving.

31. The driving worm itself which is often at fault must be most carefully made. It must be turned and the worm cut as truly as possible and finished by grinding. The screw part should be left considerably longer than will be used and ground and lapped in a long nut to remove all chance of periodic error.

32. The driving worm wheel shall be as large as possible in diameter. If the design of the polar axis is properly carried out, the worm wheel might, when the telescope is turned to the pole, the only place where interference can occur, project up behind the mirror cell for at least a foot as the spectrograph or any other attachment below the cell

will not be greater than 3 feet in diameter. The worm wheel is to be spaced and cut with the greatest possible accuracy. The teeth shall be smoothed up and any remaining irregularities removed by running worm and wheel together with polishing material, care being taken that all grinding material is removed from worm and wheel. The whole driving mechanism must be carefully made as periodic error in driving is a most annoying and troublesome defect.

33. A complete and permanent system of wiring for illuminating the circles and guiding eyepieces and for the quick and slow motion motors with 12 additional wires for the spectrograph shall be provided on the telescope but bearing rings and brushes to be avoided if possible.

34. For transport conditions it is desirable and almost essential that no single piece of the telescope weigh more than five tons.

35. The price given shall include the cost of boxing and delivering f.o.b. at the place of manufacture and the services of a competent person to superintend the erection of the instrument, which shall not be considered completed until it operates to the satisfaction of the representative of the Government.

36. Terms of payment desired should be stated in the tender.

TENDERS

Preliminary enquiries had been sent early in March to a number of firms who were deemed competent to construct the optical parts and mounting of a large telescope and after the specifications were prepared, they were sent to the following firms with the privilege of tendering for either the optical or mechanical parts or for the complete telescope :—

Sir Howard Grubb, Dublin, Ireland.
The Jno. A. Brashear Co., Pittsburgh, Pa.
The Warner & Swasey Co., Cleveland, Ohio.
The Alvan Clark Son's Corporation, Cambridge, Mass.
T. Cooke & Sons, York, England.
O. L. Petitdidier, Chicago, Ill.
G. W. Ritchey, Pasadena, Cal.
Carl Zeiss, Jena, Germany.

In the meantime, I had sailed for Europe and first visited the Grubb works at Dublin. Sir Howard Grubb did everything in his power to assist me in regard to the design of the telescope, and showed me the various telescopes under construction in his works. He explained his proposed design for our reflecting telescope and we thoroughly discussed all details. I found that our ideas in regard to the essential features were in substantial agreement, although I did not like his design so well as the preliminary design of the Warner & Swasey Co.

He advised me to consult Sir David Gill and suggested that if he, Sir Howard, got the contract, Sir David would probably be willing to supervise the construction, as he was already doing in the case of telescopes for other distant clients, and kindly made an appointment for me with the latter in London. Sir David I found a most charming person, very interested in the project and he offered several valuable suggestions, but nothing radically different from what was already incorporated in the design. Similarly the Astronomer Royal was eager to be of any possible service and I have the same story to relate of all whom I consulted. There is no question but that all these opinions were of service and I certainly obtained the widest possible viewpoint and the benefit of the most varied experience in these discussions of the design of the telescope.

While in Paris, through the kindness of Comte de la Baume Pluvinel, I had the pleasure of a conference with M. Delloyé, the manager of the St. Gobain Glass Co., the firm who would be entrusted with the casting of the mirror disc, and I was very pleased to learn from him that they did not expect any serious difficulty in making a 6-foot disc with a hole in the centre. I suggested to him a method of forcing a core through the glass after pouring, in preference to pouring around a core in place. Prof. G. W. Ritchey had been especially insistent on the impossibility of obtaining a good disc with a hole cast in it, stating that when the molten glass flowed around the central core the continuity of the flow was broken and the metal did not perfectly unite on the opposite side. However, M. Delloyé did not inform me how they expected to accomplish the task, but I imagine from the appearance of the hole in the disc as received that it was produced by a core being forced through after pouring. The final result showed that Prof. Ritchey's misgivings were not borne out and there was absolutely no evidence of lack of homogeneity in the disc in any place.

On my return from Europe I found that actual tenders for construction had been received from the following firms :—

For the construction of the mounting :—

Sir Howard Grubb of Dublin, Ireland.
The Warner & Swasey Co. of Cleveland, Ohio.

For the construction of the optical parts :—

Sir Howard Grubb of Dublin, Ireland.
The Jno. A. Brashear Co. of Pittsburgh, Pa.
The Alvan Clarks Sons' Corp. of Cambridge, Mass.

Tenders were given for both 60-inch and 72-inch apertures, the latter being about 30 per cent higher in price. In view of the comparatively small difference in price it was decided to recommend the construction of a 72-inch telescope.

The tenders of the Warner & Swasey Co. of $60,000 for the mounting and of the Jno. A. Brashear Co. of $30,750 for the optical parts were considerably lower than the others, the only serious competitor being Sir Howard Grubb. Owing to the fact that the Warner & Swasey Co. had considerably more experience in the construction of large telescopes, and were much better equipped than Sir Howard Grubb for work of this character, and to the further important fact that they were situated in a place readily accessible from Ottawa, where the design and workmanship could be efficiently supervised, it was a matter for congratulation that their tender and that of the Brashear Co's. for the optical parts, to whom the same considerations apply, were the lowest. No difficulty in regard to price was in the way of awarding the contracts to the firms, whom it was considered were in a position to produce the best instrument.

The next stage naturally was the placing of the orders for the telescope and as the preliminary authorization from the minister had only been for making enquiries and obtaining prices, it was necessary to obtain the authority of the Governor General in Council for the awarding of the contracts. Under instructions from the minister, Dr. King prepared a memorandum setting forth the reasons for the construction of the instrument, the proposals and prices received and recommending the awarding of contracts to the Warner & Swasey Co. and the Jno. A. Brashear Co. for the construction of a 72-inch reflecting telescope.

The minister's recommendation based on this memorandum was assented to by the Government on October 18, 1913, and the construction of the telescope hence assured. It is easy to imagine the relief and delight of those interested in the undertaking when it was learned that the matter was finally settled, and that the project initiated three years earlier, and carried out only by constant and untiring efforts during the interval, had been finally brought to a successful issue, and Canada was to have a telescope more in keeping with her character and aspirations and one with which the work so successfully inaugurated with the 15-inch telescope could be enormously extended.

I wish to express here my sincere appreciation of the help so readily and cheerfully given by so many scientific associations and individuals in bringing the matter to the attention of the Government, and of the co-operation and active help of members of the Cabinet and members of Parliament in interesting the minister and through him in finally having the construction authorized by the Government. Finally I desire to particularly express to the Hon. Dr. Roche, the Minister of the Interior during the development, construction and organization stages of the undertaking, my deep gratitude for his hearty support and cordial co-operation, in the carrying on of the work during a difficult time, and for his just and sympathetic treatment in the final organization. I venture to hope that not one of the smallest of Dr. Roche's claims to the recognition of posterity will be his progressive and public-spirited attitude in regard to the cause of astronomical research in Canada. I am also very much indebted for the success of the undertaking and for the arranging of the organization to the hearty co-operation of Mr. W. W. Cory, Deputy Minister of the Interior.

CHAPTER III—DESIGN, CONSTRUCTION AND LOCATION.

Immediately upon the passing of the order in council authorizing the construction, the successful tenderers were notified. Contracts were then prepared governing the relations of the two parties, the character of the work, the method of inspection and approval and the terms of payment, which were finally signed.

In the matter of the optical parts, preliminary details were fairly well settled by the specifications and moreover, when the optical constants of the instrument had once been settled on, there are no alternative means of accomplishing the desired objects as is the case in the mounting. For example when the specifications say the mirror must be of 72 inches aperture, of 360 inches focal length, and must be a paraboloid of revolution within certain close limits, no modifications are possible and there was no room for change of detail or method as in the case of the mounting.

The glass discs for the principal mirror, 73 inches diameter, 12 inches thick, the auxiliary plane 55 inches diameter, 9 inches thick and for the Newtonian and Cassegrain secondaries were ordered by the J. A. Brashear Co. from the St. Gobain Glass Co. in November 1913. After one unsuccessful trial the principal mirror was successfully cast and annealed in July 1914. Although the disc for the auxiliary plane was not ready, fortunately the 73-inch disc and the small mirror discs were shipped to the Brashear Co. late in July 1914 from Antwerp, only three or four days before war was declared. They arrived in Pittsburgh about the middle of August and work was at once begun on the rough grinding and shaping. This was completed and the fine grinding and polishing of both back and front finished in August 1915. Various delays then occurred and actual figuring was not commenced for a year and not completed until April 1918. More complete details will however be given in the description of the telescope.

In the case of the mounting the specifications were purposely and necessarily not so specific as for the optical parts, as it was deemed very desirable to allow the makers, especially with their valuable experience in the construction of large refracting telescopes, every scope to exercise originality in design and to improve upon existing methods in the details of the mounting and in the means employed to accomplish the desired operations.

A preliminary design had already been prepared by the Warner & Swasey Co., which embodied fairly closely the main features of the specifications and this design was elaborated and modified as soon as their tender was accepted.

I was deputed by Dr. King to collaborate with them in the design of the instrument and it was agreed by all that it would be very desirable to give a great deal of attention to this part of the work. Various consultations were necessary and as these could not be effectively carried on by correspondence, it was decided that I should go to the works of the Warner & Swasey Co. whenever necessary for the proper working out of the design, to decide between alternative proposals and to approve details when satisfactory.

Consequently, very soon after construction was authorized I visited Cleveland and spent three or four days most profitably and pleasantly in discussing and deciding upon the main features of the mounting. A young engineer of the company, Mr. Walter Feeker, was entrusted with the preparation of the detail drawings under the supervision of the works manager, Mr. E. P. Burrell, who is responsible in great measure for the working out of the design, while the general features of the mounting and its harmonious appearance are due largely to the genius of Mr. Swasey.

The plan adopted at these conferences, of which several took place before the completion of the drawings, was to go over the work already done, discuss and note all features in which modifications seemed desirable and plan the means to be employed for accomplishing the desired ends. These conferences undoubtedly were of great value in perfecting the design and in serving to efficiently combine the astronomical and mechanical requirements of the telescope. On the one hand the great experience and knowledge of Mr. Swasey as exemplified in the design of the largest and most successful refractors ever built, and the ingenuity and engineering skill of Mr. Burrell and his engineering staff ensured an instrument mechanically and structurally correct, while on the other hand, my own mechanical knowledge and training enabled me to more correctly gauge and adapt astronomical requirements to mechanical execution. The result was, I firmly believe, a telescope very considerably in advance in design, construction, and perfection of workmanship and operation of any hitherto made.

I would not be doing justice to the Warner & Swasey Co. if I did not warmly express my appreciation of the spirit in which they undertook and carried through this work. Once the contract was awarded, their one aim was to make the telescope the best possible, regardless of cost or of whether the specifications called for the inclusion of any particular feature. Not once in all our conferences did they offer objection to any improvement or addition suggested by me and often they themselves, even at considerable additional cost, incorporated features in the design which would increase the efficiency, accuracy or convenience of the instrument.

Our relations throughout the design, construction and erection of the telescope were of the most cordial nature and I carry the pleasantest memories not only of the interesting and friendly character of our business relations but of the kindly and hospitable way in which I was looked after and entertained by the members of the firm during my numerous visits to Cleveland. These and the equally cordial and pleasant relations with the Jno. A. Brashear Co. in the construction of the mirror, made the superintendence of the construction of this telescope an especially agreeable and interesting task.

The various features of the design and the variations from general practice will be dealt with particularly in the description of the mounting and it has seemed best in this place to give merely a summary of the stages in the progress of the work. Even before the contract was entered into, in October 1913, considerable progress had been made in the preliminary design, which was elaborated, detailed and modified as soon as construction was decided on. The greater part of the design and most of the detail drawings were completed by the summer of 1914, although some small changes were made in minor details after construction had been commenced. The Warner & Swasey Co. have not the facilities for machining and handling the heaviest parts of such a mounting and consequently the large steel castings for the polar axis, the central section of the tube and the mirror cell were sublet to the Bethlehem Steel Co. A local concern made and machined the largest of the iron castings such as the south bearing for the polar axis and the large worm wheel and spur gears. All the other work and the assembling and fitting were done at the works of the Warner & Swasey Co.

The larger parts of the mounting hence were ordered and the construction of the small parts begun at Cleveland in the fall of 1914. Most of the heavy parts were completed and on hand in Cleveland in the early summer of 1915 and the fitting and temporary erection of the mounting begun at Cleveland. There was insufficient head room for the erection in the main factory so this was carried out in an annex especially adapted for this purpose and proceeded without hitch or serious delay.

The work on the mounting was completed and the fitting and preliminary erection finished early in 1916. Before the telescope was dismounted preparatory to shipment to Victoria, the Warner & Swasey Co. were desirous of having a reception and private view of the mounting for astronomers and others interested in it. Owing to the ill health and absence of Mr. Swasey, and to the illness and subsequent death of Dr. King, this was postponed until May 25, 1916. Invitations were sent to leading astronomers and men of science in America and although not many astronomers were able to be present, a pleasant and successful reception was held and the mounting was duly shown and appreciated.

Immediately after this function the mounting was taken down, some further detail work whose need had arisen in the erecting was completed and it was then packed and shipped in four cars via car ferry Ashtabula to Port Burwell and thence C.P.R. to Victoria. Shipped about the end of July 1916, it arrived in Victoria about the middle of August. Final erection commenced on Sept. 6 and was completed about Oct. 15.

LOCATION OF TELESCOPE

Before proceeding to the description of the optical parts and mounting, it is desirable to give an account of the steps that led to the location of the telescope near Victoria and of the stages of construction there.

During the early stages of the project and until the memorial of the Royal Society of Canada was brought forward in 1912, there had been no thought on the part of either Dr. King or myself, of locating the telescope elsewhere than at Ottawa. This idea was first broached by Prof. J. C. McLennan who was good enough to bring forward and heartily support the resolution before the Royal Society. He urged that a clause should be incorporated in the memorial making provision for placing the telescope at the most suitable location, for astronomical purposes, in the Dominion. I am frank to confess that neither Dr. King or myself were at first in favour of this clause as we felt that the difficulty of getting the project authorized by the Government would be much increased if location away from the observatory at Ottawa, which would necessarily mean considerably increased cost of construction and maintenance, were considered. We were well aware of the difficulties in the way of inducing the Government to consent to the large appropriation for purposes of purely scientific research without complicating the matter by further requiring the establishment of a separate institution, a new observatory at some point in Canada away from the seat of Government.

However, I am glad to say that Prof. McLennan insisted on this clause being inserted and the memorial went through in this form and was finally assented to as related above. After Dr. Roche had authorized the making of enquiries, in regard to the design and cost of the telescope, consideration was given to the question of location. The first step was to carefully compare the meteorological records for various regions of Canada, selected on the advice of Sir Frederic Stupart, the director of the Meteorological Service, as being representative of different climatic conditions in the Dominion. Ottawa was considered as being fairly representative of conditions in the eastern part of the country as although some other localities might have a greater quantity of clear sky, there was little likelihood of the important factors of " seeing " and diurnal range of temperature being much more favourable at any location east of the great plains. From the meteorological records, Medicine Hat was selected as being probably the most favourable situation on the prairies, Banff in the Rockies, Penticton at the foot of Okanagan Lake for the dry belt in British Columbia, and finally Victoria, a region of low precipitation and remarkably small diurnal range of temperature, for a situation influenced by the presence of surrounding sea water.

These places were visited by me on my journey to obtain information in regard to the design of the telescope and arrangements were made to have the sky around the pole photographed every night in order to determine the relative clearness of the night skies at the various places. Although from the meteorological records it was possible to determine the relative merits of these locations so far as clearness of sky in the day-time, range of temperature, wind velocity and humidity were concerned, these records furnished no information in regard to what experience has shown is the most important factor, the " seeing ", the relative steadiness of the atmosphere which governs the crispness of definition of the star image. The quality of the " seeing " can only be judged by actual observations with a telescope, the larger the better, for it is quite possible that " seeing " apparently good with a small aperture may go to pieces under the much severer test imposed by a telescope such as the 72-inch.

Consequently, Mr. W. E. Harper, the senior officer in the Department of Astrophysics in the Observatory at Ottawa, was deputed to observe the conditions at the locations mentioned above with a 4½-inch Cooke Photo-Visual telescope, the largest portable instrument available. Observations were made at Ottawa first and a plan devised which enabled the relative value of the " seeing " at the various stations to be accurately compared. Mr. Harper spent most of the summer of 1913 in this work and a full account is given by him in the Publications of the Dominion Observatory, Ottawa, Vol. 2, p. 275.

This account may be briefly summarized by saying that so far as the conditions of " seeing " and small daily range of temperature are concerned, Victoria was much superior to any other place tested. The " seeing " was on the average 3·5 on a scale of 5 as compared with 2·5 at Penticton and about 2·0 at Ottawa. In daily range of temperature Victoria had only slightly more than half the range present at either Penticton or Ottawa. So far as Banff and Medicine Hat were concerned, the " seeing " was hopelessly poor and these places were not further considered. Again as there was little difference between Ottawa and Penticton the latter was eliminated from the discussion which was hence narrowed to Ottawa and Victoria. Meteorological records of the number of hours of bright sunshine at the two places showed an advantage in favour of Ottawa of about 10 per cent. This difference, however, is negligible in view of the superiority of Victoria in the " seeing " and temperature conditions and recent experience has shown there is probably also a greater number of hours of clear night sky at Victoria than at Ottawa.

To obtain some definite numerical conception of what these differences entailed in the amount and quality of the work possible at the two places, the matter was referred to Prof. Campbell, director of the Lick Observatory and Prof. Adams of the Mt. Wilson Observatory both of whom have had experience in work with reflecting telescopes. When their replies were analysed and combined they indicated, so far as could be definitely judged, that the superior conditions of " seeing " and the low daily temperature range would enable more than double the quantity of work of higher quality and accuracy to be performed at Victoria and would further render possible of production certain kinds of work at Victoria which the poor " seeing " conditions at Ottawa would prevent.

There seemed, therefore, to be no room for doubt that the telescope should be placed at Victoria and from this time, October 1913, I was a strong advocate of Victoria as the only place for the telescope. Dr. King, however, was not so enthusiastic, as he probably realized more clearly than I did the financial and administrative difficulties involved. As the tests had been made only during the summer months he thought it desirable to also compare Victoria and Ottawa during the winter. Consequently, Mr. Harper was sent to Victoria in November 1913 and remained there until Christmas. Although the weather was cloudy and broken the relative advantage of Victoria over Ottawa in both " seeing " and temperature was increased and there hence remained no reasonable doubt that the telescope should be placed at Victoria. Although I am convinced that if he had consulted his personal feelings, Dr. King would have much preferred this splendid instrument to have been placed at Ottawa, as part of the great scientific institution he had built up, where it would have been under his direct supervision and control, yet he placed the scientific work to be done as the first consideration and prepared a strong recommendation in favour of locating the telescope at Victoria.

As the capital cost of installation away from Ottawa would be much greater, an office building and residences for the astronomers being required in addition to the observatory building and dome, which only would be needed at Ottawa, it was considered desirable to see if the Government of the Province of British Columbia would assist the project in some way. The erection of such a large telescope near Victoria would be a great educational and advertising asset and if some aid could be obtained from the Province, the Dominion Government would be much more likely to sanction its location away from Ottawa. Consequently, I visited Victoria in February and March 1914 on such a diplomatic mission and interviewed the Premier, Sir Richard McBride, and several members of the Government to see if they could help the project and thus make its location at Victoria more probable. In this mission I had most effective aid from Mr. Arthur W. McCurdy of Victoria, a gentleman interested in scientific pursuits who had considerable influence with the Premier. As the upshot of the matter, the Government of British Columbia offered to give $10,000 towards the purchase of the site and to build a road to the summit of the hill on which the observatory was to be located.

Provisional selection was also made at this time of the most suitable site in the neighbourhood of Victoria. It was felt that the conditions which gave Victoria its good " seeing " might be quite localized in extent as less than ten miles away the rainfall was doubled. Consequently, some situation near to and easily accessible from Victoria on an isolated hill to obtain the advantages of air drainage and more uniform temperature was sought. On the Saanich peninsula are five elevations of this character, Mt. Wark, 1,400 feet, Mt. Newton, 1,000 feet, Mt. Douglas, 728 feet, Bear Hill, 725 feet, Saanich Hill, 730 feet. Both Mt. Wark and Mt. Newton are much more difficult of access than the others and though higher, it is doubtful if the conditions would be superior as the former is in a mountainous district and is not an isolated hill, while Mt. Newton has very gradual approaches and would have no advantages over lower hills rising more directly from the general level. Of the other three, Saanich Hill is in every respect the most suitable. It is situated about 7 miles north of Victoria, the electric interurban railway passes the foot of the hill making it much more easy of access than the other two, and there is a considerably greater area around the summit suitable for the buildings required. Hence, pending the final decision of the Government as to location of the observatory, the summit of this hill was provisionally selected as the site.

As soon as the definite offer of the Provincial Government was received, I returned to Ottawa, and Dr. King prepared a complete memorandum to council on the question of location, strongly recommending the placing of the observatory at Victoria. This was finally approved and the matter definitely settled in April 1914, thus enabling the design of the mounting, which depends on the latitude of the observatory, to be completed. Further, as soon as it was settled and before the public announcement, steps were taken to obtain the land required for the observatory grounds. Consequently, I returned to Victoria and attempted to obtain options at a reasonable figure. Real estate even over the rocky inaccessible summit of this hill was held at fancy prices and it was only after protracted negotiations that the 50 acres needed were obtained at $280 per acre.

After the land had been obtained and surveyed, the question of a water supply and of the road had to be arranged. Three alternative surveys of a road from the West Saanich road to the summit were made by Mr. Devereaux, a very capable Provincial surveyor, but it was only after a struggle with the Provincial Department of Public Works that the only one which would serve our purpose and give access to the proposed buildings was agreed on. The road was built in the spring of 1915, is of a uniform and gradual grade of about 7 per cent., is splendidly constructed and a credit to the surveyor and the Department. The water question was also a difficult one as there was no supply within reasonable distance. A well drilled on the lowest part of the property proved a failure in the dry season, while a second well on adjacent property gave only about 1½ gals. per minute, an inadequate supply. Finally, a running spring of about 4 gallons per minute on the right of way of the B.C. Electric Railway, which the management generously allowed the observatory to use, was piped into a reservoir and from thence pumped up by electric power to the summit under a head of 500 feet, into a large tank of 30,000 gallons capacity. This spring gives water of excellent quality, though somewhat hard, and will probably be sufficient for the immediate future.

Chapter IV—Construction of Observatory Building and Erection of Telescope.

Contemporaneously with these problems the question of the design and construction of the building and dome for the telescope were also pressing questions, and required a great deal of urging and diplomacy to get them under way in time to be ready for the telescope. The building and the concrete pier for the telescope were designed by the Department of Public Works and contracts for their construction were let in the early summer of 1915. The dome, which, in the case of a large reflecting telescope, really acts as a working accessory, had necessarily to be designed by the Warner & Swasey Co., who spent a great deal of time and ingenuity in making it most complete and convenient in every particular. The contract for its construction and erection was let to the Warner & Swasey Co. by the Department of Public Works in the fall of 1915, and was at once got in hand.

The massive concrete pier for carrying the telescope was commenced in June 1915 and required two visits by the writer, the first for giving a meridian line for orienting properly and the second for setting the templates and foundation bolts for the north and south pier heads of the polar axis. The latter task was a difficult one as little range for adjustment was allowed and the bolts had to be most accurately placed, the upper set at an angle of 48° 31′ to the lower. The pier was finished in September and the surrounding circular steel building which serves as substructure for the dome, erected during the fall and winter of 1915-16.

The dome was constructed very rapidly, temporarily erected in Cleveland in March 1916, and shipped to Victoria arriving there in April. Erection proceeded promptly and the structural members were in place and the operating mechanism partly installed by the end of June. The installation and adjustment of the operating mechanism was completed during the erection of the telescope mounting in October. The double sheet metal covering was started in July but proved a tedious process, also not completed until October, about the time of the completion of the erection of the telescope mounting. Fortunately no rain fell during this period and everything proceeded smoothly and without trouble or delay.

As previously related, the telescope mounting which had been entirely erected and fitted in Cleveland, was taken down during June and July 1916 and packed on 4 cars for shipment to Victoria. Wherever possible, the auxiliary mechanism was left attached in place and such pieces as the driving clock, which is an independent unit in a separate case, was shipped intact and consequently much adjusting and fitting at Victoria avoided. The heaviest single pieces were the polar axis, 9½ tons, the central section of the tube 7 tons and the south pier head 7 tons.

According to the provisions of the contract the Warner & Swasey Co. were to provide a competent man to superintend the erection of the telescope, and their superintendent, Mr. Decker, an able and experienced engineer, was chosen for this work. In order that his services might not be lost to the Company for a longer period than necessary, I had agreed to do all the preliminary preparatory work possible before he was sent for.

I arrived in Victoria early in July and found the erection of the structural work and most of the mechanism of the dome completed but none of the operating accessories had yet been tested as the motor generator set was not installed. The first thing to be done was to arrange for the hoisting tackle and for the methods of handling the heavy and at the same time delicate mechanism with the greatest ease and safety. The most difficult part of the erection would be the hoisting of the polar axis and setting it in place in its bearings. For the axis alone weighed 9½ tons and before putting in place, the driving worm wheel, the main driving gear, the hour and sidereal circles, the clamping mechanism in right ascension, and the radial and thrust bearings had to be placed on the axis and adjusted in position. The total weight to be hoisted then was about 14 tons and as it had to be lifted at the proper angle and let down into position with the greatest nicety and care, it was evident that hoisting tackle of ample strength and yet capable of being controlled with accuracy and ease was required.

I was fortunate in securing for this work a firm of contractors, Messrs. Skillings and Hamon, who had experience in handling heavy work and who undertook to haul the parts of the mounting from Victoria to the building, to provide the necessary tackle and experienced help for handling the work. As the main ribs of the dome were sufficiently stiff to carry any of the weights to be hoisted, the problem was thereby simplified and there only remained the question of the tackle. I was unwilling to trust any of the rope tackle obtainable in Victoria and it was decided to use wire cable. Mr. Skillings was able to rent a house moving outfit consisting of a horse driven capstan, about 700 feet of $\frac{7}{8}$-inch wire cable, the part to be used being in good condition, and a set of heavy cable blocks with the necessary snatch blocks, etc. The capstan which had been so long exposed to the weather as to be rather shaky was practically rebuilt and was fastened to the roadway north east of the building, being securely anchored by cables to adjoining trees. The cable from this capstan passed horizontally over the ground floor of the building and was led up by a snatch block to the set of blocks attached to the main ribs of the dome. By means of a horse attached to the walking beam of the capstan any piece attached to the lower block was raised slowly and gradually about one foot per minute, a pawl and ratchet on the capstan cylinder acting as a safety catch and allowing the piece to remain in one position as long as desired. This device proved very safe and convenient and the difficulties of the erection were thereby lessened.

The mounting which was shipped from Cleveland the last week in July via car ferry Ashtabula to Port Burwell, thence C.P.R. direct to Vancouver and thence by car ferry again to Victoria, arrived about the middle of August and Skillings and Hamon at once started the hauling to the observatory. This required nearly two weeks but as soon as some of the heavy parts were on hand the hoisting from the ground floor to the observatory floor began. The first pieces to be handled were the north and south pillow blocks or pier heads, the latter weighing 7 tons and the former about 5 tons. These were lifted directly up from one of the main ribs and set in position over their foundation bolts. The south pier head was levelled by steel wedges and the relative position of the two measured. It was found that the two bearings were closer together than they should have been, although still within the range of adjustment provided. This was probably due not to error in setting, but to settlement of the inclined forms of the north pier owing to the great weight of concrete, or to shrinkage or settlement in the setting of the mixture.

I determined that before the polar axis was installed these two bearings should be adjusted as closely as possible so that the final adjustment of the axis, which if of any magnitude, would require readjustment of clock and driving worm, would only be small. Consequently, a steel wire was stretched between the centres of the north and south bearings and the north adjustable bearing was moved until this wire was as nearly as possible parallel to the axis of the earth. This parallelism was determined first in azimuth by setting up a 6-inch micrometer transit theodolite over a fixed reference point about 50 feet south of the building from which the whole of the wire was visible and from which the bearing of certain objects in Victoria 7 miles away had previously been determined in orienting the pier. It was hence comparatively simple to adjust the north bearings so that the wire lay in the meridian. The transit was then placed in the building close to the south pier, on the same meridian line as the wire, and the bearings adjusted in altitude until the wire made an angle of 48° 31′, the latitude of the observatory, with the horizontal.

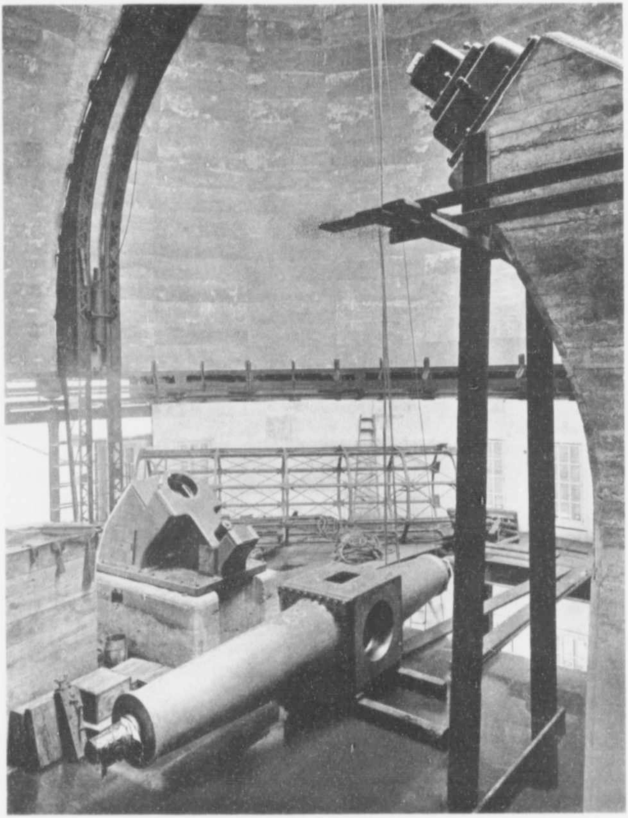

Fig. 1. Parts of Telescope on Observing Floor.

This preliminary adjustment saved considerable trouble in the final adjustment, by following, of the polar axis as the north end was found to be out of position in a length of 20 feet about 0·03 inch in azimuth and 0·02 inch in altitude and no secondary adjustment of clock and driving worm was necessary for these very small angular deviations, less than one-half and one-third of a minute respectively.

The balance of the mounting with the exception of the central section of the tube, the worm wheel, and the declination axis were hoisted to the observing floor and left in convenient positions for the final erection. A general idea of the arrangement can be seen in Fig. 1.

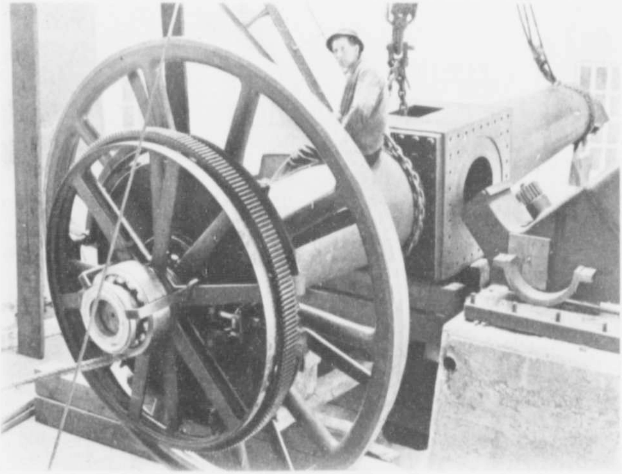

Fig. 2. Polar Axis ready for hoisting.

This preliminary work was completed about Sept. 1 and as soon as Mr. Decker arrived, on Sept. 5, erection was commenced. The polar axis itself had been hoisted to the observing floor from one of the main ribs and the first step was to place in position on it the worm wheel, main driving gear, circles and bearings. As in setting in position the axis had to be central the hoist was taken from both ribs connected by a long double link and the axis was hence raised directly over its position of rest. The axis was so attached to the lower block that when it was raised from the floor the north end was at approximately the right elevation and when elevated above the bearings only small changes in position had to be effected in order to let it down into place. As previously stated, the weight was about 14 tons and it was necessary that no strain should be put on any of the wheels or circles. Hence as it had to be lowered in one particular way and into a close fitting position, it was an anxious time until finally in place. A photograph of the axis ready to be hoisted is given in Fig. 2.

After the polar axis was in place, about three days after erection commenced, the other large parts in the order, declination sleeve, declination housing, declination axis, centre section of tube, skeleton tube and mirror cell were soon erected and all the large parts of the mounting were attached ten days after erection started. The attachment and adjustment of the clock and smaller parts, especially the electrical work, took considerably longer and it was not until Oct. 15 that the wiring was completed and all the switchboards, motors, solenoids, condensers, etc., correctly connected.

In the meantime, and while waiting for the completion of the electrical work, the operating accessories of the dome had to be fitted and adjusted, the cables for dome, shutter, curtains and platform attached, the canvas wind screens put in place, the trolleys and trolley wires for carrying current to the shutter curtain and platform motors erected, the silvering car and declination strut put together and in place, and numerous other details attended to.

However, the whole work was completed in about six weeks without hitch or accident of any kind, a remarkably short time considering the magnitude of the undertaking, giving convincing evidence of the care used in the design, construction, and preliminary fitting and erecting of the installation.

Adapters had been made for attaching the long focus finder objective and ocular centrally along the axis of the tube, and the adjustment of the polar axis was tested and improved by Schlesinger's method of following a star through the meridian. The adjustment was made nearly correct at this time but was not finally completed until the following summer to allow for further settlement of the piers. As previously stated, only a very slight change was found necessary in the position of the axis, which did not require readjustment of clock and worm.

I returned to Ottawa early in November as there was no prospect of the mirror being finished until the following spring, Mr. T. T. Hutchison, who had been appointed Engineer, being left in care of the mounting. In the spring of 1917, the observatory was formally organized as a branch of the Department of the Interior, the writer being appointed Director of the institution, which was named the Dominion Astrophysical Observatory, while Dr. R. K. Young was given the title of Assistant Astronomer. Preparations were then made for permanently moving to Victoria and as it was still uncertain how soon the mirror would be finished, it was decided to go to the observatory in July, as there was a very considerable amount of necessary preparatory work which could profitably be done before the mirror arrived.

As related elsewhere, the completion of the mirror was delayed until April 1918, but the spectrograph arrived about the first of January and its installation and adjustment the preparation of dispersion tables, preliminary work on the observing programme, and other details were attended to so that no time should be lost in commencing work when the mirror was completed. As detailed in the description of the optical parts the mirror was completed early in April 1918 and was packed and shipped to Victoria.

The 72-inch mirror was left in the strong cast iron cell in which it had been ground and polished and a strong wooden cover was bolted on the open top of this cell, thereby

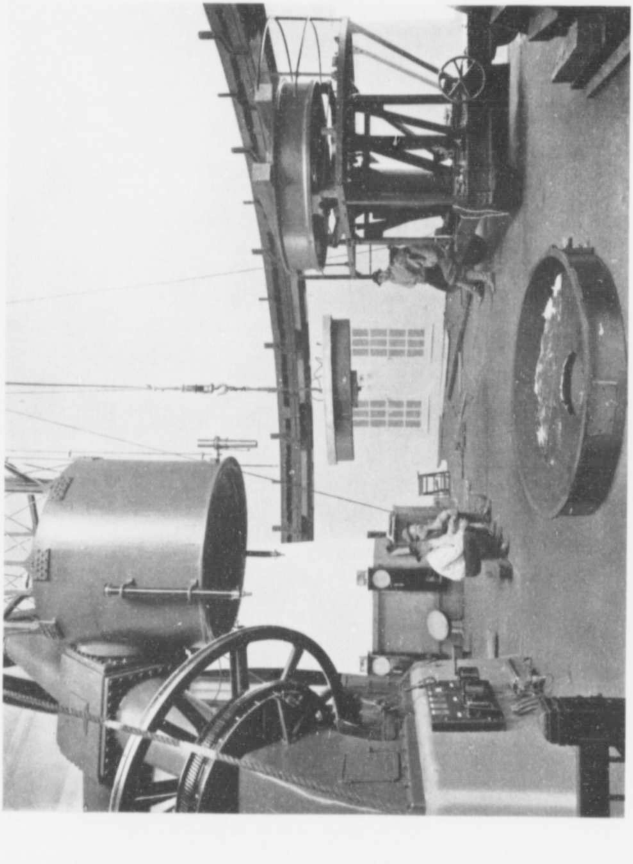

Fig. 3. Raising the Mirror.

completely enclosing the mirror. This was then packed in a large wooden box with excelsior, and it and the other optical parts were shipped by express in a through car to Victoria, so that no trans-shipment at any point was necessary. It went through without delay, arriving in Victoria on April 28, six days after leaving Pittsburgh, and was hauled out to the observatory the second day following without accident or hitch of any kind.

A very satisfactory and safe way of handling the mirror, placing it in its cell and installing on the telescope had been devised. No risk of accident could be taken and consequently great care in the selection of the hoisting apparatus, and in the hitches and fastenings required was exercised. The wooden box in which the mirror was shipped was about 7 feet 6 inches square and 2 feet deep, and in order to get inside the entrance door, was turned up on edge and run in on rollers. The opening in the observing floor through which it had to be lifted, was about 7 feet 6 inches by 3 feet 6 inches and would not allow the outer box to pass through. The Brashear Co. had provided a strong eyebolt screwing into one of the trunnions of the iron cell, and consequently the mirror, encased in its iron cell with wooden cover, was lifted the 21 feet to the observing floor on edge and gently let down, face up, on blocking.

In the meantime the mirror cell of the telescope had been removed from the tube and the wooden box filled with boiler punchings of the same weight as the mirror, which had been used to balance the telescope similarly to its final condition, was removed by means of the silvering car which is elsewhere described.

A good view of the silvering car and of the methods used in handling the mirror is given by the three photographs showing the installation of the mirror. The vertical truss supporting the outer end of the declination axis can be seen in Fig. 5, and when not used is pushed down in its guides below the floor and a cap placed in the opening.

The silvering car was used in the installation of the mirror, as the figures indicate. The mirror was lifted vertically upward between the tube and the silvering car, by tackle attached by an eyebolt to a padded wooden block below the central hole Fig. 3. The silvering car was then rolled on its track directly under the mirror, which was let down on the timbers shown in Fig. 4. Three shorter pieces of 6 by 6 timber were cut, placed vertically on the frame of the silvering car, passing up between the ribs of the cell. The plunger was then run downwards until the mirror was supported on these three timbers. The tackle and horizontal timbers were removed and the cell raised by the plunger slowly and steadily into position about the mirror. The only risk involved in this process was the chance of accident with the tackle, and a very large factor of safety had been provided. After the mirror was placed in its cell, in proper position with regard to its counterweighted bottom and edge supports, it was only a matter of half an hour to attach it to the tube and, although every precaution against accident had been taken, every one concerned felt very much relieved when the mirror was finally in place and the telescope at last completed.

It was only a week after the mirror reached Victoria until it was installed, collimated, and the first star spectrum obtained, which is, I think, a record-breaking performance for such a large telescope. Even though the mounting had been erected and adjusted, still all the tackle had to be placed and attached, the Cassegrain silvered and collimated

Fig. 4. Mirror resting on Cell on Silvering Car.

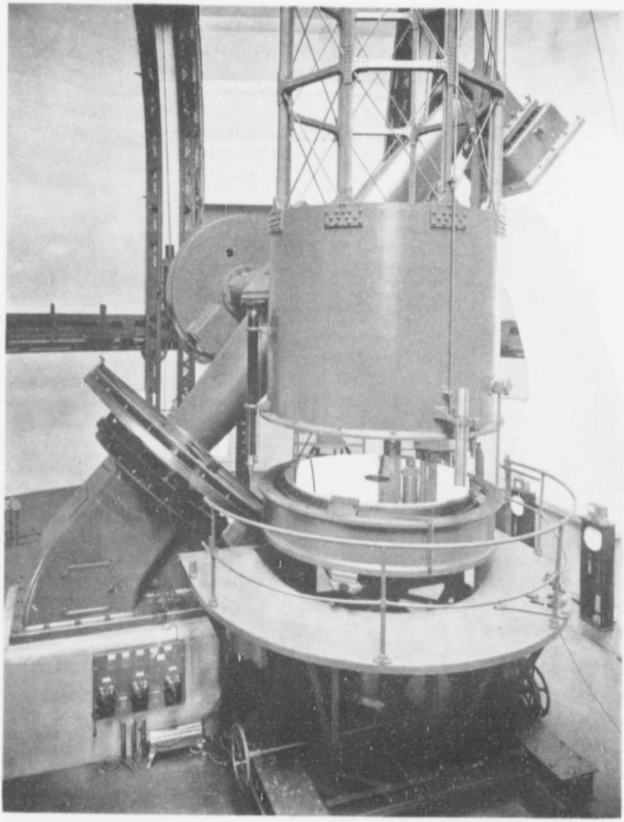

Fig. 5. Mirror and Cell ready to attach to Tube.

and the telescope rebalanced. I think it speaks volumes for the care used in the design and construction of the mounting and accessories, that there was no delay or hitch from any cause and that the telescope operated perfectly from the first without any alteration or further adjustment being required.

Chapter V—Description of the Optical Parts

The telescope was planned to be used in the Cassegrain or Newtonian form or directly at the principal focus to do away with the additional reflection. For the same reason, the presence of a central hole in the main mirror was deemed essential, as otherwise three reflections would be required with the Cassegrain form besides forcing the spectrograph into an awkward, unsymmetrical and inconvenient position at the side instead of being as now in a prolongation of the axis of the tube.

As previously mentioned strong objections were brought forward by Prof. Ritchey to the idea of having a central hole cast in the mirror on account of the probably non-homogeneous character of the resulting disc. But the great advantages of the direct passage for the beam from the Cassegrain made an opening through the centre of the main mirror so desirable that I decided to take chances on having a hole cast in the disc, as being less dangerous than attempting to bore one later, especially as the manager of the St. Gobain Co. did not seem to anticipate trouble. As matters turned out, the disc is a beautiful piece of glass with not a sign of a bubble or lack of homogeneity anywhere near the central hole.

The disc when received by the Brashear Co. in August 1914 was about 73½ inches in diameter, from 13 to 13½ inches thick and with a central cored hole tapered, irregular and slightly eccentric about 6 inches in diameter at one side of the disc and 8 inches at the other. The weight was very nearly 5,000 lbs. The appearance of the hole seemed to indicate that the core had been forced through after pouring rather than that the glass had been poured with the core in place. Even the first inspection before grinding showed the glass to be an exceedingly fine specimen when its size is considered, and this good opinion was enhanced when the surfaces were polished and the interior could be readily examined. Only at one place in the mass, a place near the edge and extending tangentially about six inches and radially two or three, are a few small bubbles. Elsewhere the material is remarkably free from bubbles or other defects and appears perfectly homogeneous and uniform. It is of course unnecessary to say that the few bubbles present will be absolutely without effect on the performance of the mirror.

Although the disc was apparently well annealed, the greatest care was used in the rough grinding process, especially around the central hole, to take off the outer skin slowly, and to avoid any temperature effects in the grinding. Over 600 lbs. of glass were removed in the grinding, the finished mirror weighing 4,340 lbs., being 12 inches thick at the edge, 73 inches in diameter, while the central hole was increased in size to 10⅛ inches in diameter to enable direct photographs to be made in the Cassegrain focus if desired.

In the preparation of the specifications questions had arisen as to the best thickness to make the mirror and many authorities favoured having it as thin as possible, consistent with maintaining its form during the figuring processes and when in use. The idea was that it would more rapidly assume the observing temperature and would not be so much deformed under changing temperature. My own idea was that, as it would hardly be safe to attempt to figure a mirror of this size if less than 8 inches thick, it might as well be 12 inches thick so far as accommodating the interior to changing temperature was concerned, while the greater stiffness as well as the greater distance between back and front would tend to diminish any deformations due to changing temperature. Consequently as the opticians preferred it to be as thick as possible to avoid danger of change of form during figuring and testing, the disc was left 12 inches thick.

After the disc had been rough ground all over, the back was fined and polished approximately flat and the front surface was fine ground to the correct radius, 720 inches, and polished.

The surface was polished and ready for the figuring in August 1915, about a year after the disc was received, but the actual figuring did not begin until about a year later. This was due to the fact that the material for the auxiliary testing plane which was to be 55 inches in diameter was not available. Various attempts were made to have such a disc cast in America and one was poured in 1916 at the works of the Pittsburgh Plate Glass Co. However, it devitrified in annealing and as the mounting was now being erected at Victoria, it seemed unwise to wait longer in the hope of getting a disc made.

Prof. Geo. E. Hale, director of the Mt. Wilson Solar Observatory, had kindly offered to loan the Brashear Co. the 60-inch plane used by Ritchey in parabolizing the 100-inch mirror. Unfortunately at the time it was needed at Pittsburgh, it was being used at Pasadena in parabolizing the 100-inch and would be required some months longer for the testing of the Cassegrain secondaries.

Hence it was decided after consultation with the Brashear Co. to go on with the parabolizing, depending upon measurements of the radius of curvature of different zones of the surface to obtain the required amount of parabolization and using a plane 33 inches in diameter which the Brashear Co. already had, and which had been proved very accurate, for detecting any slight zonal irregularities in the surface. Indeed as the hole in the main mirror was 10 inches in diameter, it is evident that this plane would more than cover a section along a radius and that theoretically at least it could be used for testing the whole surface. Practically, however, it was found that difficulties arose in attempting to use it wholly in the testing and some misleading results were obtained by its use. Consequently it was found necessary to depend chiefly on the tests at the centre of curvature, the difference of radius for different zones being computed and compared with the measured values, while the plane was chiefly used in testing the smoothness of the curvature and in detecting minor zonal irregularities.

This is quite in line with the experience of Prof. Ritchey in figuring the 100-inch mirror for, according to the 1916 report of the Solar Observatory, it was found that even with a 60-inch plane, considerably larger in proportion than the 33-inch with the 72-inch, the principal reliance was placed on tests at the centre of curvature.

A very convenient method of making these radius tests was devised by Dr. Brashear and merits description here. The whole surface of the mirror was covered by a paper diaphragm along the horizontal diameter of which a number of concentric slots were cut about an inch wide and six inches long. These slots were spaced every four inches along the diameter, thus enabling the radius of curvature of 8 zones of the mirror to be measured. These zones were spaced 35, 31, 27, 23, 19, 15, 11, 7 inches on each side of the centre and enabled the character of the correction obtained to be accurately determined. Each of these zonal slots was covered by a cardboard valve and these valves could be lifted by strings carried back to the centre of curvature enabling any particular zone to be uncovered by the measurer as desired. This was a great advantage over having all the zones uncovered as it removed all confusing effects and difficulties of identification and enhanced the ease and accuracy of determining the radius of any particular zone.

The artificial star was fixed in position near the centre of curvature, and instead of making micrometer measurement by the Foucault method of the position of the knife edge, it was fixed on an accurate and easy moving slide to which a short straight edge at right angles to the movement was attached. A piece of paper or card was pinned under this straight edge and when the position of equal darkening for any particular zone was determined, a line was ruled on the paper by a sharp pencil against the straight edge. When all the zones were measured there would be 8 transverse lines on the card whose positions could be compared at a glance with the positions of similar lines ruled on a card at the theoretically required distances. This method enabled the condition of the surface to be determined at a glance, was more direct, simple and rapid than micrometer measures and of practically equal accuracy.

Experience showed that these charts could be repeated with only very slight deviation and that the probable error of determination of radius of a zone would not exceed 0·01 inches equivalent to 0·0025 inches at principal focus. Naturally the radius of the outer zones, where the convergency of the pencils was greater, could be determined much more accurately than those nearer the centre.

The parabolization of the surface was begun about September 1916, was halted for two or three months by the cold weather of the winter and resumed in March 1917. The Brashear Co. expected to complete the surface in the spring or early summer of 1917 but unexpected difficulties arose, most of which were due to the presence of the central hole. This large opening, 10⅛ inches in diameter, necessitated the cutting away of a similar portion in the centre of the full-sized parabolizing tool and this caused an irregular and unexpected shape of the surface near the central opening. The only remedy was local polishing by smaller tools, and the surface was nearly finished in August 1917, when through some unexplained cause it became scratched. Although these scratches would not have affected the performance of the mirror, Mr. McDowell would not consent to allowing them to remain and the only recourse was to polish them out by a full size tool and refigure.

By October the surface was again nearly finished but unfortunately in smoothing up some minor irregularities produced in the local work, the centre was deepened too much, and although about 90 per cent of the usable surface was practically perfect, and the remainder not far out so that the mirror would have done excellent work, the

Brashear Co. were still unwilling to let it go and another fresh start was made. Although the cold weather was now coming on and the firm were very crowded by important war work the figuring of the mirror was persistently continued and profiting by past experience was finally completed on April 3, 1918.

I was summoned by telegram on March 20 to come to Pittsburgh and test the mirror as the Brashear Co. were undecided whether to continue the correction a little further or to allow it to remain as on that date. On arriving there on March 28, I found the outside zones practically perfect while there was a slight undercorrection in the inner 40 inches diameter. This undercorrection was equivalent to a longitudinal aberration at the focus of about half a millimetre, this part of the surface being of longer focus than the remainder. Although this is very small and would probably have no discernible effect on the definition, it was decided to see if the effect of changing temperature would tend to increase or diminish the error. A series of measurements of the radii of the various zones showed that all changes of temperature possible inside the testing tube appeared to increase the deviations from true figure and although the mirror would probably behave quite differently when silvered and under observing conditions it was considered that it would be preferable to reduce the undercorrection and to have the surface as nearly correct as possible under constant temperature.

Consequently local polishing on the required part of the surface was carried on for four times and on April 3, the mirror was considered finished as the measurements showed no deviation between the measured and computed positions greater than one millimetre, equivalent to a quarter millimetre at the principal focus.

The 72-inch mirror was then accepted and after silvering, was tested by the Hartmann method of extra focal images in the constant temperature testing tube at the Brashear factory. For this purpose a diaphragm of stiff manilla paper was stretched on a light wooden frame of such size as to cover the whole surface, and 60 circular holes about 1½ inches in diameter were cut in this diaphragm. These holes were spaced along 6 diameters of the mirror 30 degrees apart, 10 holes in each diameter and were so arranged that on each of 15 zones of the mirror, spaced 2 inches apart between a radius of 7 inches and a radius of 35 inches, were 4 holes on two diameters 90 degrees apart. Hence two measurements of the radius of each of the 15 zones at points on the mirror 90 degrees

Fig. 6. Images from Zone Plate.

apart could be obtained and complete information in regard to astigmatism as well as zonal aberration could be secured. The extra focal images, *a* and *b*, Fig. 6, taken at the principal focus give a good representation of the spacing of the diaphragm.

As a parallel pencil of 72 inches diameter could only be obtained in the testing tube by the aid of a 72-inch plane which was not available, it was necessary to make this test at the centre of curvature. Consequently an artificial star formed by an acetylene flame and a small pinhole was set up slightly to one side of the centre of curvature of the inner zones and a plate holder carrying plates 2 by 3 inches and held in a sliding frame was placed on the other side in a position to intercept the reflected pencil from the mirror. With the star fixed at twice the focal length from the centre, the intersections or foci of the pencils from the various zones do not all come to one point as in the case of a sphere but are spaced, with a paraboloid of revolution, at various points along the axis given by the formula $\rho = 2F + \frac{R^2}{2F} + \frac{R^4}{16F^3}$ where

ρ = Radius of curvature of zone of diameter 2R.
F = Focal length of mirror.
R = Radius of any zone of surface

or the intersections will be at distances of $\frac{R^2}{2F} + \frac{R^4}{16F^3}$ beyond the star.

These distances have been computed for the actually measured radii of the zones uncovered by the Hartmann diaphragm and are given in Table I. It is evident that at points a short distance inside and outside the position of the star the reflected pencils will form on a screen or plate an image or pattern somewhat similar to the diaphragm over the mirror but that owing to the spacings of the intersections over a distance of about 1·6 inches these will be differently distributed in the two positions of the plate, crowded together at the centre for the plate inside the focus and towards the outside for the plate beyond the focus. A reproduction of two of these plates are given at *c* and *d* Fig. 6 where *c* is the plate taken inside, *d* that outside the focus. Owing to this unsymmetrical arrangement and to prevent confusion of the images, it was necessary to separate the two positions of the plates to a much greater distance than would have been necessary if the test could have been made at the focus with parallel light. Observations with an ocular showed that the most advantageous positions were about 5 inches inside and 7 inches outside the focus. Several exposures were made at these two positions on both Seed 23 and Process plates. As there was no chromatic aberration, which in the case of this test with a lens tends to elongate the images, the resulting images were round, uniform and easy to accurately bisect in a micrometer miscroscope.

After the mirror was silvered it stood about 28 hours when the first series of plates were made in the evening hours. But as it was felt that perhaps the temperature conditions might not have been normal, owing to disturbances caused by setting up the apparatus, adjusting collimation, etc., a second series was made early the following morning after the tube had been undisturbed for over 10 hours. Six of these later plates were measured, three on each side of the focus, and the reliability of the determination was shown by the very close agreement of the measure of the different sets. As the plates were all made at the same distance inside and outside focus, the means of the three sets of measures were taken and the position of the intersection of the pencils from the different zones determined from these mean values. The principle of the method is very simple as is shown by the accompanying diagram. Fig. 7.

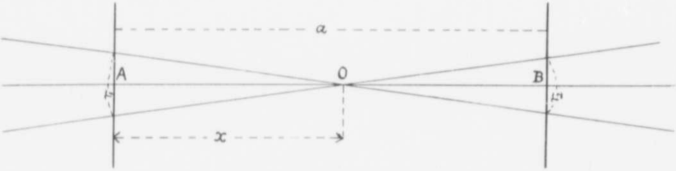

Fig. 7. Principle of Hartmann Method.

If the two pencils intersect in O, the distance between the plates A and B is a, and the distance apart of corresponding zonal images on A and B is r_1 and r_2 then from similar triangles the distance OA or x is obtained from $\frac{r_2}{a-x} = \frac{r_1}{x}$ or $x = \frac{ar_1}{r_1+r_2}$.

The results of the measures are given in Table I.

TABLE I—ZONAL ABERRATIONS OF 72-INCH MIRROR

Separation of Apertures in Zone Plate.		Computed Focal Distances.		Measured Focal Distances.		Residuals O–C.		Mean Zonal Difference.	Aberration at Focus.
1st Quad.	2nd Quad.	1st Quad.	2nd Quad.	1st Quad.	2nd Quad.	1st Quad.	2nd Quad.	Inches.	Millimetres.
70·10	70·12	1·702	1·703	1·689	1·680	−·013	−·023	−·018	−0·11
66·14	66·16	1·515	1·516	1·539	1·499	+·024	−·017	+·003	+ ·02
62·04	62·16	1·332	1·338	1·394	1·262	+·062	−·076	−·007	− ·04
58·12	57·98	1·169	1·164	1·152	1·129	−·017	−·035	−·026	− ·16
54·00	54·10	1·011	1·015	1·026	·983	+·015	−·032	−·008	− ·05
50·13	50·00	·870	·865	·884	·821	+·014	−·044	−·015	− ·09
46·12	46·01	·736	·732	·743	·730	+·007	−·002	+·002	+ ·01
42·09	41·98	·613	·610	·644	·596	+·031	−·014	+·008	+ ·05
38·00	38·00	·499	·499	·563	·513	+·064	−·014	+·039	+ ·24
34·12	34·12	·403	·403	·463	·405	+·060	+·002	+·031	+ ·19
29·96	30·06	·310	·312	·328	·295	+·016	−·017	·000	·00
25·94	26·24	·232	·238	·272	·215	+·040	−·023	+·008	+ ·05
22·06	22·00	·166	·167	·211	·145	+·045	−·022	+·011	+ ·07
18·12	17·96	·114	·111	·126	−·050	....	....	....	....
13·93	14·12	·067	·069	−·024	−·054	....	....	....	....

NOTE.—In this table the first two columns are the measured distances between the separate pairs of apertures in the zone plate, the angles between any two pairs in the 1st and 2nd quadrants being 90°. The third and fourth columns are the computed distances of the knife edge from the star, the latter being at the centre of the osculating sphere. The fifth and sixth columns contain the measured distances of the intersections of the pencils from the corresponding apertures, the zero point of the scale corresponding to the weighted mean position of best focus. The seventh and eighth columns contain the residuals between the computed and observed positions of the intersections for the various zones. The ninth column contains the mean zonal difference in inches and the tenth the deviation or aberration at the principal focus in millimetres.

As previously stated for every zone two measures are made in directions 90° apart. As the mirror was in a closed tube only two or three inches wider and higher than the mirror it is likely there would be some stratification of the air in horizontal layers and that the bottom of the tube would be the coolest and the top the warmest. Unfortunately no thermometers to determine the temperatures were available but the measures themselves show an indication of this effect. The diaphragm was so placed on the mirror that the one set of zonal openings were all situated in or within 30 degrees of the vertical plane and the other set in or within 30 degrees of the horizontal plane. The measures show that the residuals around the vertical plane are generally positive and those around the horizontal plane negative. The mean difference in focal length for the two planes is about a quarter of a millimetre, the focal length in the vertical plane being the longer and although such difference, if real, would have little effect on its performance, I am convinced that it is wholly a temperature effect. Indeed the zonal plates themselves show evidence of this as will be noticed in the reproductions in Fig. 6 where the asymmetry at the bottom is markedly shown. The effect is probably due partly to unequal differential refraction of the pencils in passing through the stratified layers and partly due to temporary astigmatic form produced in the mirror by the horizontal temperature gradients from bottom to top. The enormous quantity of polishing with a full-sized tool which was required to remove scratches inadvertently obtained at two stages of the figuring would ensure almost absolute certainty of the figure being a perfect surface of revolution.

That such is the case is seen below from the tests of the mirror in the telescope where, at any rate for the plates of May 19 where the temperature was practically stationary, there is little likelihood of unequal temperatures at different orientations and though there appear to be accidental and irregular small variations due possibly to errors of measurement, there is no indication whatever of any systematic differences or of any astigmatism in the mirror.

Consequently the mean value for the two sets was taken and the differences in inches at the centre of curvature for the different zones was reduced to residuals in millimetres at the principal focus.

It will be noticed that the residuals in the last column, (those from zones of 7 and 9 inches radius which are entirely covered by the shadow of the Newtonian and Cassegrain mirrors being not determined) representing longitudinal abberations at the principal focus, are remarkably small, the maximum 0.24 mm. for a zone 19 inches radius, and the mean less than 0.1 mm. These figures show that the surface is remarkably close to the theoretical form, with apparently little greater deviation than about an eighth of a wave length from the true paraboloid. This accuracy is much within the unavoidable aberrations produced by changing temperatures on the form of the surface and by unsteadiness of the seeing on the definition of the image and the mirror may be considered practically perfect.

These tests were made in the testing tube at the Brashear factory, where the daily change of temperature is very small, and it was not expected that the mirror could show the same perfection of figure under actual observing conditions. It was consequently a matter of great interest and importance to determine the figure of the mirror after it had been installed in the telescope when it was exposed to the changing temperature conditions in the dome, rising during the day and falling at night.

The mirror was finished on April 3 and at once silvered and as soon as the Hartmann test was completed the figuring of the Cassegrain secondary was begun. In order to test this surface during figuring a parallel pencil was needed and to provide this only the 33-inch plane was available. Consequently only a section of the Cassegrain along a radius could be seen in the test, less than half the diameter, and the difficulty of figuring and testing was much increased. Nevertheless the skill of Mr. McDowell soon overcame these difficulties and the figuring of the secondary only occupied about a week. This figure could not be tested by the Hartmann method in the optical shop but was tested later in the telescope with the result to be given below.

Immediately on completion, arrangements for packing and shipping were made and the principal and auxiliary mirrors left Pittsburgh on April 23 in a special express car, came through direct to Victoria without transhipment, arriving in six days, on April 29th. The mirror was soon installed on the telescope, a description of the method being given in another place, and the first test spectrum obtained on May 6.

Hartmann tests of the figure of the 72-inch mirror under actual observing conditions were made on May 12th and 19th. The same zone plate as used at Pittsburgh was placed over the surface of the mirror, the double slide plate holder placed on the focussing ring at the centre of the tube, which has a total movement of about 6 inches, hence enabling extra-focal photographs to be readily obtained. Exposures of 5 to 10 secs. on Vega or 30 seconds on a second magnitude star suffices to give good extra-focal zonal photographs on fine-grained plates and a set can be obtained in a few minutes. The distance inside and outside focus in this case when the photographs are practically replicas on a reduced scale of the zone plate is not very material but from an inch to an inch and a half both inside and out seemed to give the best defined and best measurable images, two of them being reproduced in Fig. 6, *a* inside, *b* outside focus. The measures of the plates in this case of course gave at once the residual zonal aberrations at the principal focus of the mirror without reductions as was necessary when the test was made at the centre of curvature.

The results obtained are particularly interesting and instructive as the test on May 12 was made under conditions representative of the average good night's temperature range while on May 19 the temperature variation was abnormally small, thus giving the figure of the mirror under average observing conditions, and again under nearly the ideal case of constant temperature.

The temperatures on the two days are given for short intervals in Table II and the times of tests are also indicated so that the temperature conditions surrounding the mirror can be seen at a glance.

TABLE II—TEMPERATURE CONDITIONS AT TESTS

May 12			May 19			May 19—con.		
Time	Temp.	Exposures	Time	Temp.	Exposures	Time	Temp.	Exposures
	F.			F.			F.	
6 A.M.	52°		Mt.	56°6		10.30 P.M.	53°6	
8 "	54·8		2 A.M.	56·0		11.00 "	53·5	Exposure 4
10 "	56·8		4 "	55·7		11.30 "	53·0	
12 "	58·2		6 "	55·7		12.00 Mt.	52·4	
2 P.M.	59·3		8 "	56·0		12.30	52·4	" 5
4 "	61·0		10 "	56·1		13·00	52·2	
6 "	62·0		12 "	56·1		14.00	52·1	" 6
7 "	62·0		2 P.M.	56·0		15.00	52·1	
8 "	61·0		4 "	56·0		16.00	52·3	
8.15 "	60·8	Dome opened	6 "	56·1		17.00	53·0	
9·10 "	56·9	Exposure 1	8 "	56·0	Dome opened	18.00	54·2	
9.30 "	56·3		8.20 "	54·4	Exposure 1	20.00	56·8	
10 "	55·8		8.30 "	54·0	" 2			
10.30 "	55·2		9.00 "	54·0				
11 "	55·1		9.30 "	54·0				
11.30 "	54·9	Exposure 2	10.00 "	53·9	" 3			

Table III gives the zonal foci for the two tests on May 12 and as in Table I the positions of focus are given for two positions at right angles to one another for each zone. This is done in order to show whether there is any sensible astigmatism in the surface.

TABLE III—ZONAL TESTS MAY 12

Radius of Zone	Exposure 1			Exposure 2			Differences of Focus	
	Focus Quad. 1	Focus Quad. 2	Mean Focus	Focus Quad. 1	Focus Quad. 2	Mean Focus	Exp. 1	Exp. 2
in.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.
35	45·75	45·81	45·78	43·23	43·44	43·33	0·00	0·00
33	46·26	45·74	46·00	44·03	43·50	43·76	·22	·43
31	46·08	46·34	46·21	43·87	43·96	43·81	·43	·48
29	46·81	46·42	46·61	44·06	43·83	43·94	·83	·61
27	46·84	46·75	46·80	44·51	44·18	44·34	1·02	1·01
25	46·87	47·52	47·20	44·51	44·77	44·64	1·42	1·31
23	47·68	47·11	47·40	45·11	44·84	44·97	1·62	1·64
21	48·05	47·03	47·54	44·98	44·98	44·98	1·76	1·65
19	47·41	48·04	47·72	45·02	45·35	45·18	1·94	1·85
17	48·02	47·48	47·75	45·56	45·00	45·28	1·97	1·95
15	47·92	48·07	47·99	45·09	45·27	45·18	2·21	1·85
13	47·94	48·83	48·23	44·52	46·05	45·28	2·45	1·95
11	49·79	48·92	49·35	46·55	45·21	45·88	3·57	2·55

TABLE IV—ZONAL TESTS MAY 19

Radius of Zone	Foci at Exposure 2			Mean Foci at Exposures			Differences of Focus at Exposures			
	Quad 1	Quad. 2	Mean	3	5	6	2	3	5	6
in.	mm.	mm.								
35	44·11	43·89	4·00	3·65	3·09	2·93	0·00	0·00	0·00	0·00
33	44·50	44·74	4·62	4·08	3·52	3·51	·62	·43	·43	·58
31	44·52	44·45	4·48	4·07	3·54	3·33	·48	·42	·45	·40
29	44·30	44·41	4·36	3·82	3·31	3·07	·36	·17	·22	·14
27	44·61	44·57	4·59	4·04	3·30	3·00	·59	·39	·21	·07
25	44·74	44·54	4·64	3·90	3·35	3·05	·64	·25	·26	·12
23	44·67	44·73	4·70	4·17	3·60	3·33	·70	·52	·51	·40
21	44·99	44·64	4·81	4·25	3·34	3·26	·81	·60	·25	·33
19	44·97	44·82	4·89	4·25	3·51	3·25	·89	·60	·42	·32
17	44·80	44·54	4·67	4·07	3·48	3·13	·67	·42	·39	·20
15	44·98	44·47	4·67	4·00	3·44	2·91	·67	·35	·35	− ·02
13	45·03	44·29	4·66	3·91	3·36	2·96	·66	·26	·27	+ ·03
11	44·69	44·66	4·67	3·80	3·15	2·13	·67	·15	·06	− ·80

Table IV gives the zonal foci for four tests on May 19 when the temperature was nearly constant but in only one of these are the positions given for the two quadrants as the other three are practically similar.

An examination of Tables III and IV in comparison with Table I is illuminating as showing the effect of changing temperature on the figure of the mirror. On May 12 the dome temperature had gradually risen from 52° F. at 6 A.M. to a maximum of 62° at 6 to 7 P.M. and, when the dome was opened at 8.15, the temperature had fallen to 60°.8. When the first exposure was made about an hour later, it is hardly probable the decreasing temperature had been acting sufficiently long to change the figure appreciably and the resultant under-corrected figure, over 3 mm. longer focus at centre than edge, is due probably to the increase in temperature in the dome during the day. At the second exposure made 2 hours and 20 minutes later, the decreasing temperature has begun to show, and the positive aberration, under-correction, is slightly reduced.

On May 19th when the temperature had been practically constant throughout the day and had only dropped about 2° in the half hour between the opening of the dome and exposure 2, the first measured, the figure is very nearly normal and were it not for the outer zone of 35 inches radius, would be practically perfect. The same is true for all the exposures although the focal length of the centre is continually shortening relatively to the edge under decreasing temperature. The action of falling temperature on the mirror evidently is to introduce negative aberration and to apparently curl up the outer edge, the exact opposite of what might be expected. It appears almost as if the contracting action which must take place more strongly at the exposed edge of the mirror acts in the greatest degree about two inches in, leaving the extreme edge curled up. This curling up of the edge remains persistent and of about the same extent over about 8 hours exposure to decreasing temperature. The general change in the figure during exposure to the night sky, however, seems relatively small, and it appears that, if the daily rise of temperature could be diminished, the working figure would be much improved.

It will be noted, Tables III and IV, where the figures are given for the separate quadrants, that there is no evidence of astigmatism and that the difference appearing in the test at the optical shop must have been due to stratification and changing temperature gradient in the tube and mirror. Especially in exposure 2 in Table IV, where the mirror except at the very edge must have been nearly normal in temperature, are the differences between the two quadrants very small and quite accidental in character and the general figure, obtained in the tests on May 19 at the principal focus under constant temperature and that in the optical shop at the centre of curvature, agree closely with one another and indicate a remarkably good figure.

The result of these tests then was taken as indicating the necessity of some device, such as the "canopy" used on the Mt. Wilson 60-inch reflector, to diminish the rise of temperature around the mirror during the daylight hours. Considerable thought was given to the best method of accomplishing this. The arrangement of mounting and dome made a suspended canopy impracticable and it was at first planned to make a box in two halves with refrigerator walls, mounted on castors to be rolled up to the tube placed in the vertical position, encircling it and covered over at the top of the closed section by a removable pad of blankets. But these two sections would be unsightly, bulky, cumbersome and difficult to get out of the way when observing.

The plan of placing a permanent insulating cover entirely surrounding the lower closed section of the tube containing the mirror was finally decided on and the encasing of the mirror was made complete by similar permanently placed insulating material at the bottom of the cell and a removable pad of woollen blankets placed on light boards laid over the top of the closed section of the tube. In addition, insulating felt was packed all around the edge and bottom of the mirror so that radiation could only take place from the silvered surface and this, owing to the polish, would be very slow.

The insulating material employed was the cotton felt used in making mattresses. The conductivity of this felt is not much greater than wool and its cost is less than one-fourth. Quilted pads about two inches thick covered with heavy cotton were made of this material and the outer cylindrical sections of the cell and central section of the tube were covered from top to bottom. These pads were covered with a close-fitting cover of khaki-coloured duck laced tightly over the padding, making a permanent and neat looking job. Similar pads were placed directly above the circular metal plates covering the bottom of the cell and the space between these pads and the mirror was completely filled in with the felt. Similarly around the edge of the mirror between it and the cell, pads of the felt were placed above the counterpoise ring extending up to the very edge of the surface while below these pads the space between cell and mirror was completely filled in with the loose cotton.

The mirror and closed section of the tube were now completely encased in insulating material with the exception of the top which, during observing, must of course be open to the sky. As previously stated, this was covered during the day by a removable pad of three thicknesses of the best woolen blankets laid on light boards placed across the top of the central section.

There is hence enclosed within this protective covering 12 tons of steel and 2 tons of glass and the quantity of heat stored there makes the change of temperature within the insulator very slow. Tests with a thermograph inside have shown that in general the change of temperature around the mirror is only about one-third that in the dome. In practice, as the cover is put on as soon as observing is finished in the morning, slightly above the minimum temperature reached during the night, and as the range inside is about one-third of that in the dome, the mirror is hence, when the dome is opened, usually from 2° to 3° F. below the temperature at the beginning of observing. As the average fall from then until dawn is about 5° F., it is evident that there is never any high temperature gradient between the mirror and the surrounding air, that all except the slowly radiating upper surface is protected by felt and that hence the changes in figure will be slow.

Practical experience has shown that the performance is much improved and that the aberration present in the mirror is generally negligible. Hartmann tests have only been made on two nights since the covers were applied. On September 26, 1918, the general temperature, interrupted of course by the usual daily increase and decrease, had been gradually rising from 52° F. on Tuesday, September, 24 at 6 A.M. to 58° on Thursday, September 26 at 6 A.M. Both Tuesday and Wednesday had been cloudy and when the sun came out on Thursday morning the temperature in the dome rose from 58° at 6 A.M. to 71°.4 at 5 P.M., an unusually large change and a much severer test on the figure than it is normally exposed to. A thermograph placed inside the tube near the mirror had risen from 55°F. on Tuesday at 6 A.M. to 62° F. on Thursday at 7 P.M. when the dome was opened. On being placed outside the tube in the dome it immediately rose 6° showing that the dome temperature was about 6° above that of the mirror. Nevertheless the previous change around the mirror had been slow and, even with this great difference the protection of the felt around edges and bottom and of the silver on the top seemed to keep the change gradual enough to prevent much distortion. Table V, which contains the result of two Hartmann tests on this date, the first one hour, the second two and a half hours, after the mirror was open to the sky, shows that the aberration even under these unusually severe conditions is quite moderate, less than one-half that on the unprotected mirror on May 12 with a much smaller change of temperature, and that the mirror has a good working figure.

Similarly on April 29, 1919, another Hartmann test was made at the principal focus. In this case the temperature during the early morning hours from 3 A.M. to 7 A.M. had been practically constant at 48°.5 F. The insulating cover was not placed over the top until about 10 A.M., when the temperature had risen to 53° F. The mirror was opened to the sky at 9 A.M. to test the collimation of the secondary when the temperature was at 52°.3 and closed and covered at 10 A.M. From then until 6 P.M. the temperature gradually increased to 57°.5 when the dome was opened. When the mirror was uncovered at 7 P.M. the dome temperature was 55°.5, at 8 P.M. 54°.0, at 9 53°.8, and from 10 P.M. until 1 A.M. remained practically constant around 53°.0. Hartmann tests were made at the Cassegrain focus between 9.35 and 10.15 and at the prime focus between 12.00 and 12.45. The results of the latter, also given in Table V, show a very good working figure.

TABLE V—ZONAL TESTS SEPTEMBER 26, 1918, AND APRIL 29, 1919.

FOCI IN MILLIMETRES.

Radius of Zone	Sept. 26, 1918 Foci at Exposure 1			Exp. 2	Foci on April 29, 1919			Differences of Focus		
	Quad. 1	Quad. 2	Mean	Mean	Quad. 1	Quad. 2	Mean	Sept. 26, 1	Sept. 26, 2	Apr. 29
in.										
35	33·52	33·90	33·71	33·90	29·80	29·96	29·88	0·00	0·00	0·00
33	33·69	33·82	33·75	34·02	30·45	30·16	30·30	0·04	0·12	0·42
31	33·82	33·41	33·61	33·92	30·34	30·18	30·26	−0·10	0·02	0·38
29	33·59	33·68	33·63	33·70	29·83	30·34	30·08	−0·08	−0·20	0·20
27	33·64	33·74	33·69	34·10	30·22	30·25	30·23	−0·02	+0·20	0·35
25	33·90	34·34	34·12	34·28	30·49	30·39	30·44	+0·41	0·38	0·56
23	34·23	34·01	34·12	34·57	30·28	30·82	30·55	0·41	0·67	0·67
21	34·09	34·16	34·12	34·67	30·34	30·66	30·50	0·41	0·77	0·62
19	34·69	34·60	34·64	34·92	31·19	30·79	30·99	0·93	1·02	1·11
17	34·51	34·89	34·70	35·10	30·49	31·03	30·76	0·99	1·20	0·88
15	34·85	34·76	34·80	35·04	30·71	31·09	30·90	1·09	1·14	1·02
13	35·61	34·15	34·88	35·63	31·24	30·95	31·09	1·17	1·73	1·21
11	35·58	35·81	35·69	36·54	30·80	31·84	31·32	1·98	2·64	1·44

The results of these tests are also shown graphically in Fig. 8 where the ordinates represent the positions of focus in millimetres, the scale being indicated on the figure, of the various zones shown as abscissae, the edge of the mirror being at the left. The cross-sectioned parts at the bottom represent the relative positions of principal and Cassegrain mirrors.

The straight line at each curve represents the weighted mean position of best focus, taking account of the relative areas of the different zones. Distances from this line to the curve represent the deviations of the foci for the different zones, above the line longer focus, below the line shorter focus.

The change from the shop test at constant temperature to that of May 12 where practically the maximum range at Victoria was present is very marked as is also the great improvement when the temperature change was very small on May 19. After the insulating cover was applied the effect of the greatest probable temperature change is shown by the test of September 26, while the figure under average working conditions probably closely approximates that of April 29, 1919.

There seems no doubt that the introduction of the insulation has markedly improved the performance, reducing the aberration to nearly one-third of the former amount. There further seems no doubt that rising temperature produces positive aberration, falling temperature negative aberration, that the amount and the rapidity of the change is dependent on the temperature gradient, but that in no case, with the temperature changes taking place at Victoria, will the mirror be distorted sufficiently (since the insulation has been applied) to appreciably affect the definition.

If we compute the circle of confusion arising from the zonal aberrations at constant temperature, considering only the geometrical theory, the diameter will be approximately

0.025 millimetre, 0.001 inch, only a fraction of the diameter of the tremor disc caused by atmospheric disturbances. Similarly, if the departure from the paraboloidal form due to a zonal longitudinal aberration of 0.25 millimetre for a zone 19 inches radius and 2 inches wide be computed, we find a deviation of the surface from the true form of about one-eighth of a wave, considerably within the theoretical limits of the quarter wave required to give good definition.

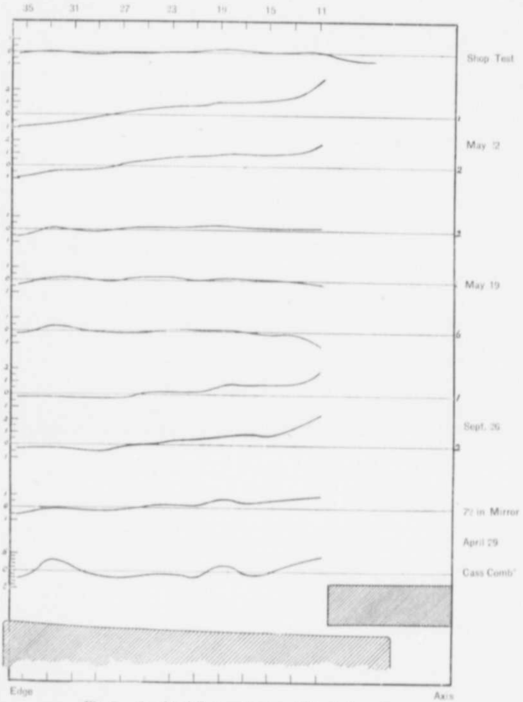

Fig. 8. Graphical Representation of Zonal Aberrations.

The mirror, as the tests show and as its use has proved, has a remarkably fine figure. The telescope has not yet been used much at the principal focus of the main mirror and only a very few direct photographs have been obtained. These few, however, are sufficient to show that the star images are very small and sharp, when the seeing is good the minimum diameter being only slightly over one second of arc, and that beautiful photographs of nebulae and clusters can be obtained. No zonal measurements that I am aware of have been published for any other large mirror but the 100-inch, where the maximum deviation was 0.15 millimetre, somewhat smaller than the 72-inch, but the much greater relative stiffness and thickness of the latter will probably enable it to withstand the changes of temperature encountered under observing conditions much better.

The Brashear Co. are to be congratulated on producing such a fine surface under such difficult and trying conditions and it is only right that I should express my appreciation to them collectively and individually for their successful efforts. The presence of the hole in the centre of the mirror doubled, according to their estimate, both the difficulty and the time of figuring. Towards the last the tremendous pressure of war orders, with the difficulty of getting suitable optical glass, and the uncertainty as to how long it would take to complete the mirror made the figuring, always a nervous strain, doubly trying. I am glad to take this opportunity of expressing my appreciation of their persistence with the work until their efforts were crowned with such notable success. Dr. Brashear himself, although of late not participating actively in the optical work, was much interested in this surface and not only prepared all the tools but rough and fine ground and polished the mirror. Many of the methods of handling and testing are due to his ingenuity. The burden of the figuring was, however, taken by Mr. James B. McDowell, the secretary and manager of the company, ably assisted by his chief optician, Mr. Fred. Hagemann. It is due to Mr. McDowell's skill and persistence in the face of difficulties that the surface was finally brought to such a satisfactory finish. Much of the figuring was done by him personally, and although at the last his other duties were too pressing to permit of this, he always tested after working and decided on and directed Mr. Hagemann as to the next stage. The final touches were given by Mr. Hagemann, who by great skill in local polishing as it was not possible to get the figure by large tools, gradually brought the surface to the accuracy given by the tests and at the same time maintained its smoothness and regularity of figure.

I am convinced, after their experience and success with such a large and difficult piece of work, no one need be uncertain as to the outcome and quality of any optical work entrusted to them.

As previously mentioned, the figuring of the Cassegrain mirror required about a week's work by Mr. McDowell. Owing to the relatively small size of the auxiliary plane, its aperture being only 0.46 that of the principal mirror, less than one-half the diameter, one-fourth the surface of the Cassegrain, could be seen when the knife edge test was made. It was consequently not an easy matter to determine exactly what the shadow figures produced in this test represented nor what should be done to the mirror to improve them. Nevertheless, the skill and experience of Mr. McDowell overcame the difficulties and the secondary was declared completed after a week's figuring.

Evidently no Hartmann test of the combination could be carried out with a parallel beam only 33 inches in diameter and as there was a provision in the contract requiring the refiguring of the Cassegrain by the makers, if found desirable after the test of actual use, I had no hesitation in accepting this mirror.

The relative smallness of the star images given by the combination, considering the great equivalent focal length of 108 feet, made it evident that the figure of the Cassegrain must be good and no tests were made until January, 1919. The same zone plate was placed over the principal mirror, the telescope turned to α Persei, then not far from the zenith, and exposures made on small plates inside and outside the focus. When plates inside the focus were obtained, the image was focussed on the spectrograph slit and the appearance of the zonal images could be examined by the auxiliary telescope used for visual observations and the plate rested on the reflecting prism cell on the end of this telescope for making the exposures. When outside the focus, and this effect was produced by changing the position of the secondary mirror, raising it until it was approximately in focus in the visual telescope, the appearance of the extra focal image could be observed in the spectrograph guiding telescope, the plate placed on the slit cap and the exposure made. The separation of the position of the two exposures was determined from the measured separation of any pair of zonal images, the distance apart of the corresponding openings in the zone-plate, and the known focal length, 108 feet, of the combination. The separation required, owing to the comparatively large size of the zonal images, was large, about 400 millimetres, as compared with about 60 at the principal focus. The diffuse character of the images was probably due to the apertures in the zone-plate being too small for the increased focal length, resulting in an increase in diffractional spread and rendered the plates difficult to measure with some loss of accuracy. However, the mean of two sets of measures of January 6 and of two sets on April 29 had fair interagreement as seen in Table VI and the final results probably represent the figure very closely. As is evident from a comparison of the results at the principal and Cassegrain focus on April 29 obtained from Tables V and VI and exhibited graphically in the two lower curves of Fig. 8 the aberrations in the two cases are quite similar and it is evident that the Cassegrain mirror reproduces and magnifies, even when reduced in scale corresponding to the relative focal lengths as has been done in the figure, the aberrations of the principal mirror. Unfortunately on January 6 no test was made at the principal focus and the figure of the principal mirror can only be surmised from that of the combination.

Nevertheless, the deviations which occur and the increase of relative aberration with the combination, which are in just the positions and of the order that would be produced if the correction of the secondary had not been carried sufficiently far, indicate a possibility of improvement. If the convex curve of the secondary were made a little flatter in the zone corresponding to a radius of 30 to 34 inches on the principal mirror, and also nearer the centre for zones on the principal mirror from 11 to 20 inches radius the figure would probably be improved but whether the actual images would be better and the spectrographic exposure time appreciably diminished is questionable. Normally, owing to atmospheric disturbance with such a large aperture and great focal length, the image is much larger than that due to the amount of aberration present and improvement in the figure now already very good would make little difference. In the not frequent instances when the "seeing" is very good there might be some improvement but as at these times practically the whole visual image disappears in the slit opening, which is about 0.3 seconds wide, probably also the exposure would not be much shortened.

TABLE VI—ZONAL DIFFERENCES OF FOCUS OF CASSEGRAIN COMBINATION

	January 6			April 29			Aberrations Cass.		Aberrations Prin. Mirror Apr. 29
	1	2	Mean	1	2	Mean	Jan. 6	Apr. 29	
35	9·18	10·35	9·76	1·13	1·65	1·39	−1·06	−1·79	−0·46
33	10·11	13·70	11·90	5·85	6·73	6·29	+1·08	+3·11	−0·04
31	8·76	11·67	10·21	4·41	4·59	4·50	−0·61	+1·32	−0·08
29	7·45	10·40	8·92	1·87	2·02	1·94	−1·90	−1·24	−0·26
27	7·13	10·07	8·60	1·10	1·50	1·30	−2·22	−1·88	−0·11
25	8·27	11·20	9·73	2·04	2·58	2·31	−1·09	−0·87	+0·10
23	9·69	12·67	11·18	2·68	2·51	2·59	+0·36	−0·59	+0·21
21	9·58	12·86	11·22	1·46	2·15	1·80	+0·40	−1·38	+0·16
19	11·67	14·87	13·27	4·63	5·33	4·98	+2·45	+1·80	+0·65
17	11·53	15·11	13·32	2·44	3·19	2·81	+2·50	−0·37	+0·42
15	13·25	16·50	14·87	2·04	3·91	2·97	+4·05	−0·21	+0·56
13	13·93	17·77	15·85	5·87	5·03	5·45	+5·03	+2·27	+0·75
11	15·12	21·26	18·19	8·27	6·28	7·27	+7·37	+4·09	+0·98

The test of actual use has shown that the images must be very good indeed for the spectrographic exposures are relatively short. The exposure times required depend upon the "seeing" to a much greater extent than is the case with a smaller telescope. At Ottawa with the 15-inch telescope of about 19 feet focal length, "seeing" conditions, provided there was no haze or cloud, had little effect on the exposure time, an increase of about 50 per cent being the maximum required in poor "seeing". At Victoria where the aperture is 72 inches and the focal length 108 feet, nearly 6 times that at Ottawa, the image for any disturbance becomes relatively much more enlarged and in very bad "seeing", fortunately very rare, the exposure times may be as much as 4 or 5 times the normal required in fair "seeing".

The spectrograph, which is now being used with one prism and a medium focus camera, gives a linear dispersion at Hγ of about 35 A per millimetre. In good "seeing" a well exposed spectrogram of a star of photographic magnitude 7.0, with a slit width of 0.05 millimetre., 0.3 seconds at the Cassegrain focus, can be obtained in 20 to 25 minutes If the star is of type A or B with only broad hydrogen or helium lines, it is generally found desirable to give about 50 per cent more exposure, making the spectrum wider and stronger, in order to render the measurement more easy and accurate. A star of 6.0 photographic magnitude at Ottawa required about 2 hours exposure, from 12 to 15 times that required at Victoria It has usually been considered owing to the atmospheric disturbances, "tremor disc" conditions, that as the aperture is increased the best that can be hoped for, so far as decrease in exposure time is concerned, is that the gain may be proportional to the ratio of apertures not areas. In these two cases the ratio of apertures are as 4.8 to 1 and of areas as 23 to 1 The gain in exposure time is about three times the ratio of apertures and one-half the ratio of areas, a remarkably favourable showing when the great focal length and consequent increase in linear scale of the image is considered. I believe, if as efficient a spectrograph could be placed at the focal plane, that owing to the smaller linear scale of the star image as well as to the superior optical properties of the main mirror over that of the combination, spectrograms with exposures nearly inversely proportional to the areas could be obtained

There can be no doubt that although it might be possible to theoretically improve the figure of the Cassegrain, it is questionable whether much practical improvement so far as shortening the exposure time on spectrograms would be effected. There is further no doubt that the effect of the ordinary temperature changes on the figure of the combination which, though undoubtedly chiefly acting on the principal mirror, yet the aberrations produced therein are magnified by the secondary, give deviations of greater magnitude than those produced by the under-correction of the Cassegrain. And even the influence of these temperature effects is entirely overshadowed by the increase in size of image produced by even a slight falling off in " seeing " conditions.

The Newtonian mirror which is the same size as the Cassegrain, 19.5 inches diameter, 3.25 inches thick, was tested in the usual way at the optical shop and indirectly tested by the Hartmann method during the process of testing the 72-inch. For some of the zonal test plates were made at the Newtonian focus and some with the flat removed, directly at the principal focus and no effect whatever of the presence of the flat could be seen in any difference or deviation produced in the measures. It is of course self-evident, as no magnification is given by the flat, that any deviations of figure will have only one-fourth the effect on the image that they have in the Cassegrain and, as the flat is undoubtedly correct within less than a quarter wave, its figure is practically perfect.

In order to be able to make visual observations at the Cassegrain focus without removing the spectrograph, which would mean considerable loss of time on Saturday nights when the public have the privilege of observing with the telescope, a special observing telescope was designed. This telescope has a reflecting prism of 2 inches aperture at its inner end, a symmetrical triplet objective of 2½ inches aperture 12½ inches focus midway, with conjugate foci at prism and ocular, and the ocular at the outer end of the tube This telescope screws, perpendicular to the optical axis, by bayonet joint into an opening in the side of the spectrograph frame above the slit, and can be attached and detached in a moment. The image formed on the upper face of the prism is transferred by the triplet to the focal plane of the ocular and can be observed there just as if the ocular were directly in the axis. The focussing of the image is effected as previously indicated by moving the secondary in and out by a hand wheel close to the visual ocular and to the guiding telescope of the spectrograph.

A full set of special three-lensed oculars from 0.25 inches to 4 inches focus, those longer than 1 inch having field lenses of from 2 to 2¼ inches aperture are provided and these are arranged to be conveniently used at either the principal, Newtonian or Cassegrain foci.

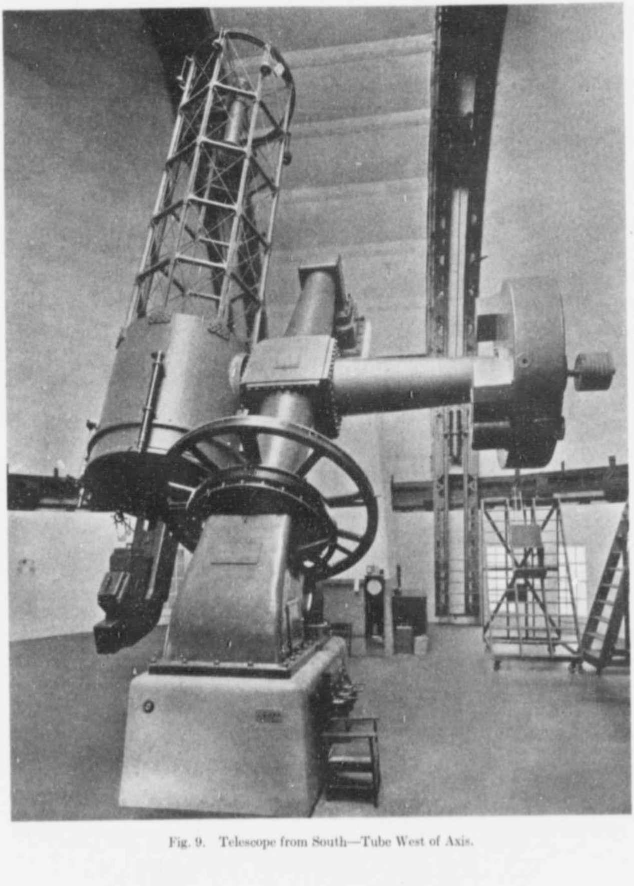

Fig. 9. Telescope from South—Tube West of Axis.

Chapter VI. Description of the Mounting

The mounting of the 72-inch telescope is similar in its general features to that of the Melbourne 4-foot, the Ann Arbor 37-inch and the Crossley 36-inch reflectors. It consists essentially of a long polar axis mounted on separate piers, the declination axis crossing the polar axis about midway, with the tube on one side and the housing containing the mechanism for moving the tube in declination on the other. A good idea of the general form of the mounting can be obtained from the illustrations, Figs. 9, 10, 11 which well show the harmonious and well balanced proportions of the design.

THE TUBE

The tube of the telescope is in three sections, the central section which is attached to the declination axis, the lower section or mirror cell which carries the principal mirror, and the upper section or skeleton tube which carries attachments for use at the prime focus and for holding the Newtonian or Cassegrain mirrors.

The central section of the tube is a large heavily ribbed steel casting of cylindrical form with a large boss 41 inches diameter near the upper end of the cylinder to which a flange on the end of the declination axis is firmly bolted. This steel casting which weighs 7 tons and is exceptionally solid, homogeneous and thoroughly annealed, is 7 feet 4 inches outside diameter, 6 feet 1½ inches high, has a flange 7 feet 10 inches diameter at the lower end to which the mirror cell is bolted and another internal flange at the upper end to which the skeleton tube is firmly attached. These two flanges were turned perfectly parallel and concentric and the boss, to which the declination axis is attached, bored and faced at right angles to these flanges in one of the large boring mills at the Bethlehem Steel Works where this and the other large steel castings were made and machined. Both the castings and the machine work are of the highest grade and contribute greatly to the success of the mounting.

Near the lower end of this central section is placed the shutter whose purpose is to tightly enclose the mirror and protect it from dust and moisture. It consists of 12 sector shaped steel leaves attached at their bases to 12 short shafts which rotate in bearings spaced around the periphery of the lower end of the centre section. These 12 shafts are connected together by universal joints and a worm wheel firmly keyed to one of them can be rotated by a worm and shaft geared to a handwheel at the lower end of the mirror cell. By turning this handwheel the 12 leaves can be quickly raised and lowered simultaneously. As the sharp edge of one leaf dovetails into a V-shaped groove in the adjacent leaf perfectly tight joints are formed. When closed down, these leaves are not flat but stand at an elevation of about 30° in the centre. They hence make an immensely strong arch and form a perfect protection for the mirror surface against any accident or falling body.

The mirror cell, also an annealed steel casting, of the same diameter as the central section, is bolted to the latter through the common flange by 16 bolts It has radial and concentric ribs, cast integral with the cylindrical part, on which are mounted the

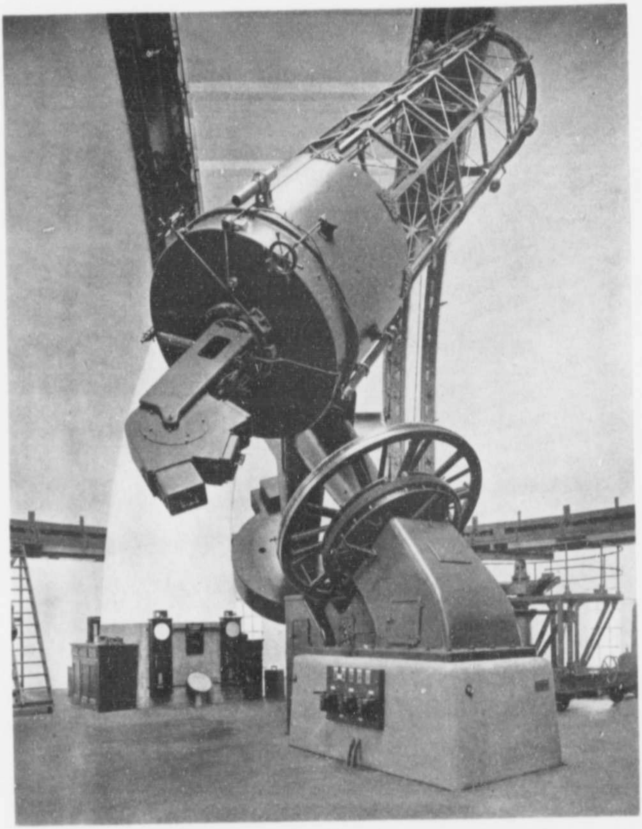

Fig. 10. Telescope from South—Tube above Axis.

bottom supports of the mirror. These consist of 12 circular pads of open section about 12 inches in diameter the circumference about 1½ inches wide being faced with cork and bearing against the back of the mirror. These twelve pads are so distributed that each supports its proper proportion of the weight of the mirror. Three of them are rigidly connected with the ribs of the cell by a screw adjustment which enables the mirror to be collimated in the tube. The remaining nine are counterbalanced by levers and weights so designed that each sustains one-twelfth of the resolved weight of the mirror whatever the position of the tube. These twelve pads hence maintain the mirror in collimation along the axis of the tube and at the same time so support and float it in the cell that no chance of flexure exists.

For collimation and support perpendicular to the axis a similar counterbalancing system is provided. A large ribbed bronze ring lined with cork surrounds the edge of the mirror midway. This ring is in four sections and can be adjusted by liners between the sections so as to just fit without strain At twelve equidistant positions around this ring are attached twelve weighted counterbalancing levers also so designed as to exactly support the resolved component of the weight of the mirror perpendicular to the axis. Hence the mirror is floated in the cell without strain or tendency to distortion in every position. It is maintained in position laterally by four blocks, 90° apart. Two adjacent ones are fixed to the cell while the opposing two maintain the mirror in contact with the fixed blocks by means of springs, which, as the whole weight of the mirror is supported by the counterbalancing ring, need only exert slight pressure This method of counterbalancing is similar to that employed by Ritchey with the 60-inch Mt. Wilson telescope, and, although the weakness of the material in the 100-inch necessitated another form of edge support, I believe the one here is much more suitable for the 72-inch mirror and it certainly seems to work beautifully. Four safety blocks firmly attached to the cell are provided so that the mirror can not fall forward in case the tube becomes depressed below the horizontal.

At the lower side of the cell, which, with the exception of a central aperture the same size as the hole in the mirror, is entirely covered with a sheet steel plate, is attached a solid cast iron ring about 30 inches diameter which can be rotated around the axis, by means of a worm gearing into teeth cut in the periphery, to any desired orientation, read on a graduated circle. To this ring the spectrograph or any other attachment such as the double slide plate holder can be attached and oriented as desired.

The upper or skeleton section of the tube is built up of structural steel It is an octagonal prism 7 feet 4 inches outside diameter and 23 feet 4 inches long, fitted with a 3-inch circular channel at top and bottom, the four intermediate sections being octagonal and built up of 3-inch I-Beams The main members which extend uninterruptedly the whole length are eight 3-inch I-Beams. These main members are firmly connected to the top and bottom channels and to the intermediate sections by steel tee and cross-shaped plates inside and out firmly rivetted to the channels and I's. The heavy T-shaped plates at the bottom are securely bolted to the central section both inside and out, further security at this vital point being obtained by bolts through the channel and corner steel castings.

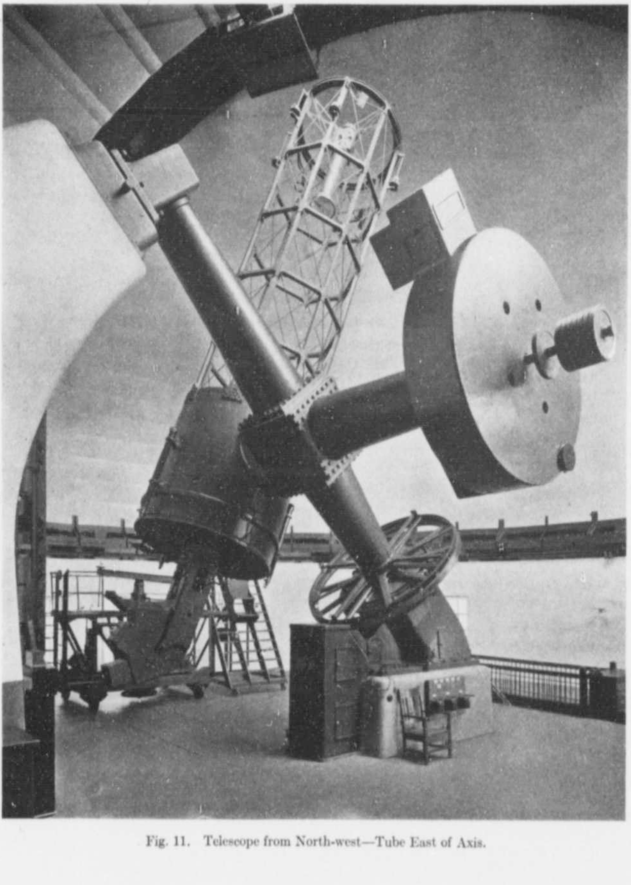

Fig. 11. Telescope from North-west—Tube East of Axis.

The design of this tube is a marked improvement over any other reflector skeleton tube in the original method employed of rendering it exceedingly stiff and rigid. It is undoubtedly relatively lighter and at the same time stiffer than any hitherto produced. It has besides the further advantage that it is entirely composed of commercial shapes and is hence of comparatively inexpensive construction. The method employed is that of diagonal tension rods, every one of the 40 rectangular sections being diagonally cross-connected by steel rods in which any desired tension may be obtained by right and left hand threads. These rods are each screwed up to a tension of about 2,000 pounds so that the whole tube is under tension, even the lower members when in horizontal position, and is hence exceedingly stiff for its weight. The total weight of the skeleton portion is 3,740 pounds and the deflection, even with the 300-pound Cassegrain in place, is very small. The general design and construction can be readily obtained from Fig. 12 and from the various illustrations of the completed telescope.

The arrangement at the upper end of the tube by means of which changes may be made of attachments for work at the prime focus, at the Newtonian focus or with a Cassegrain mirror are one of the special features of the telescope and are such a decided advance over existing methods as to merit a detailed description.

In all previous reflecting telescopes, the practice followed has been to make the tube somewhat shorter than the focal length of the mirror, and to mount each of the attachments on a separate cage or extension of the same diameter as the tube. To change from Cassegrain to Newtonian for example, as the Cassegrain mirror is mounted considerably lower than the Newtonian mirror, it would be necessary to unbolt the short Cassegrain extension, lift it off the end of the tube and replace it with the longer Newtonian cage. In a 72-inch telescope these cages would weigh considerably over half a ton, would be cumbrous, difficult and dangerous to handle, upsetting the balance of the telescope both in declination and right ascension. Indeed I understand the practical experience has been that such change can not be made under less than two or three hours, which practically prohibits it from being done during observing hours.

To Mr. Swasey's mind, a method of changing mirrors weighing only 80 lbs. which required the moving of two awkward pieces weighing say 1,500 lbs. seemed especially unworkmanlike and cumbrous. He suggested therefore that a method be developed by which only the mirrors and cells need be interchanged, the tube remaining always the same length and serving, when both mirrors were removed, for direct work at the prime focus.

By co-operation between the writer and Messrs. Burrell and Fecker, the present method was worked out, which possesses all the advantages of permanency of adjustment of the various attachments without any of the inconvenience, difficulty and delay entailed by the removable cage extensions hitherto employed.

The principle employed is well shown in the illustrations, Figs. 12, 13. The tube is of a fixed length such that the focus of the main mirror is about 6 inches above its upper end. The circular channel which forms the upper member is reinforced and stiffened by a flat ring of steel ⅜-inch thick, 76 inches in internal diameter and 7 inches wide. This has bevelled edges, is faced true with the axis and to it can be clamped and rotated to any desired position the guiding and viewing eyepiece and the rods for operating the

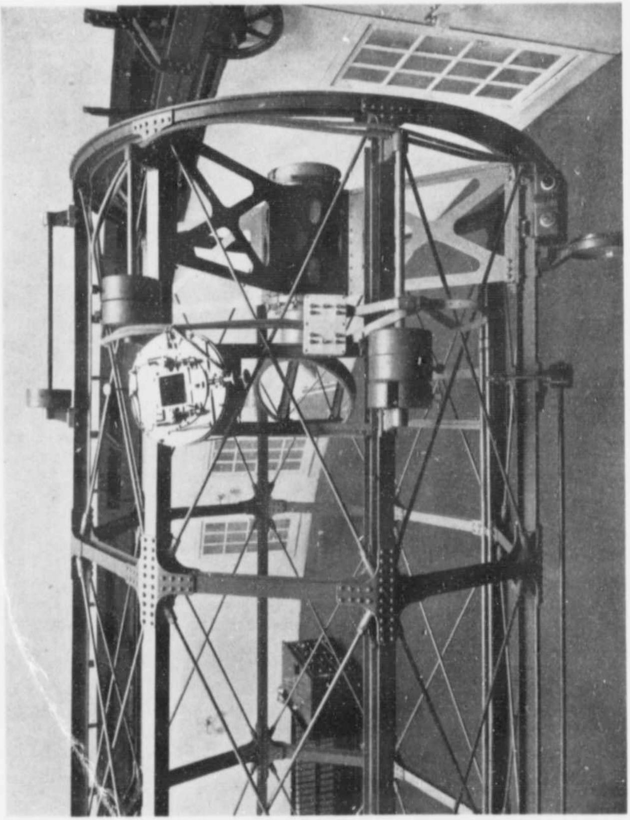

Fig. 12. Photograph of Upper End of Tube—Plate Holder and Newtonian attached.

double slide plate holder when it is placed in the prime focus. This latter and the Newtonian and Cassegrain mirrors are attached to and held rigidly and centrally by a central aluminum casting about 20 in. long and 14 in. diameter, of circular section which is attached to four of the main members of the tube by four thin perforated webs of sheet steel placed edgewise so as to obstruct little light. These webs, although thin, are deep and attached to the tube by screw adjustment which enables the aluminum casting to be adjusted and rigidly held concentric with the axis of the tube. On the lower edge of this casting is a flange provided with winged nuts on hinged bolts by means of which either Newtonian or Cassegrain is rapidly clamped in position. An inner tube sliding in the upper end of the aluminum casting is movable up and down by an ingenious and smoothly working focussing and self-clamping ring and to a flange on the upper end of this tube the double slide plate holder, or if desired, a focal plane spectrograph, is attached by four hinged bolts with wing nuts. The plate holder is hence held concentrically perpendicular to the optical axis and can readily be focussed by the rotating ring which is graduated so that the focal position can be accurately read off or replaced. The plate holder may be left in position if desired, as it in no way interferes with the use of the telescope in Cassegrain form, and all that is necessary to change from work with the Cassegrain to photography at the prime focus is to remove the Cassegrain attachment, and vice versa, the device for performing this operation to be presently described.

The Newtonian mirror which has a clear aperture of 19 inches is held in a simple cast iron cell, attached at an angle of 45° to a bronze tube, the latter being rotatable in an external tube, a flange on the latter attaching to the flange of the central aluminum casting. A spring stop fixes the Newtonian mirror so that the image is formed in any one of four positions 90° apart around the sides of the tube. The double slide plate holder is held on the end of a flanged focussing tube which slides to approximate position in a simple tubular adapter bolted to any one of these four positions. Final focussing and the perpendicularity of the plate to the optical axis is obtained by three micrometer head focussing screws in the flange by means of which the plate holder may be finally adjusted. The bronze tube holding the Newtonian is comparatively short, about 2 feet long, as the centre of the mirror is only about 4 feet below the principal focus.

When we come to the Cassegrain mirror, which is situated about 7 ft. 2 in. below the principal focus, it is evident that a longer attaching tube is required, the total length being about 5 feet. Instead of being a drawback as would be expected, this is rather an advantage. It is necessary not only to move this mirror longitudinally for the focussing of the secondary image below the principal mirror, but also to collimate it so that its axis may coincide with the axis of the principal mirror. The focussing must be possible without disturbing the collimation and hence the mirror cell is attached to the lower end of an inner tube which can be moved up and down in an intermediate tube by a screw, this screw being connected by shafts and gearing to a handwheel on the lower side of the mirror cell, convenient to the observing oculars. A very smooth slow motion is imparted to this inner tube by turning this hand wheel. The secondary image moves about twelve times as fast as the secondary mirror and hence the image on the slit of the spectrograph or in the observing ocular can be readily and accurately focussed. This inner tube, which carries the mirror, moves in an intermediate tube rotating around a spherical seat at the lower end and can be adjusted until the mirror is exactly in collimation by two pairs of opposing screws with lock nuts placed at the upper end. Once this collimation is obtained neither the focussing nor removal and replacement of the attachment will alter it. The intermediate and inner tubes are held in a fixed outer tube a flange on the upper end of the latter enabling it to be readily attached to and detached from the central support, while the lower end is supported and flexure prevented by four thin adjustable stay rods in line with the supporting webs in order to offer no additional obstruction to the incident light. The length of this tube allows a long bearing for the focussing and collimating motions thus rendering them sensitive and accurate.

The method of interchanging Newtonian, Cassegrain or prime focus attachments is very simple and expeditious. The dome with the observing platform in its normal or lowest position is rotated to the east, the telescope turned until the upper end of the tube rests on the platform where it is lashed down with a piece of rope. A small traveller carrying a quarter ton differential block at its outer end, is slipped on an auxiliary I-beam permanently attached to the main member of the tube which is uppermost in its present position. If the Cassegrain attachment, which weighs about 300 lbs., is to be attached to the tube, a pin connects the pulley block to the correct position on the attachment which can now be lifted to the correct height by the block and the traveller carrying it slid in the end of the tube. All that remains is to lower into position, push in the swivel bolts and clamp the nuts, then push in the four stay rods which stiffen the outer or lower end of the tube near the mirror and connect the focussing shaft. The whole operation or the reverse one can easily be performed in fifteen minutes. Balance is restored by removing or replacing six weights at the upper end of the tube, no change being needed at the lower end nor in right ascension. The handling of the Newtonian mirror is effected in the same way but is even simpler as this attachment only weighs about 200 lbs. All these attachments and the extra weights are kept on the observing platform as can be seen in Fig. 13 which shows the Newtonian hoisted into position on the traveller, ready to be rolled into position in the tube, while the Cassegrain attachment is on the platform floor in the lower part of the figure.

THE DECLINATION AXIS, BUSH AND HOUSING

The total weight of the tube is approximately 15 tons and it is carried by the declination axis, a gun steel forging 15½ inches in diameter, 14½ feet long having a flange at one end 41 inches in diameter and 4 inches thick which fits into and is securely bolted to the boss on the central section of the tube. This axis weighs over 4½ tons and is carried in ball and ball thrust bearings, which will be later described, at the two ends. The declination axis passes through the cubical central section of the polar axis at right angles to it and extends through and is carried at the outboard end by a conical tubular steel casting, which may be called the declination bush, which is bolted to the cubical section of the polar axis. At the outer end of this bush a circular casting about 9 ft. in diameter and 2 ft. deep is bolted which serves the two-fold purpose of helping to balance the weight of the tube on the opposite side of the polar axis and of forming a supporting base for the mechanism required to turn the tube in declination both in quick and slow motion. The

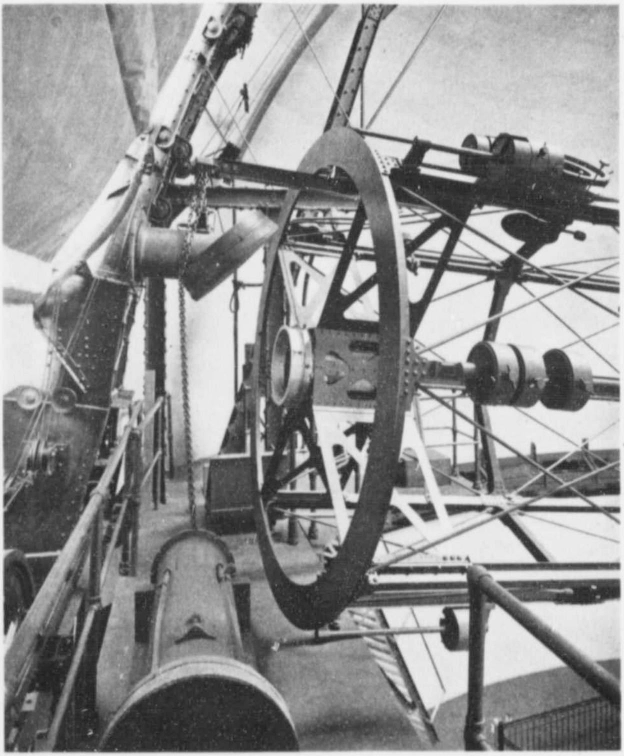

Fig. 13. Method of Changing Mirrors.

declination axis carries at its outer end and within this housing a large spur gear 8 ft. in diameter firmly keyed to it, which serves to move the axis and hence the tube in the quick motion in declination. Outside of this spur gear is the declination circle 8 feet in diameter and graduated in degrees. Counterweights for balancing in right ascension are screwed on a bronze cased extension of the declination axis.

THE POLAR AXIS

The polar axis is in three sections, a central cubical section 3 ft. 8 in. a side and upper and lower conical tubular sleeves which have square flanges on the inner ends securely bolted to the central section. These are all steel castings of the highest grade and thoroughly annealed. The outer ends of the upper and lower sleeves have forged steel pivots forced into them which serve to carry the ball bearings on which the axis rotates. The assembled axis which is 21 ft. long and weighs 9½ tons was turned up as a unit, ensuring true concentricity of all the bearings, and was not afterwards separated but handled as one piece. Mounted on ball and ball thrust bearings on the axis near the lower end is the driving worm wheel 9 ft. in diameter and below this is keyed the quick motion spur gear 6 ft. in diameter and the hour circle graduated to 5 minutes of time. Fig. 2 shows the polar axis with these wheels and the radial ball bearings attached ready to be lifted into place between the upper and lower pier heads.

THE NORTH PIER HEAD

This consists of two parts of cast iron weighing together 5¼ tons, the pillar block which is bolted to the concrete pier and the bearing head which is movable and carries the bearing for the north end of the axis and which is attached to the pillar block by push or jack screw and holding down bolts. By these screws and bolts the correct elevation of the polar axis can be obtained. The bearing head is also movable sidewise so as to enable the axis to be placed exactly in a north-south direction.

THE SOUTH PIER HEAD

This is a single iron casting of the shape well shown in the figures and weighs 7 tons. It carries the ball and ball thrust bearings of the lower end of the polar axis and within it is the mechanism for the quick motion in right ascension to be presently described. The driving clock although it may appear part of the pillar head is an independent unit resting on and adjusted from a separate base plate.

THE DRIVING MECHANISM

The telescope is driven in right ascension at the sidereal rate by the regular worm wheel, worm, and weight driven governor mechanism generally called the driving clock. Although of the well known and efficient Warner & Swasey form there are some novel and valuable modifications from the standard type which add much to its accuracy and convenience.

The worm and worm wheel are probably the parts of the driving mechanism requiring the greatest care in construction as any inaccuracy in either produces a most annoying irregularity in the following. The worm which is 3½ inches in diameter of ½-inch pitch, the thread being 9 inches long of which only 4 inches of the central part is used, is of the best tool steel thoroughly annealed, was rough milled and then finished-turned most carefully. It was then ground in a long nut to remove any periodic error and finally lapped until a fine-bearing surface was obtained.

The worm wheel is a semi-steel casting with a bronze rim, in which the teeth are cut, shrunk on. Its diameter is 9 feet and it runs free on the polar axis rotating on two radial ball bearings while the end thrust is taken by a ball thrust bearing. It weighs complete nearly 2 tons and when mounted on its bearings, it takes a pull of 2 lbs. at its periphery to start it and ½ lb. to keep it rotating.

After the worm wheel had been bored and turned as true as possible on a boring mill, it was mounted on its own bearings on a heavy cast iron pivot of the same diameter as the section of the polar axis on which it is placed. This pivot was mounted on one end of a long bed on the other end of which was a gear cutter head rotated by an electric motor. The worm wheel was rotated by hand and a fine cut taken off the bottom and top of its rim and on its periphery to make it perfectly true. On the upper flanged hub of the worm wheel, a 42-inch cast iron circle was clamped. This circle had a strip of silver inlaid in it which was divided on the very accurate Warner & Swasey dividing engine to half degree spaces. Two micrometer microscopes were firmly mounted on the pivot and the circle was accurately centred and clamped. It was now ready for indexing and cutting the teeth in the rim. The gear cutter head was set at the proper helix angle, the wheel rotated until two of the half degree divisions were exactly bisected in the microscopes and a tooth cut. This was repeated until the whole 720 teeth were roughed out. In order to prevent inaccuracies due to springing or heating, the wheel was cut three times around. After cutting, the driving worm in its box was bolted to the bed and worm and worm wheel were run together with rouge and oil for nearly a week which gave a fine smooth bearing on all the teeth. Undoubtedly this process produced a very perfect worm and worm wheel as no trace of periodic error or other irregularity in driving can be detected when the telescope is set on a star.

The driving clock proper is similar in design to the driving clocks on the Lick and Yerkes telescopes but has several improvements. The principal one is the addition of the slow motion mechanism on the principal driving shaft, thus doing away with the heavy, cumbrous slow motion arm in right ascension and with all possibility of backlash in guiding. Another advantage lies in making the connection between the main drive shaft and the worm wholly by spur gears instead of by bevel gearing, by which periodic error is likely to be introduced, as in other driving clocks. The clock is built as a separate unit, enclosed in a dust proof case, and rests on a cast iron base bolted to the main pier. The clock case is adjusted exactly in position on this base by adjusting and holding down screws. The worm is carried on an adjustable slide on the south pier head and in adjusting the clock all that is necessary is to bring it up until the intermediate spur gear, which communicates the motion from the main drive shaft to the worm, is in correct mesh with the pinion on the worm. The winding drum and clock gears occupy the upper half of the clock casing while the governor or pendulum is in the lower half. The governor is of the standard Warner & Swasey type and revolves once per second. This speed is reduced by the gearing so that the worm revolves once every two minutes. The clock and telescope are driven by a series of weights on a cable and these are automatically wound up when necessary by an electric motor situated on one side of the lower half of the clock case. On the opposite side is a similar motor used for slow motion in right ascension which will be later described. Owing to the great ease with which the 45 tons weight rotated on the polar axis moves, a relatively small weight is required. About 400 lbs. of weight is sufficient, giving 200 lbs. tension on the winding cable, although about 50 per cent more is employed to take care of inaccurate balance.

QUICK AND SLOW MOTIONS

A great deal of thought was given to and time spent on the design of the mechanism for moving the telescope quickly to any desired position and accurately setting and guiding it during observing. It is evident that the efficiency of the instrument will greatly depend upon the quickness, ease and accuracy with which its motions may be governed. The great weight of the moving parts, 45 tons, required that the mechanism be both positive and smooth in action in order that, especially in the guiding motions, the telescope may respond immediately to the impulse of the operator, move smoothly to the desired position and stop positively and quickly.

The quick motions are operated by electric motors situated, for the right ascension in the hollow south pier head and for the declination in an auxiliary housing on the declination housing. It is evident that some method of connecting and disconnecting the axes with the motors is necessary as it is only when the position of the telescope is changed that this connection is required. When being driven by the clock or moved in slow motion, the axes must be free from the quick motion motors. Both motors are connected, by double worm reduction, reducing the speed from 1,100 revolutions to ½ revolution per minute, to a differential gear box. The shaft on the other side of this differential carries a pinion meshing into the quick motion spur gear in the case of the declination axis, while for the polar axis the motion is transmitted by an auxiliary shaft and bevel gears. If the motors are running, the differential housings evidently revolve or idle without any tendency to turn the telescope. Similarly if the telescope is being moved by hand or driven by the clock or slow motions, the differentials also idle with no tendency to turn the motor shafts. Each of the differentials has a V-shaped groove on its periphery and a clamping band operated in right ascension by a hand wheel and in declination by an electro-magnet set in action by a push button switch. If either of these bands are clamped and the differential housing thus prevented from rotating, it is evident that the motion of the motor shaft will be transmitted through the differential gearing and turn the telescope. The speed in each co-ordinate is 45° per minute, sufficiently fast to turn from one position to another with little loss of time and yet slow enough so that no dangerous momentum is thereby generated.

The slow motions are also motor operated but on an entirely different principle in the two co-ordinates and must hence be separately described. They are designed to give two speeds, a fast one for fine setting and a slow for guiding. The setting slow motion moves the telescope at the rate of 10 minutes of arc in 1 minute of time or one revolution in 36 hours. The guiding slow motion is one-twentieth of the setting speed or 30 secs. of arc in 1 minute of time or one revolution in 720 hrs. or 30 days. Although this last speed may seem excessively slow, it will not be found so if we consider the linear motion of the star image at the secondary focus. The equivalent focal length is 108 ft. and hence one second of arc is 0.0064 inches, 0.16 mm. hence the rate of motion is about three one-thousandths of an inch, eight one-hundredths of a millimetre in one second of time. The slit width of the spectrograph which will be the principal instrument used at the secondary focus, will be about two-thousandths of an inch and hence it is readily seen that with any faster speed it would be difficult to keep the star accurately centred on the slit.

The slow motions in declination are transmitted to the declination axis by means of a slow motion arm about 6 feet long of very rigid construction which can be clamped to a boss on the declination quick motion gear. The upper end of this arm, and with it the tube of the telescope when the clamp is engaged, is moved in either direction by a reversing motor. This motor moves, by worm reduction, through a two speed gear box of 20 to 1 ratio, a screw which engages in a nut on the upper end of the arm. The shift from the setting to the guiding speed is effected and can be actuated whether the motor is moving or stationary.

The slow motions in right ascension are actuated, without the intervention of a movable arm, by varying the speed of the driving worm and hence that of the telescope when the worm wheel is clamped to the polar axis. This variation in speed is effected by placing on the main driving shaft of the clock, the one that gears through an intermediate into the worm shaft, two differential gears, the left hand one for accelerating, the right for retarding. When the clock runs the differentials with their cases or housings run as units and the worm drives at the sidereal rate. If now the left hand differential case is stopped, the driving worm is accelerated in the ratio of one revolution in 30 revolutions of the worm. If this housing is released and the right hand differential case is stopped, the driving worm is retarded at the same rate. This gives the guiding slow motion speed. For the setting slow motion speed which is 20 times as fast as the guiding speed, the differential housings are rotated in the opposite direction to which the clock drives them, and at 20 times the speed, which accelerates or retards the worm 20 times as fast depending on which housing is rotated. This rotation is given by the slow motion motor, situated at the right hand side of the pendulum housing, which drives by worm reduction to ratchet tooth clutches on the differential housings. Normally the motor stands still and to stop either of the differential housings for the guiding motion, the corresponding clutch is engaged by a solenoid. Owing to the worm reduction the mechanism is irreversible and the throwing in of the clutches stops the differential and gives the guiding motion. To get the setting motion 20 times as fast, it is merely necessary to start the motor.

The method of clamping the worm wheel to the polar axis and the slow motion arm to the declination axis should now be described. On a hub on the lower side of the worm wheel a V-shaped groove is turned while on the quick motion gear are pivoted four bronze shoes which fit and bear into this groove. Around these shoes are two semicircular arms hinged at one end and drawn together at the other by a right and left hand screw which when drawn up tight forces the shoes into the groove on the worm wheel and hence causes the worm wheel to turn the quick motion gear (and hence the polar axis and telescope). A similar right and left hand screw clamps the slow motion arm in declination firmly in the V-groove in the hub of the declination quick motion gear and hence causes the tube to move with the arm. These screws are drawn up tight by means of half horse power motors working through worm reduction to a differential gear box on the clamping screw. The housing is prevented from rotating, thus driving the clamping screw home, by an adjustable spring clamp which will slip before unnecessary or injurious strain can be placed on the mechanism, and though the motor may not be stopped immediately the clamp is tightened, no damage will be done. The unclamping is positive as a ratchet action prevents the housing from rotating in the reverse direction and the motor is automatically stopped when the clamp is completely free by a switch cut-out.

A notable feature of all the mechanism for quick and slow motions and clamping on this telescope is that it is entirely enclosed and protected from dust. Further all the worm reductions and differentials are enclosed in dust proof housings filled with oil or grease, thus reducing the wear of the moving parts and reducing to a minimum the number of places requiring oiling and cleaning.

THE SETTING CIRCLES

My aim in the design and arrangement of the setting or finding circles was to effect a compromise between the easy reading and comparatively rough setting of the coarse painted circles and the troublesome reading though accurate setting of the finely divided silver circles; to combine, so far as might be, the advantages without the expense of both, and this, I believe, has been successfully accomplished.

As has been previously mentioned, the declination circle, contained within the declination housing, is 8 feet in diameter and graduated to single degrees. The graduation on this and all the other circles are relatively narrow, are cut to a considerable depth by the graduating tool and the grooves filled with white paint while the ground is painted black. The index mark is a groove of the same width also filled with white paint and coincidence can be readily seen and tenths of the graduation space estimated in any position of the telescope through a celluloid window in the declination housing. However, this circle is merely used to indicate the degrees, while subdivisions of degrees are obtained on an auxiliary circle, which is rotated by a pinion meshing into an internal gear on the rim of the declination circle. This secondary circle is subdivided into 5-minute spaces and single minutes can readily be estimated. A miniature electric lamp illuminates both circles simultaneously and the operator at one of the switchboards on the south pier can at a glance read the position in declination to a minute of arc and can also of course set the telescope as accurately as he can read.

In right ascension is a plain hour circle graduated to 5 minutes of time which serves to roughly indicate the hour angle of the telescope. The setting in right ascension is, however, made by means of the sidereal circle which is nearly nine feet in diameter, graduated on the periphery to single minutes of time. This circle revolves around a boss on the upper side of the worm wheel and its friction in this bearing will evidently carry it around at the same rate as the worm wheel, although at the same time allowing it to be set to any desired position. It evidently will revolve at the sidereal rate, when the driving clock is going, and, if set to the sidereal time by a fixed index on the top of the clock case, will indicate sidereal time as long as the clock is kept going. Attached to the polar axis directly above the sidereal circle are four long index arms with index marks exactly adjacent to the graduations on the circle. These index marks are exactly 90 degrees apart and are respectively parallel and perpendicular to the declination axis. It is therefore at once evident that, after the circle has been once set at the beginning of observing, all that is necessary to find a star in right ascension is to turn the polar axis until one of the index arms points to the graduation corresponding to its right ascension. No mental arithmetic is therefore needed to compute the hour angle, as is necessary when an hour circle is employed for setting, and this method has the further advantage that the index position is not continually changing with the time as is the hour angle. Further, the graduations are close to the operator at the switchboard and can be accurately estimated to fifths and even tenths of a minute of time.

It will at once be seen that these setting circles enable settings to be made as accurately as necessary to find any object, indeed so accurately that flexure of the mechanical parts will probably induce greater errors. At the same time, they are read just as readily and easily as the ten-fold coarser graduations commonly used and have not the drawbacks and additional expense entailed by the finely graduated silver circles that were formerly employed.

THE BEARINGS

The main bearings on the declination and polar axes are evidently a very important part of the mechanism. The enormous masses to be moved, 45 tons on the bearings of the polar axis, are so great that unless the friction is reduced to the lowest possible limit, it will be difficult if not impossible to get smooth and regular action in the driving and slow motions and the efficiency of the telescope may be much diminished.

The practice hitherto universally employed, so far as I know, in the main bearings of equatorial telescopes, has been to employ plain cylindrical bearings and to relieve the friction on these bearings, which would be prohibitively great for smooth action in telescopes of even moderate size, by relieving devices of various kinds. These relieving devices have usually consisted in rollers forced up against the axes by levers, springs or weights and devised to carry about nine-tenths of the weight, thus materially reducing the friction. The latest relieving device has been that notably and successfully employed at the Mt. Wilson Solar Observatory on the polar axes of the 60-inch and 100-inch telescopes. This depends on the upward thrust, caused by the displacement of mercury in a trough attached to the pier heads, on enormous cylinders rotating with the polar axis. Although this is undoubtedly effectual and any desired proportion of the weight may be relieved by simply varying the depth of mercury in the close fitting trough, it is at the same time expensive, while the mercury is messy and disagreeable and hence to be avoided if possible.

I am of the impression that the reason cylindrical bearings have always been used is due to the idea that they were necessary to maintain the collimation of the axis and is a logical development of the procedure used in the axes of transit instruments where carefully lapped cylindrical bearings rested in V's and the weight of telescope and axis was in some cases partly relieved by anti-friction rolls. I maintain, however, that there is by no means the same necessity for accurate collimation in the equatorial as in the meridian instrument and that even so the collimation maintained by the modern ball or roller bearing where the races are hardened and ground with the highest possible mechanical accuracy will be quite equal and probably superior to that given by a plain cylindrical bearing unless the latter has been most carefully lapped, a procedure which I am frank to say, I do not believe has been followed in equatorial telescopes.

I was hence determined from the first to employ ball or roller bearings only on the axes, for the purpose of simplifying the mechanism and reducing the friction. I found the Warner & Swasey Co.'s opinion entirely in agreement with mine and the only point to decide was whether to employ roller or ball bearings. The first preference was for the Timken bearing, a commercial product of high grade, widely employed in automobile bearings. This bearing uses conical rollers which, when opposed at the two ends of a shaft or axis, allow compensation for wear. This, however, is of no particular moment in a telescope where the motions are so small that the wear is reduced to a negligible quantity. These bearings are not self-aligning so would have had to be mounted in a spherical seat, but this again is not of great moment. The difficulty was that the Timken Co. did not regularly make bearings of a large enough size and were not willing to make them specially. It was highly desirable that the bearings be made by a firm accustomed to this work and the S.K.F. self-aligning ball bearings (manufactured in Sweden) were finally selected.

Regular commercial sizes of this bearing were available for the polar axis and the outer declination axis bearing but special bearings had to be made for the inner declination radial, the double thrust for the declination and the bearings for the worm wheel. These bearings are beautifully made, have a mirror-like finish on the bearing sleeves, and are evidently extremely accurate. They are of the self-aligning type and will work just as freely and smoothly whether the shaft and journal are true and correctly lined up or not. This feature is obtained by grinding the bearing surfaces spherical, the centre of the sphere being the geometrical centre of the bearing. Hence the inner sleeve of the bearing can be rotated at any angle with the outer sleeve and as the balls are held in cages, everything remains intact and secure. A good idea of the form of the bearing is given in Fig. 14 where the inner sleeve is shown rotated through 90° and in Fig. 2 where the bearings are seen in place on the end of the polar axis.

On the upper end of the polar axis the bearing is 8·740 inches bore, 18.26 inches outside diameter and 5.25 inches thick with balls 3 inches diameter. The lower radial bearing dimensions are 9.025 inches, 19.31 inches, 5.25 inches, with balls 3⅛ inches diameter, slightly larger than the upper as it has a greater weight to carry. The thrust is taken by a S.K.F. regular ball thrust bearing resting on a rocker. This rocker has a cylindrical surface on top and bottom, the axes of the two cylinders being perpendicular to one another, so that even if the end of the polar axis were not true or normal to its axis of rotation, this rocker would allow the bearing to properly seat itself in any position.

On the outward end of the declination axis, the bearing is of the same dimensions as that at the lower end of the polar axis but owing to the large diameter of the axis near the tube the bearings had to be specially made. Both the radial and the double thrust bearing are mounted in a self-contained sleeve which bolts to one side of the cubical centre piece of the polar axis. The radial bearing is 16 inches bore, 21 inches outside diameter, 3 inches thick with two rows of balls 1¼ inches diameter. The double thrust ball bearing rests in spherical seats in order to be self-aligning as the others and is 15⅞ inches bore, 20⅞ inches outside diameter and 5¼ inches thick.

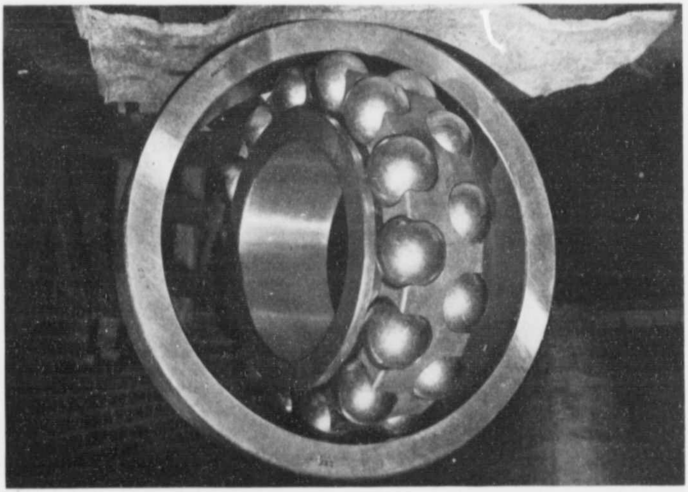

Fig. 14. Ball Bearing for Polar Axis.

The ball bearings of the worm wheel have 1½-inch balls and are 16 inches bore, 22 inches diameter and 2½ inches wide while the thrust bearing dimensions are 18 inches 23 inches and 2½ inches.

All these ball bearings have a rated capacity between 5 and 10 times the load they have to carry at a speed some hundred times as great as they will be used at. They are all enclosed in dustproof housings filled with light grease and will evidently operate for an indefinite time without attention.

The frictional coefficient is remarkably small due doubtless to the mechanical perfection of the bearing surfaces. Some experiments have been carried out with the finished telescope in an attempt to determine the force required to turn it on its bearings, but the actual frictional drag in the ball bearings cannot be determined as there are other factors entering. If we take the polar axis for example and attempt to revolve it on its bearings, we have to turn it against the friction in the ball and ball thrust bearings at the ends of the axis, the friction of the worm wheel in its bearings, the drag of the clamping mechanism in right ascension which cannot be entirely removed even when completely unclamped, and finally and most important, the friction in the quick motion differential gearing, its connecting shafts, and in the differential housing clamp. However, the friction in the differential mechanism can be differentiated from the rest by taking off the quick motion pinion, when there will remain only the first three frictional drags.

The tube was set at declination 0°, at right angles to the polar axis, and turned down below the axis until horizontal. A string was attached to the upper end of the tube running over a pulley so placed that the pull was tangential to motion around the polar axis. Weights were then placed on the string until it started to move and were found to be :—

With all mechanism attached........................9 lbs.
With differential mechanism detached...............3.25 lbs.

The distance from the axis to the point of attachment is 26 feet. As the friction of the worm wheel on its bearings is 2 pounds at 4.5 feet, this will leave 2.9 pounds for the friction on the bearings of the polar axis plus the drag of the right ascension clamp. Probably, therefore, the bearings alone would not require more than 2 pounds pressure at a radius of 26 feet to set the mass of 45 tons in motion, a striking confirmation of the mechanical perfection of the bearings, not only as regards absence of friction but also in respect to maintenance of collimation, for if the bearing surfaces were not almost truly spherical, the friction would undoubtedly be much larger. It seems to me also undeniable proof of the superiority of well made ball bearings alone for the axes of equatorial telescopes over the combination of cylindrical bearings and any kind of relieving system. I have no data as to the friction in bearings relieved by mercury flotation but doubt whether it can be made as small as that given by these ball bearings.

The force required to move the tube in declination is somewhat greater than in right ascension, undoubtedly owing to the greater drag of the heavy slow motion arm in its clamping groove. But even at the lower end of the tube the telescope can be readily moved by hand to any desired position when unclamped and its great freedom of movement will be a great advantage in operation, as well as contributing markedly to the smoothness and certainty of operation of the slow motion mechanism.

ELECTRICAL EQUIPMENT

A great deal of the success of the mounting and of its efficiency in operation depends upon the care used in the design and installation of the electrical equipment. Practically all the operations of setting, clamping and guiding are performed electrically. There are seven electric motors in the mounting of the telescope besides several magnets, solenoids and interlocking switches and mechanism and there is necessarily a rather intricate system of wiring and connections, which, unless carefully designed and thoroughly constructed and installed, would be bound to give trouble. One of the weak points of some telescope mountings has been the slipshod way in which the wiring has been done and the faulty means employed to transfer connections to the moving parts. It was very necessary in this mounting, where some 90 odd wires were required to enter the polar axis from the main switchboard for the various operations, that the wiring be done in a thoroughly mechanical and permanent manner, and that the connections to the parts between which there was relative motion should be made in a way to prevent future trouble. The usual means employed for this latter purpose had been insulated rings with sliding contacts, but owing to the great number of such connections that would be required and the very large diameters of the shafts on which they would have to be placed with the practical certainty of faulty connection sooner or later, it was decided to avoid these if possible. The greatest angular rotation of either polar or declination axis is not much greater than 180 degrees in this mounting and it seemed that a flexible permanent connection between the wires coming down the polar axis and those going along the declination axis would serve the purpose. Some 96 wires come from the main switchboard situated at the north side of the north pier and go in a pair of conduits to the upper end of the polar axis where they are loosely bundled and taped together, enter a hole in the bearing cap and axis 2 inches in diameter and pass down the hollow upper section of the polar axis to the declination axis. Here they divide, part of them going to the outboard end of the declination axis in conduit through the hollow declination bush, where they serve to operate quick and slow motion motors, clamps, etc., in declination, and part of them going through a hole in the declination axis into the centre piece of the tube, where they are led through flexible armoured conduit to terminal boxes at the upper and lower ends of the tube and serve to make the connections to the slow motion operating switches, the spectrograph and illumination. The rotation of the polar axis produces torsion in the bundle of wires passing down it but as this torsion is only over 180° in a distance of 10 feet, it will evidently not have appreciable action on the permanency of the connection. Similarly, the wires that pass through the declination axis into the tube will also be subject to bending as the declination axis rotates. Injurious effect on these wires by the rotation of about 180° is avoided by coiling them loosely around the declination axis about one and a half times before they enter the hole. Rotation of the declination axis therefore simply winds and unwinds this turn and introduces no abrupt bend in the wires but only a very gradual change in curvature as the axis rotates. No sliding contacts whatever are used, and I am confident that the connections will give no trouble for an indefinite period. The most likely place where trouble would occur is in the wires passing through the hole in the declination axis to the tube. However, they end in a terminal board on the flanged end of the axis and if any of them break by the winding and unwinding there will only be the length of 3 or 4 feet between this board and their connection to the bundle coming down the polar axis that would need replacing.

It was at once seen when the required operations came to be considered, that continuous current would have to be used, for not only are direct current motors more easily started and reversed than alternating but they have more initial torque and are in every way more suitable Further, direct current would be required in any case for operating the magnets and solenoids so a motor generating set of 10 kilowatts capacity supplying direct current at 220 volts was installed on the ground floor of the observatory The motor side is a 220 volt 3-phase 60 cycle motor supplied by current from the B C. Electric Railway Co

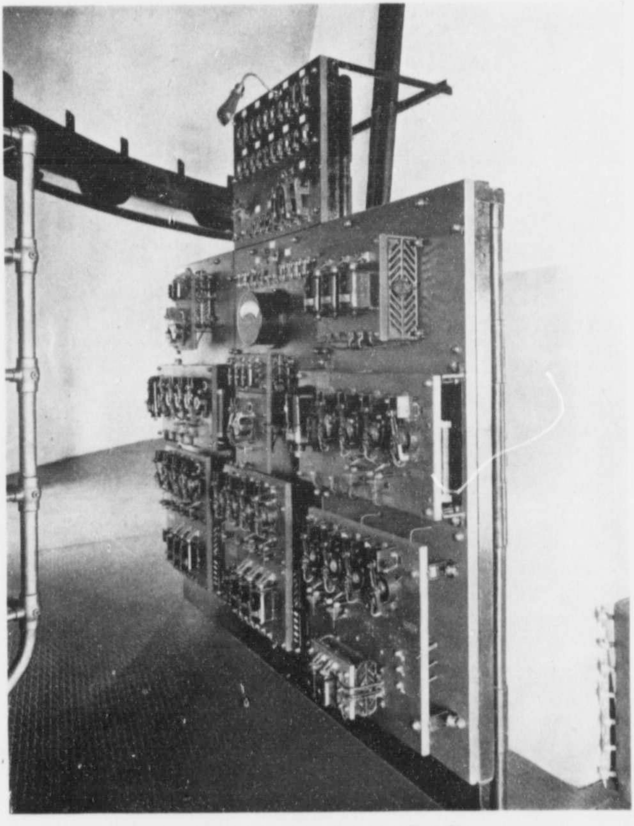

Fig. 15. Main Switch Board—North of North Pier.

The distribution and operation are controlled from five switchboards :—the main control board on the north side of the north pier, two auxiliary operating boards connected in multiple and duplicates of each other on the east and west sides of the south pier, and two small portable observing boards one each at the upper and lower ends of the tube.

The main control board has three slate panels and is about 9 feet wide and 6 feet high and the general appearance is well shown in Figure 15. As the motors are required to be started and reversed instantaneously and without using any hand rheostat, automatic electric controls for each motor are installed on this switchboard. By simply pushing a button or moving an operating handle to left or right on the operating boards the motors may be started in either direction or instantaneously reversed, resistance in the armature circuit being automatically cut out as the speed increases. On this board also are fuses and switches for each circuit, a direct current ammeter, and a reduction transformer from 110 to 6 volts for the illuminating lamps.

The operating boards on the east and west sides of the south pier are so placed that the setting circles can be conveniently read from them and are intended for the approximate setting of the telescope to the catalogue position of the star. In the operation of the telescope, although it would be easily possible for one person to manage it, some time will be saved by having the observing assistant make the approximate setting from these switchboards and the observer at the finder, the fine setting by the portable switchboards. The arrangement of the switches on these operating boards, which are duplicates of each other, are shown in the general photographs of the telescope. The three operating handles are, from north to south: R. A. quick motion motor, Dec. quick motion motor, dome revolving motor. The push button switches similarly are from north to south : R.A. slow motion clamp, Dec. slow motion clamp, Dec. quick motion clamp, R.A. Illumination, Dec. Illumination. The two plugs at the lower part of the board are for hand lamps for general illumination. Hence the assistant, at the one of these boards from which the declination setting circles can be most easily read, can simultaneously, if desired, turn the telescope in R.A. and Dec. to the desired positions and revolve the dome to suit. As soon as set, he unclamps the quick motions and by pushing the respective switches, clamps the telescope in the slow motions. Interlocking automatic switches form safety arrangements, which prevent the slow motion clamps being engaged while the quick motions are clamped, or, vice versa, prevent the quick motions being engaged while the telescope is clamped in slow motion.

The portable fine setting and guiding boards at the upper and lower ends of the tube are light aluminium boxes with a series of push button switches arranged on them as shown in the photograph of the upper end of the tube, Fig. 12. The board for the upper end of the tube has in addition to the slow motion switches, clamping switches in R.A. and Dec. These are intended for the observer to throw in the clamps as soon as the telescope is accurately set. At the upper end of the tube, it can be readily moved by hand to the desired position and at once clamped. At the lower end, however, owing to the shorter leverage, the telescope cannot be so readily moved by hand, the assistant can be readily told when to clamp, and clamps on the portable board are not necessary. The arrangement of the fine setting and guiding switches is clearly shown on the photograph, Fig. 12. The upper buttons in either R.A. or Dec. actuate the slow guiding motion in either direction, while when this button is held down and the lower button pressed, the fine setting motion, 20 times as fast as the guiding motion is actuated. With the fine setting motion, the observer can readily and rapidly centre the telescope on the object while the guiding is sufficiently slow and delicate to enable accurate guiding to be obtained If the object moves too slowly with the fine guiding a simple pressure on the lower button rapidly accelerates it. The slow motions operate most satisfactorily, the telescope responding instantaneously and smoothly and without apparent backlash, to the operating switches. The similar arrangement of the two slow motions and the identical speeds in the two co-ordinates are a distinct advantage and I can not see how the arrangement and operation could be improved.

The illuminating lamps for the R.A. and Dec. setting circles are operated from the boards on the south pier while the lamps for the guiding microscopes on the double slide plate holder and the ocular on the long focus finder are actuated by small switches adjacent to them. The intensity of the guiding illumination can be made as desired by an adjustable rheostat.

THE FINDERS

Three finders are provided, one long focus 7 inches aperture and 30 feet focus situated 180° from the place of attachment of the declination axis, and two short focus finders each of 4 inches aperture and 60 inches focus situated 90° on either side of the long focus finder. The short focus finders are of the usual type with coarse cross wires that can be seen against the sky background without illumination. The long focus finder is tubeless, the objective being attached to a bracket near the upper end of the tube and the ocular in a short length of tube adjustable laterally to enable it to be collimated parallel to the main optical system. This ocular is provided with illuminated cross wires of fine wire and was intended for getting stars centred on the slit of the spectrograph. The whole surface of the slit jaws only subtend slightly more than a minute of arc at the Cassegrain focus and it was thought stars might be troublesome to pick up if only centred by the ordinary finder. However, experience has shown that careful setting with the 4-inch finder is sufficient and the long focus finder is not necessary in setting on the slit.

OCULARS

A very complete set of high grade three-lensed oculars for visual observations was supplied by the Brashear Co. with focal lengths ranging from ¼ inch to 4 inches. From ¼-inch to 1-inch focus the oculars are as usual mounted in 1¼-inch tubing but the 1½-inch, 2½-inch and 4-inch oculars have 2-inch field lenses mounted in 2½-inch tubing and cover a wide field.

For observing at the principal focus at the centre of the upper end of the tube, an auxiliary system is provided consisting of a right angled prism of sides 1¼ inches square mounted in an adapter attached to the double slide plate holder in place of the regular plate holder. This prism is some 2 inches above the focus and reflects the pencil from the principal mirror at right angles towards the side of the tube. Mounted on the same adapter with its axis along the axis of this reflected pencil is a symmetrical triplet designed by Hastings of 2½ inches aperture and 11 inches focus. The conjugate focus of this lens corresponding to the principal focus of the mirror is situated at the edge of the tube where it can be observed by an ocular held in an adjustable adapter attached to the flanged circular plate at the upper end of the periphery of the tube.

When the Newtonian mirror is used another adapter holds the ocular directly in the double slide plate holder. When the Cassegrain attachment is used, with the spectrograph not attached, a simple casting which carries a focusing tube for holding the ocular bridges the hole in the centre of the cell and observations can be made directly. If, however, the spectrograph is in place a tube containing a right angled prism and triplet objective similar to those used at prime focus with place for ocular at the outer end is attached to the spectrograph frame above the slit by a bayonet joint and can be inserted or removed instantly. All that is required, if visual observations are desired when the spectrograph is in place, is to insert this tube, which intercepts the pencil from the secondary about 8 inches above the focus, and focus. This is a great advantage if visitors desire to see any object when the spectrograph is being used as this tube can be attached in a moment without interfering with the spectrograph or any other adjustments, and it can be detached as quickly and the spectrograph brought back into use.

THE DOUBLE SLIDE PLATE HOLDER

This attachment for making direct photographs at the principal or Newtonian focus is a beautifully designed and constructed piece of mechanism. The size of plate used is 4 inches square which subtends an angle of nearly 40 minutes of arc square, quite large enough to cover the whole field of good definition. The plate holders, of which there are two, are made of steel with hardened steel bevelled guides which are clamped against corresponding hardened stops on the carrier so that the plate holder may be removed when desired for refocussing and put back exactly to the same position. Adapters for holding knife edges, whose plane is in precisely the same plane as the plate in the plate holder, for focussing either at the principal or Newtonian foci, are provided with similar guides to insert in place of the plate holder. So also are adapters for holding the prism and objective system for the principal focus and the oculars for the Newtonian focus previously described. The carrier for the plate holder is movable by a double slide mechanism quite similar to that of plate holders previously described but as this is to be used at the principal focus, means must be provided for transmitting the motion from the side of the tube to the two slides at right angles to each other. As it would not do to have the two rods and handles for rotating the slide screws 90° apart, as it would be impossible to reach both, a rod and concentric tube each with wooden handle reach from the side of the tube to one of the slide screws. This screw is turned by the central rod while the outer tube turns a concentric sleeve on this screw which is geared by bevel gears and flexible connecting shaft to the other slide screw. Hence both slides can be moved from the one position at the side of the tube. When the plate holder is at the Newtonian focus a similar very short rod and tube is attached and both slides can be moved from the one place as before. This mechanism is well shown in the figure, Fig. 16, and works admirably.

The guiding microscopes, of which there are two, one on each side of the plate holder also require special appliances to adjust them over suitable guiding stars when

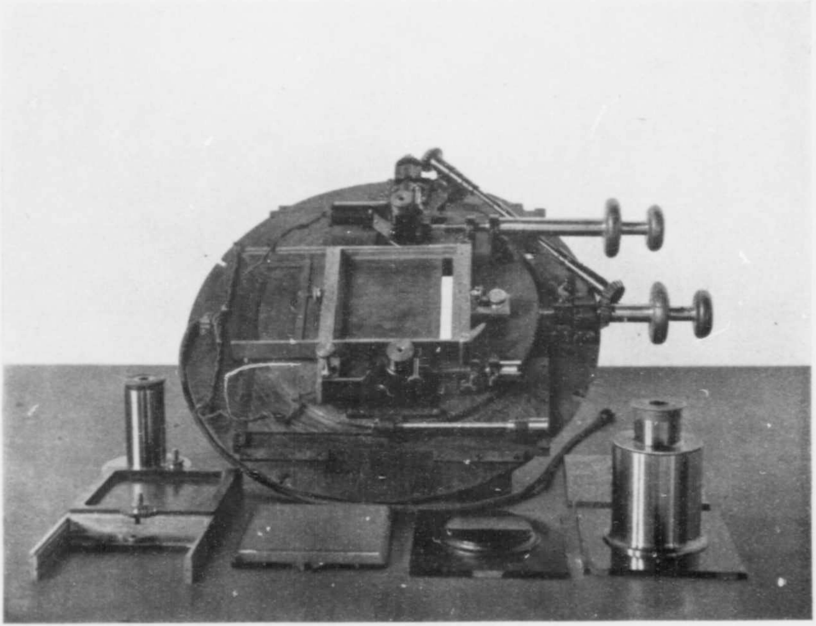

Fig. 16. Double Slide Plate Holder.

the plate holder is used at the principal focus. When used at the Newtonian only, such appliances would not be necessary and they could be adjusted by hand while the illuminated cross wires and image can be viewed by simple oculars as in the ordinary double slide plate holder. When the plate holder is at the centre of the tube, however, one can neither reach over to move the ocular nor to see when it is over a suitable star. Similar right angled prisms and triplet objectives, though of course much smaller, are used for carrying the light to the side of the tube where it is viewed by oculars held in other parts of the same adjustable adapter that carries the main observing ocular previously referred to and which also holds the extension rod and handles for moving the slides. The frames which carry the cross wires, illuminating systems and prism objective systems for each of the guiding microscopes, move also on two slides at right angles to each other, the longitudinal one being moved rapidly by a triple screw while the transverse motion is effected by a pinion concentric with the screw gearing into a rack on the slide. The same rod and tube that moves the main slides is also interchangeable with the two microscope frames and as they can be rapidly moved over a considerable range both longitudinally and laterally at each side of the plate, suitable guiding stars, which can be observed through the oculars adjacent to the handles, can be readily picked up. The use of two microscopes is for the purpose of guarding against rotation of the field which may be caused by differential refraction or imperfect adjustment of the polar axis and this can be corrected by rotating the upper part of the slide carrying plate holder and microscopes by a tangent screw also operated by a similar handle.

In case of any unforeseen, unavoidable motion of the telescope or one uncorrectable by the slides, which would produce wings on the brighter stars, the holder is fitted with a spring-flap shutter which instantaneously closes and shuts off the light from the plate by releasing a catch.

Focussing is done at the principal focus by moving the central tube which carries the plate holder by a focussing ring as previously described. At the Newtonian focus the plate holder is attached to a flanged tube which can be slid in and out of the adapter attached to the side of the telescope tube to the approximate position. The final focussing and placing of the plate perpendicular to the optical axis is effected by three micrometer screws on the flange.

The position of focus is determined by the knife edge test, a knife edge being provided accurately placed in the same plane as the sensitive film and the illuminated mirror surface can be viewed directly by the eye at the Newtonian focus, and through the intervention of prism and lens system with the ocular removed at the side of the tube when the plate holder is in the principal focus.

The whole plate holder was very carefully thought out and is beautifully made so that it works with the greatest ease, smoothness and precision.

THE SILVERING CAR

Although this is perhaps not strictly an accessory of the telescope it is as essential for its successful operation as any other part of it. Owing to the great weight of the mirror and cell, about 6 tons, and to the necessity of removing them together for resilvering the surface of the former, it is evident that some thoroughly safe and easy way of removing and attaching this heavy and awkward piece and of rocking it in some way to flow the solution evenly over the surface must be devised, and what is called the silvering car, which can be seen more or less fully in Figures 3, 4, 5, is the successful result of the efforts of the Warner & Swasey Co.

For removing the mirror and cell, the telescope tube is placed in the vertical position on the east side of the polar axis and the car which is a massive rectangular structure, running on 4 pairs of wheels of 8 feet gauge, and built of structural steel, is run directly under the mirror cell on two tracks 8 feet apart of cast steel bars, $\frac{1}{16}$ inch thicker than the steel plate floor, which are laid on two of the girders directly under them. One each of the pairs of wheels are flanged the flange running in a half-inch space between the steel bar and the plate floor. The tracks run due east from the telescope pier to the east wall of the dome and are exactly centrally situated north and south. As the flanges keep the wheels aligned on the tracks, the car can be moved only east and west along a diameter of the dome and will hence come vertically under the tube when placed on the meridian and at Dec. 48° 31′ N.

On the heavy girders forming the base of the car to which the wheels are attached, a massive casting consisting of a hollow cylindrical centre section with flanges at top and bottom is bolted and thoroughly braced by angles at the top. This cylinder which is bored to a diameter of 12 inches and is about 3 ft. high, is vertical and moving up and down in it is a plunger actuated by a screw. This screw can be turned by geared-down hand wheels or by an electric motor so as to move the plunger in the cylinder up and down over a range of two feet. As some 840 turns of the hand wheel are required for this movement it is evident that the motor will be a very useful accessory leaving only the final two or three turns for the hand wheels.

This plunger is conical at the upper extremity ending in a hemi-spherical cavity in which is placed a two-inch steel ball.

Resting on this ball is a three-armed rocker built up of steel castings, the arms being nearly 4 feet long and carrying projections on their ends which will fit on the outer edge of the mirror cell. The ball support is situated some eight or ten inches above the plane of the supporting blocks on the three arms so that the rocker, cell and mirror will be supported at the centre of gravity of all three and a comparatively slight effort is required to move the rocker on the plunger there being a freedom of motion of about 10 degrees all around.

When this rocker is brought centrally under the mirror cell, the plunger is elevated until the rocker arms are bearing firmly on the cell. Before removing the bolts which fasten the cell to the central section of the tube, it is necessary to prevent the rotation of the tube on the declination axis and the polar axis on its bearings which would inevitably result in great damage unless the unbalanced weight caused by the removal of six tons from the end of the tube was supported in some way. Consequently, the outer end of the declination axis is supported by a vertical steel box girder which is counterpoised and moves vertically in an outer telescoping girder which extends between the steel observing floor and the ground floor of the building a distance of 21 feet. A small trap door in the steel floor allows this girder to be easily run up on its guiding rollers until a conical point on the top enters a corresponding socket in the declination housing. The girder is seen in position in Fig. 4. A hole in the proper position through this girder enables a short piece of I beam resting on the floor to be pushed through and this holds up the outer end of the declination axis and prevents rotation on the polar axis. As the tube is vertical and in equilibrium, though unstable, it can be easily prevented from turning by lashing the upper end to rings in the main ribs of the dome provided for this purpose.

The cell can now be safely unbolted, the plunger lowered as far as desired, see Fig. 5, and the car moved to the east on its tracks until well out of the way of the tube. A light steel platform of suitable height for working at the mirror with a railing around it is built concentric with the cell, and from this platform the operations required in silvering can be readily performed. A band of paraffined paper about 8 inches high securely tied around the periphery and a tight fitting central plug for the hole make the mirror into a dish to hold the solutions while the rocker enables them to be moved uniformly and regularly over the surface. Pulling out the central plug allows the solutions to drain away into any receptacle and the silvering can hence be easily performed.

After being silvered, the mirror and cell can be as readily attached by the reverse operation.

The silvering car also serves to remove and replace the spectrograph on the tube but this operation will be described under the spectrograph.

CHAPTER VII.—DESCRIPTION OF THE SPECTROGRAPH

GENERAL

Although in one sense not an accessory of the telescope, indeed the telescope may more properly be called an accessory of the spectrograph as its only function is to increase the quantity of star light incident upon the spectrograph slit, yet in another sense, in that it will be practically permanently attached to the telescope and can not be used without it, it may be called accessory and as such should be described along with the telescope.

Most of the early stellar spectrographs attached to telescopes were of the universal type as they could be adapted to use in various forms, with different dispersions, and at different regions of the spectrum. These adjustable instruments were probably selected in the beginning as observing methods had not become standardized and it was felt that a choice of different dispersions and regions would prove useful in general experimental research. Good examples of these types were the spectroscopes supplied by the Brashear Co. to the Allegheny, Yerkes, Ottawa and other observatories which, though undoubtedly fine examples of the instrument makers art and well adapted for general use, were unsuitable for the particular line of work—the determination of stellar radial velocities—into which stellar spectroscopy was soon narrowed. It was soon found that only one limited region of the spectrum was used and at first only one dispersion and that the adjustable features were not needed and were indeed a source of weakness in rendering the spectroscope more subject to differential flexure, causing relative displacements of star and comparison lines, thus introducing errors into the results.

Consequently the universal form of spectroscope was abandoned for radial velocity work, and a rigid fixed form developed such as the Mills Spectrograph of the Lick Observatory, the Bruce of Yerkes and the Hartmann of Potsdam. These were all satisfactory instruments and very accurate observations were obtained by them. They had the drawback, however, that the spectrograph proper and the truss which attached it to the telescope tube were one and the same construction and the flexure, just as in a beam supported at one end, was a maximum. A great improvement in design was introduced by Campbell and Wright at the Lick Observatory who made the spectrograph proper self-contained and attached it to the telescope by an external supporting truss frame in which the spectrograph was held flexibly at two suitably chosen supporting points. The flexure in such a case was evidently only a fourth or less of that of the earlier type and this form has been adopted in all recent spectrographs, including the Ottawa single prism where flexure in the extended form of a one prism instrument was reduced to a minimum by adding a third suitably automatically counter-balanced support system.

In the spectrograph for the 72-inch reflector, I have attempted to combine the advantages of the self-contained spectrograph box carried in an attaching frame by a two point flexible support system, with the flexibility and general usefulness of a universal instrument.

In more recent years the narrow field of radial velocity observation of the stars in the spectral region around $H\gamma$ with a three prism spectrograph of linear dispersion about 10 A per millimetre has been broadened to include observations with one and two prisms, with various lengths of camera and at various regions of the spectrum. No single spectrograph, indeed no two or three spectrographs, would be likely to meet the varied demands in spectroscopic investigation that might arise with such a powerful instrument as the 72-inch reflector. Hence, owing to the expense that would have to be incurred for such a battery of spectrographs, it seemed wise to try and devise a universal type of instrument, in which the change from one type to another could be made as quickly as or even more quickly than spectrographs could be changed on the telescope, while at the same time any desired or used adjustment could be rapidly and certainly re-obtained. At the same time the spectrograph must be as rigid and as little subject to flexure as any of the fixed form types.

This purpose has been, I am convinced, accomplished and the methods employed will be developed as the description proceeds. The optical parts of the spectrograph were made by the Brashear Co. and the mechanical parts by the Warner & Swasey Co. The material, size and form of the optical parts were determined by the writer and the principles and general form of the mounting with the details of the minimum deviation link work, slit head, comparison and guiding apparatus, constant temperature arrangements, etc., were given to the Warner & Swasey Co. The latter are, however, responsible for working out the mechanical construction, the form and material of the spectrograph box and attaching frame and the general details and style of construction and finish of the instrument. I need say no more in commendation of their work than to state that it is quite in keeping both in harmony of design and character of workmanship, with the work on the telescope mounting.

THE OPTICAL PARTS

I was influenced in determining the effective aperture of the spectrograph, the material of the prisms and the form of collimator and camera lenses chiefly by my own experience and experiments with spectrographs, but Adams' successful use of prisms of 2½ inches, 63 mm., effective aperture showed the possibility of obtaining good prisms as large as this and influenced me in the decision to use a large aperture.

Practically all spectroscopists are agreed as to the advantage of a long collimator and the only drawback hitherto has been the uncertainty of obtaining suitable large prisms. I had used successfully a prism of 2-inches aperture in the Ottawa single prism and Adams prisms of 2½ inches aperture at Mt. Wilson. Hence it was decided to use prisms of 2½ inches aperture for this spectrograph and as the ratio of aperture to focal length in the Cassegrain is 1 to 18, this would make the collimator of 45 inches focal length.

The most suitable material for the prisms was the subject of considerable thought, experiment and calculation. As I have previously said,[1] I have long been of the idea that the O 102 dense flint used in most spectrographs is too dense and absorbing and some experiments of mine recorded in the same publication show marked advantages for a light baryta flint prism over the O 102 glass. The measurements of the absorption of various glasses of the Jena Co. were obtained and compared and calculations were made of the absorption and reflection of prisms of 2½ inches aperture of different materials. Using these calculations they were reduced to similar conditions in regard to dispersion and the relative efficiency of spectrographs with prisms of these materials was computed. These data are given in the accompanying table (Table VII) and unmistakeably indicate the superiority of O 118—ordinary flint—of the Jena Works. These conclusions as to its superiority were confirmed by Selesinger's measures of the absorption of the flint element of the 30-inch Allegheny objective, made of this material which came out remarkaby low. Moreover, this glass is made in large quantities and is much more likely to be homogeneous than some of the less used types. Consequently, I had no hesitation in choosing it for the prisms of the spectrograph.

Material for the three prisms was ordered from the Jena Co. by the Brashear Co. in August 1914 but owing to the war was not obtainable. But that the choice of material was a wise one has been proved by the use of a 60° prism of 2½ inches aperture made of the same material by the Hilger Co. for a Littrow Spectrograph for Toronto University, which has kindly been temporarily loaned to me by Prof. Chant. Experimental work with this prism shows it to be remarkably transparent in the violet considering its density and dispersive power. Although its dispersion is only some 20 per cent less than the O 102 glass, its absorption at λ4000 is certainly less than half the denser glass.

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[1] Pub. Dom. Obs'y., Ottawa, I. p. 188.

TABLE VII—TABLE OF TRANSMISSION, DISPERSING AND RESOLVING POWER

(Prisms of 63 mm. aperture of various glasses)

Material Jena Numbers	Number of Prisms	Deviation at λ 4200	Angle of Prisms	Transmission of Prisms	Angular Dispersion at Hγ	Linear Dispersion A per mm. at Hγ Cameras of Focal Lengths			Resolving Power at λ 4200
						381 mm.	711 mm.	965 mm.	
		° ′			″				
U.V. 3248	1	48 31	65 45	·822	5·24	103·3	55·3	40·8	16,160
Ultra-violet flint	2	97 02	....	·703	10·84	51·6	27·7	20·4	32,320
	3	145 33	....	·615	15·72	34·4	18·4	13·6	48,480
	4	194 04	....	·556	20·96	25·8	13·8	10·2	64,640
O 722	1	51 41	64 15	·657	5·90	91·8	49·2	36·2	18,260
Baryta light flint	2	103 22	....	·451	11·80	45·9	24·6	18·1	36,520
	3	155 03	....	·321	17·70	30·6	16·4	12·1	54,780
O 578	1	52 07	64 0	·636	7·12	76·0	40·7	30·0	22,000
Baryta flint	2	104 14	....	·422	14·24	38·0	20·4	15·0	44,000
	3	156 21	....	·291	21·36	25·3	13·6	10·0	66,000
O 118	1	50 00	60 0	·768	8·51	63·6	34·1	25·1	....
Ordinary flint	1	54 40	63 0	·756	9·86	54·9	29·4	21·7	30,450
	2	109 30	....	·603	19 72	27·4	14·7	10·8	60,900
	3	164 00	....	·503	29·58	18·3	9·8	7·2	91,350
O 102	1	60 00	64 0	·467	12·89	42·0	22·5	16·6	52,700
Dense flint	2	120 00	....	·235	25·78	21·0	11·2	8·3	105,400
	3	180 00	....	·126	38·67	14·0	7·5	5·5	158,100

The dimensions of the three prisms were to be as follows:—

1st prism sides 4·83 in., 122·9 mm.; Base 5·05 in., 128·2 mm.
2nd prism sides 5·07 in., 129·1 mm.; Base 5·30 in., 134·6 mm.
3rd prism sides 5·31 in., 135·3 mm.; Base 5·555 in., 141·0 mm.
Refracting angle of each prism 63°.

Again following the results of the calculations and experiments detailed in the publication previously referred to, the collimator objective was made of the regular Brashear Triplet form, and not of the Isokumatic form which absorbs too much light, and to prevent internal reflections and consequently loss of about 20 per cent of the light, was cemented with watch oil. This was tried at Ottawa but the low winter temperatures prevailing there congealed it and it was not usable. However, during its use at Victoria through the winter where the temperature rarely gets below freezing, the oil showed no signs of giving trouble in that regard and as the oil can not possibly induce strain as balsam is likely to do, it seems likely to answer every purpose. The aperture of the collimator objective is 2·5 inches, 63 mm., and its focal length 45 inches, 1143 mm.

The choice of central ray was taken considerably further to the violet than usual, at λ4200. This was done to take better advantage of the number of lines in early type stars to the violet of this wave length while at the same time there are comparatively few to the red of λ4500. Further, the lesser absorption of the O 118 glass in the violet and the absence of any absorbing material in the objective if the slight selective absorption of the silver coat be left out of account seemed to justify placing the central wave length at λ4200. However, the adjustable nature of the spectrograph will readily admit of shifting the camera and prisms in a few minutes to any other position and with the same objectives it could be shifted to any other part of the photographic spectrum without the colour curve becoming unmanageably steep.

Three camera objectives were ordered from the Brashear Co. all of 3 inches, 76 mm., aperture. Two of these have been received, both of the Hastings Brashear Triplet form, one of 28 inches, 711 mm., focus and one of 38 inches, 940 mm., focus. Both of these objectives are oil cemented like the collimator and perform beautifully. The third objective is a short focus, one of the Cooke separated triplet type, of 15 inches, 381 mm., focus. This has not yet been received but is expected shortly.

The linear dispersions given by these cameras with the one, two and three prisms ordered but not received are given in Table VII, and also the dispersion given by the 60°, O 118 prism now in use.

GUIDING APPARATUS

The guiding is done by the usual reflecting slit method, the jaws being inclined at an angle of $3\frac{1}{2}^\circ$. About 4 inches above the jaws is the guiding telescope parallel to the surface of the slit jaws, a reflecting prism at the inner end sending the diverging pencil from the slit along the tube of this telescope. A symmetrical triplet objective, adjustable by rack and pinion in the tube, has conjugate foci at the slit and ocular. Near the ocular the tube is broken a reflecting prism deviating the pencil 45° and this part of the tube can be revolved in the other for convenience in guiding.

SLIT AND DIAPHRAGM MECHANISM

The slit jaws are of polished nickel, being much less liable to chipping and injury than the speculum metal previously used, and one of them is pushed away from the other against a spring by a micrometer screw reading to thousandths of an inch. The method of applying star and comparison spectrum is new and offers considerable advantage, I believe, over methods previously employed. Directly above the slit are two small right angled reflecting prisms which reflect the comparison light from its original direction, perpendicular to the optical axis of the spectrograph and also perpendicular to the slit, down through the slit. These prisms are placed with their edges parallel to the slit and can be brought into contact or separated symmetrically with respect to the centre of the length of the slit by means of a right and left hand screw. The cells which hold the prisms, the mechanism for separating them and consequently the prisms themselves, can be moved as a whole perpendicular to the slit, towards or from the comparison source. The prisms are held in their cells by thin metal plates which are just above and just clear the slit jaws. These plates are accurately shaped as shown in the diagram, Fig. 17, and serve also as diaphragms to limit the length and position of star and comparison spectrum. The wedge shaped opening *a* between the two plates limits the length of star spectrum exposed and normally when the plates and prisms are in contact will give any length of spectrum from 0 to 0·5 mm. In order to allow the star light to pass through, a rectangular notch of sufficient width is made on the adjacent front corners of the prisms where they come over this wedge shaped opening. Just outside the wedge shaped opening rectangular openings *b*, *b*, about 1 mm. wide and 6 mm. long is made in each plate and these openings allow the comparison light, reflected from the hypothenuse of the prisms, to pass through the slit and form a comparison spectrum on each side of the star spectrum, perfectly symmetrical with respect to the latter, with lines always the same length and separation from one another so long as the distance apart of the prisms is not changed.

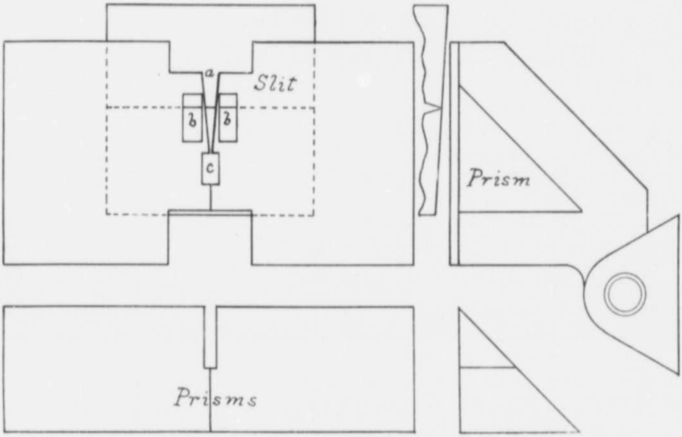

Fig. 17. Slit diaphragm and comparison prisms, three times natural size.

For all ordinary stellar spectral work the prisms and diaphragm plates will be in contact, and the width of the star spectrum may be adjusted to anything desired between 0 and 0·5 mm. by simply moving the prism mechanism across the slit by the rack and pinion until the desired width in the wedge opening is obtained. Three adjustable stop screws which can be turned in and out of engagement as desired serve to fix this lateral movement to any one of three positions, which evidently can be reproduced at will and without uncertainty or looking to the adjustment. At whatever width of star spectrum required within the above range the stop screw is set, the rectangular comparison openings are above the slit, and the comparison can be turned on when and as often as desired without touching the slit head or changing the adjustment in any way and without stopping or interfering with the exposure on the star.

If nebular or planetary spectra are desired all that is required is to turn the right and left hand screw until the prisms and diaphragm plates are separated the diameter of the object, which can be carried to the full length of the slit, when the celestial and comparison spectra can be exposed as before and whatever the width of object the comparison spectra are always separated from it by the same distance.

A further convenience is provided in this diaphragm mechanism. Just back of the point of the wedge in the adjacent edges of the diaphragm plates two notches *c*, as shown in the figure are filed. The side of these notches are in line with the inner edges of the comparison openings so that if the diaphragm and pinion mechanism is moved forward by the rack and pinion until these notches are over the slit, a comparison spectrum can be made there, the ends of whose lines will just touch the inner ends of the lines of the outer regular comparison strips. Hence, by simply moving the prisms and diaphragm from one stop to another a single comparison spectrum, about a millimetre wide, can be placed between and touching two comparison spectra also about a millimetre each wide. This makes a very convenient and useful method of determining the camera focus by the Hartmann method of extra focal exposures. A simple shutter mechanism was placed just below the collimator objective so that by turning knurled knobs on the outside of the spectrograph box, either the front or rear half of the objective could be covered or left entirely unobstructed as desired. If now the camera focus be placed at any desired setting and the inner strip of comparison be exposed through the half of the prism containing the refracting edge and the outer strips through the base half, it is evident that, if the camera is at the correct focus, the spectrum lines will be continuous and if not they will be displaced. If another pair of exposures is made at a slightly different setting, and this can be done on the same plate by moving it transversely, preferably so that one is within and the other without the focus by 0·1 or 0·2 mm., by simple comparison of the relative displacements of the spectral lines in the two exposures, the correct focus can be estimated easily to 0·05 mm. This method of focussing the camera is more certain and accurate than by the definition test and can be carried out in a very few minutes.

This diaphragm mechanism offers all the advantages of Wright's comparison device where there are separate electrodes for each comparison spectrum placed in a prolongation of the slit and sending the light through the slit by small prisms with their edges perpendicular to the slit whose distance apart, which limits the length of star spectrum, can be adjusted as desired. Either device allows star and comparison to be exposed simultaneously and can be adjusted for any width of spectrum. But in the device on this slit head only one comparison source is required, which is permanently attached to the frame and entirely independent of the slit head. It is very easy to adjust and has the advantage over Wrights device in that the spectrum lines are perfectly uniform in intensity over the whole length in the two halves, a condition which is, I believe, very difficult to obtain in the other. Further, by a simple turn of a knurled head, adjacent comparison spectra for the Hartmann method of determining the camera focus can be obtained.

COMPARISON MECHANISM

As direct current at 220 volts was used in the electrical operation of the telescope, it seemed preferable to use the iron arc rather than the spark for comparison purposes, as being simpler and giving better lines. A slide with V-ways attached to the carrying frame of the spectrograph opposite the projecting cameras serves to carry the guiding telescope and the comparison mechanism and to adjust them vertically. The arc as at first devised, was made self striking by magnetic action as soon as the current was turned on but the magnetic field thereby produced tended to blow out the arc and it was finally struck by separating the electrodes, $\frac{3}{16}$ inch iron rods, by means of a rack and pinion while it was broken by turning off the current by a snap switch adjacent to the pinion shaft. The electrodes are vertical so that the image of the arc formed by a condensing lens with diffusing screens attached to the same adjustable base as the electrodes, is transverse to the slit. The arc works satisfactorily and silently with about 4 amperes of current and gives beautifully uniform and sharply defined lines without a trace of continuous spectrum. The time of exposure is very short but is readily increased to any desired amount, convenient in the division of the exposure time into a number of intervals, by interposing neutral tinted absorbing glasses in the path of the light.

THE SPECTROGRAPH BOX

As previously stated, the spectrograph box carrying all the optical parts is a self-contained unit and is carried and flexibly supported in collimation with the telescope by a surrounding frame to which it is attached at two points.

This box is arranged so that any one of the three cameras, short, medium and long focus may be used with one, two, or three prisms and the changes may be made with a minimum of trouble and a certainty of going into exact adjustment. In order that any region of the spectrum may be used the prisms are carried on a minimum deviation link-work with additional links which serve to maintain the cameras, whether used with one, two or three prisms, exactly along the optical axis whatever part of the spectrum is central.

The general shape of the box, which is a single aluminum casting, is well shown in the photograph of the spectrograph with the temperature case removed, Fig. 18. The circular shaped opening in the side, covered normally by the three plates shown on the floor, is directly over the prisms and link work. The three projections to the right are the places in which the cameras are inserted for use with one, two or three prisms, the medium focus camera for use with one prism being in place and the short focus camera standing on the floor. Another projection for carrying the collimator tube extends centrally up within the attaching frame and the whole box is stiffened by a box girder cast integrally between the third camera and the collimator projection. Owing to the whole box being in one casting with only the circular hole on one side as an opening it is exceedingly stiff, while, being made of aluminum, comparatively light. The collimator tube is of steel, being 3 inches in diameter. This material was selected as previous experience with similar types of lenses had shown that, with either one of the collimator or camera tubes of steel and the other of brass, the differential change of focus with change of tem-

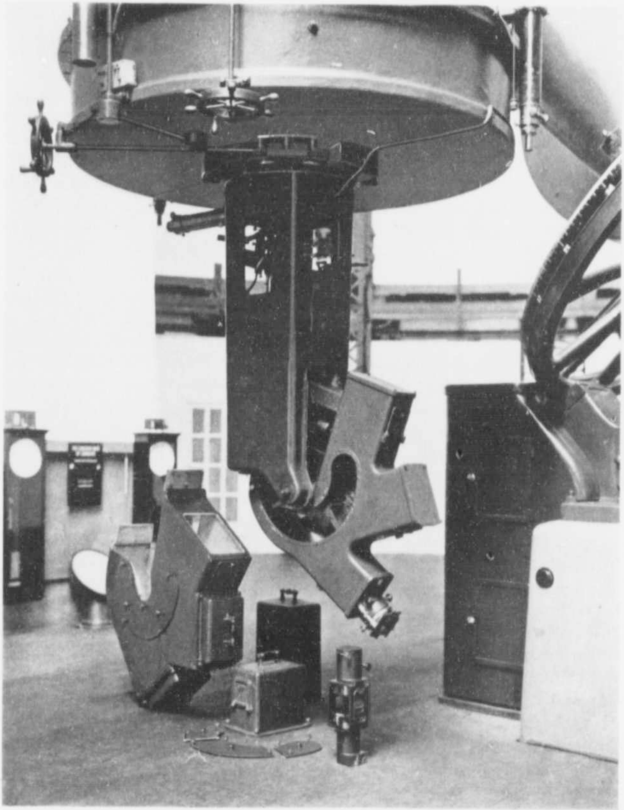

Fig. 18. Spectrograph with Temperature Case detached.

perature was vanishingly small. This has proved to be the case with this spectrograph as there is no appreciable change in the camera setting between 0 and 20 degrees Centigrade.

The minimum deviation link work which carries and adjusts the prism cells and prisms always at minimum deviation, whatever part of the spectrum is central, is similar to the link-work used by the Brashear Co. in their Universal Spectroscopes. It is exceptionally substantial and well made without any lost motion or backlash of any description. The fixed and movable gear sectors which operate the mechanism are pivoted to three substantial cast iron prism bases and these in turn are bolted through each of their three angles to the, at this part, ⅝ in. thick base of the box. These bolts move in slotted holes in the base and before the spectroscope is to be changed so that any other wave length is central, these bolts and those holding the camera, must all be loosened. Then the camera, link-work and prisms can be together automatically moved to the new position and when the bolts are firmly clamped the whole optical system is as rigid and as little subject to flexure and change of adjustment, as if it were specially made for that one wave length only. The maintenance of position and adjustment depends only upon the clamping of the prism tables and camera firmly to the base of the box, the only function of the link work being to move prisms and camera together at the proper degree when the clamping bolts are loosened. In addition to the Brashear system of link work for the prisms, an additional element for guiding the camera is provided at each of the openings (when it is used with one, two or three prisms) so that it is always in line with the central ray, the one at minimum deviation.

On each of the prism tables, a prism cell of substantial construction is fastened with four screws while two dowel pins ensure its being replaced exactly in the original position when removed. For if one prism only is to be used, the second prism with its cell must be removed to allow the objective near the first prism. Similarly when two prisms are to be used the third prism must be removed. The prisms are held in position in the cells by three adjustable abutting strips at the base and a three-pointed sheet metal spring plate at the top whose pressure can be adjusted by a screw. The cells are put on the prism plates with the dowel pins and screws in place and the prisms are then adjusted on the cells in minimum deviation for one wave length and the abutting strips which fix their positions on the base of the cell firmly screwed home. The prisms will now always be in adjustment for any wave length and, if one has to be taken off, cell and prism are removed as a unit and can be replaced by aid of the dowel pins without disturbing the adjustment.

The cameras are each held rigidly in position by four bolts, two near the plate end and two near the objective end, passing through slotted holes in the base of the prism box, though they are guided by a slot in the link work engaging a corresponding key-shaped boss on the camera base, when the bolts are loosened. They are of exceptionally massive construction in order not to be subject to flexure and are designed for the greatest convenience in handling. The plate holders are of metal opening in the middle on a hinge, the plate 2 x 4 inches in size being held down against a raised surface at the edge of an opening 3¾ inches long and 1 inch wide on the front half by a spring on the back. They are hence supported parallel to the spectrum all along its length and less than half an inch away from it and any curvature of the plates will have negligible influence on the focus or measures. The plate holder slides into a recess in its carrier where it is securely clamped by two thumb screws bearing against spring plates resting on its upper surface. As great care was taken that the distance from the margin on which the film is pressed to the front of the plate holder was the same in all four holders supplied, we may be sure that the plates are the same distance from the objective in every case. The plate holder carrier slides transversely in ways to enable a number of spectra to be made side by side on the same plate. An index and scale gives the position of the carrier while clamp screws hold it securely in any desired position. In addition, plate holder, carrier, and slide can be tilted 15° each way around an axis parallel to the spectrum lines so as to compensate for deviation of the focal plane of the spectrum from normality to the optical axis. This tilt can be read on a graduated sector and can be maintained by clamping screws. Focussing is effected by rack and pinion on the plate holder end of the camera, the objective being firmly screwed in an adapter at the other end and not being changed in position. The position is read by scale and vernier to tenths of a millimetre and can be maintained and displacement of the camera end by flexure avoided by an efficient clamping screw at each end of the telescoping tube by which the focussing is effected. The medium focus camera is shown in position for use as a one-prism spectrograph. The same plate holder and focussing end is used in the long focus tube by simply racking it out of the one and into the other which it fits equally well.

In the short focus camera the plate holder comes inside the projections on the spectrograph box and doors as shown are provided in the ends of these projections and in the temperature case for inserting the holder and drawing the slide. The general construction of the camera can be seen from the figure and the same adjustments for the plate holder as in the others are provided. This same camera would do for a 10 or 12 inch focus objective if such could be ob ained by shortening the objective adapter which screws into the end resting on the floor.

THE ATTACHING FRAME

This, as well as the spectrograph box, is of cast aluminum and both are exceptionally fine castings It is of hollow rectangular prism-shaped form with a substantial circular flange at the top, which is held by 8 screws firmly to the revolving cast iron ring at the lower end of the tube There is an opening as shown at one side into which the prism box goes, the two sides coming down and embracing the box being of hollow box construction thus rendering the whole frame very stiff.

The spectrograph box is held in the frame by two shafts, the lower one seen centrally in the extension of the lower end of the frame being the principal support, while the upper one, which is within, principally serves to keep it from rotating on the lower shaft The lower shaft passes through the box about centrally with respect to the optical system while the upper one is about two-thirds of the length of the collimator above it. Both of these shafts are so attached to the box that no relative flexure of box or frame can induce any strain whatever on the box and at the same time are adjustable in every direction horizontally to enable the optical axis of the collimator to be placed along the optical axis of the telescope. This was effected before the optical parts were installed by turning the telescope truly vertical, hanging a steel plumb line down the exact centre of the tube and adjusting the two axes until it was exactly central at upper and lower ends of the collimator tube. Flexure will of course throw it slightly out of adjustment in other positions but this can not be avoided and is in any case an effect of the second order and will not cause appreciable error in the observations. The inside of the frame where it surrounds the collimator projection of the box is lined with felt half an inch thick and part of the heating wires are on the two inside walls in order to distribute heat uniformly all over the box.

THE TEMPERATURE CASE

The temperature case, which is shown put together but not attached to the spectrograph in Fig. 18, and attached in Fig. 19, has sheet aluminum sides and cast aluminum edges. It is beautifully fitted and firmly attached to the attaching frame but has no connection with nor does not touch the spectrograph box at any point. It is lined throughout and all the joints of the case, and of the doors and covers, carefully packed with felt ½ inch thick and is hence very efficiently heat insulated.

There are three openings for the camera projections of the spectrograph box for which four covers are provided, two short to go over the openings in which no camera is placed, one intermediate for use with the short focus and medium focus cameras and one long for use with the long focus camera. Doors are provided in the two latter covers for inserting the plate holder and drawing the slide and doors in the edge of the case for similar operations with the short focus camera A circular opening with cover is provided on each side of the case for getting at the prisms and clamping bolts so that all changes in adjustment may be made without removing the case.

The inside of the case is heated by passing the 110 volt lighting current through wire attached to the felt. There are three circuits, generally used in multiple, each containing about 110 feet of No. 20 double cotton covered German silver wire used for heating. Each of these circuits has a resistance of slightly over 50 ohms and will hence pass about 2 amperes of current giving 220 watts of heat. The three circuits will hence provide over 600 watts which is sufficient to keep the prism box about 30° C. above the surrounding air As less than one-third of this difference between inside and outside temperatures will occur in practice, the current can be reduced by an external rheostat seen on the attaching frame but since removed to the switchboard for fear of radiation from it interfering with the definition of the star image. There are one of these circuits sewed on the felt uniformly over each side of the temperature case while the third is uniformly distributed over the far curved edge of the case which is parallel to the one prism camera and around the medium and long focus covers. Hence when the current is turned on heat is fairly uniformly supplied nearly all around the spectrograph box except at the top where it tends to rise by convection. To prevent stratification and ensure more uniform temperature throughout, the air within the case is stirred by a small electric fan whose body is seen between the third camera and collimator projections just below the box girder connecting the two, and to which it is attached.

The heat is turned on and off automatically by a mercury thermostat thermometer which actuates the armature of a relay which in turns moves a platinum point in and out

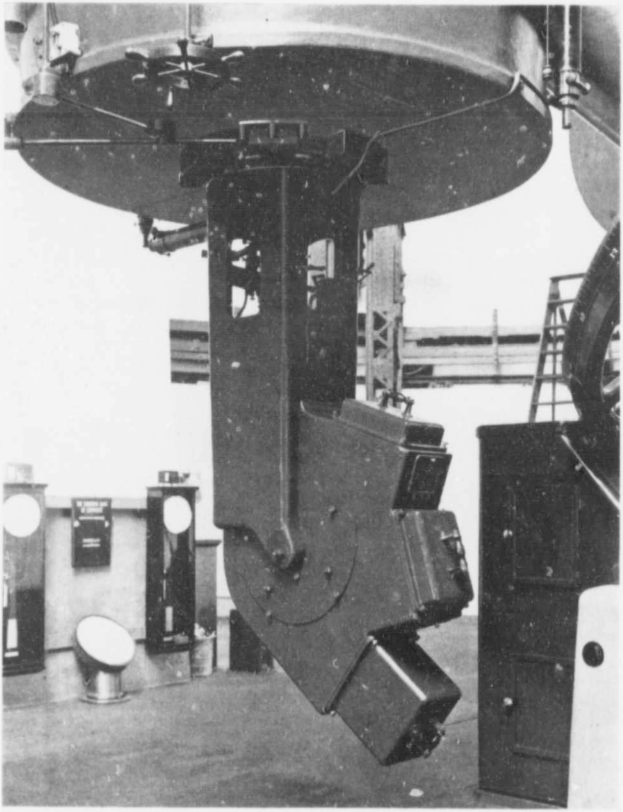

Fig. 19. Spectrograph with Temperature Case attached.

of a cup of mercury and thus turns the heating current on and off. It was intended to regulate and record the temperatures of the case and box by means of a Callendar Recorder, and this would make an eminently satisfactory procedure. But this instrument, like the prisms, was unobtainable during the war and in the meantime the present arrangement works satisfactorily. Explorations with a thermometer inside the case when the temperature there was 15° C. higher than that outside showed differences at extreme points inside not much greater than 1° and this would be much reduced in practice, when the difference between inside and outside would not normally exceed 5°. Further, owing to the very good heat insulation there seems to be no tendency to a general drop of the temperature inside the prism box as the difference between inside and outside temperatures increased, as was found at Ottawa.

The wiring to the spectrograph, consisting of thermostat circuit, fan circuit, heating circuit and arc circuit, comes from the terminal box near the bottom of the centre section in a cable and ends in binding posts on the attaching frame as shown. One of the knife switches shown is for the heating and the other for the arc circuit. The fan is controlled by a circular regulator switch seen below the rheostat. Rheostat and relay are now on the main switch board. When it is necessary to detach the spectrograph for resilvering the mirror all that is necessary is to detach the cable ends from the binding posts and slip it out from under the clips on the cell.

ATTACHMENT TO TELESCOPE

The spectrograph is attached to and detached from the telescope by a lever built of channel iron and forked at the outer end to embrace the rectangular part of the attaching frame directly under the flange. This lever has a pivot of cast steel which engages with the point of the rocker arm on the silvering car and extending beyond away from the telescope to a point over the main frame of the car to which it is attached by a threaded shaft and handwheel.

The telescope being turned until the tube is vertical and on the east side of the axis, the declination strut being run into place and the tube fastened at the top to prevent rotation when thrown out of balance by removing the weight of the spectrograph, the silvering car is run on its track until the forked end of the lever slips under the flange of the attaching frame, the bolts on those two flanges having been previously removed. The plunger of the car is then raised and the outer hand wheel adjusted until the weight of the spectrograph is relieved, when the other four holding bolts are removed, and the spectrograph lowered, by lowering the plunger and handwheel until it rests on a special wooden stand made to carry it when not on the telescope. The silvering car is then run back out of the way and the spectrograph and stand also wheeled out of the way to one side. The silvering car is then ready for removing the cell and mirror if desired or the telescope may be rebalanced if other attachments are to be used at the Cassegrain focus.

ADJUSTMENTS AND TESTS OF THE SPECTROGRAPH

The first procedure after the spectroscope was attached to the telescope was to place its optical axis along the optical axis of the telescope and this was done in a vertical position with a plumb line as previously described. The next procedure was to place the slit at the principal focus of the collimator objective and for this purpose the collimator tube was removed from the spectrograph, set up on a table with the 60° prism and one of the cameras using a carbon arc as a source and the collimator focus determined by Schuster's method. Repeated trials succeeded in repeating the settings within 0.5 mm. and the slit was finally set at the mean position.

Replacing the collimator tube in the spectrograph the comparison apparatus was adjusted and with this as source the 60° prism was adjusted for minimum deviation at λ4200. As the spectrograph was constructed for a mean deviation of 55°, which would be the deviation at λ4200 of the 63° prisms of O 118 glass proposed for the instrument, and as the deviation of the 60° prism is only 50°, the slotted holes in the base of the prism box, carrying the link-work, prism bases, and one-prism camera had to be lengthened at one side, until the λ4200 ray was central in the camera when the prism was adjusted for minimum. The camera was then carefully focussed and the plate holder placed at the proper inclination to have as long length as possible of the spectrum in focus. It was found that the field of the 711 mm., medium focus camera, was slightly convex towards the lens, the deviation from the tangent at λ4200, at λ4600 on one side and λ3900 on the other being slightly less than 0.1 mm. It is probable, therefore, that with slightly greater angular dispersion such as that given by two prisms, the field would be flat. However, by accomodating slightly, the deviation at no position of the usable spectrum will be greater than 0.05 mm., which is too small to have any effect on the measures.

Tests were then made of change of camera focus with change of temperature and this was found to be quite inappreciable.

Tests of the flexure of the spectrograph in the single prism form were carried out in two ways, first by moving the telescope in declination and observing the displacement of adjacent comparison spectra made as before described and second by leaving it at fixed declination and moving it in R.A. This latter test which more nearly corresponds to actual observing conditions, showed no appreciable or measurable displacement for a movement in hour angle of 4 hours from the meridian, while the normal exposures will be much less than half of that. The movement in declination from vertical to horizontal or through 90° showed a displacement of some 10 kilometres which is relatively small for the single prism form where flexure has the greatest possible effect. In two-prism or three-prism form the flexure would only be a small fraction of the above and it may be concluded therefore, that flexure in any possible observing practice will have absolutely no effect.

CHAPTER VIII.—DESCRIPTION OF THE BUILDING AND DOME

THE BUILDING

It was early decided that the building and dome must be entirely of metal construction in order to more rapidly assume the temperature of the external air and prevent any " dome effects " from interfering with the " seeing ". In order to avoid overheating the interior of the building by the direct rays of the sun a double covering was provided on both building and dome allowing continuous circulation of the air from openings at the base of the building to louvres at the top of the dome.

As previously stated, the designs of the building and of the concrete pier for supporting the telescope were worked out in the chief architect's office and are well proportioned and harmonious in design. The proportions of building and dome can be seen from the illustrations, Frontispiece and Fig. 20, and I do not believe can be improved much and the general effect of the structure, especially when it is remembered that it is constructed of sheet iron and the possible architectural effects thus limited, is very good.

The concrete pier is a massive structure of reinforced concrete, the north and south elements being connected by a reinforced arch below the observing floor and the north section, curved as shown in Fig. 11, to allow more room for swinging telescope and spectrograph below the axis, is supported by a latticed structural steel girder built up of 4 inch angles at each corner diagonally latticed from bottom to top. This was to enable the column to better resist the horizontal component of the thrust of the polar axis amounting to about 15 tons.

The framework of the building which rises 33 feet above the ground consists of 24 8-inch Bethlehem H columns tied together at the top by I beams on which is fastened the circular rail which carries the dome and on which the latter revolves.

The framework of the building is further stiffened by heavy diagonal bracing between four pairs of adjacent columns and the internal and external sheeting is attached by clips (to allow for expansion) to circular angles riveted at suitable spacing to the columns. The observing floor which is situated 21 ft. 6 in. above the ground floor, reached by iron stairs south of the telescope pier, is composed of checkered steel plates $\frac{7}{16}$ -inch thick supported by girders and columns entirely independent of the telescope pier which it does not touch at any point. This floor was designed to carry a load of 150 lbs. per square foot and is amply strong as even during the erection of the telescope no yielding at any place was evident.

The ground floor constructed of Terrazo is divided by temporary wooden partitions into dark room, sleeping room and two temporary offices and contains the motor generator set and main switchboard and the dome revolving motor and mechanism. The motor is a 15 H.P. three phase alternating current motor, operated by current supplied by the B.C. Electric Railway Co., and is directly connected to a 10 K.W. 220 volt direct current generator which operates the telescope and dome motors.

Fig. 20. Dome from North.

THE DOME

The dome is built up on a lower circular member 66 ft. in external diameter composed of two heavy circular angles latticed together to which is attached the revolving gear of the dome consisting of 24 roller bearing wheels carrying the weight of the dome and a series of external and internal lateral guide wheels all bearing on the turned circular rail which is mounted on the circular plate of the building. Two main ribs of deep section which serve to carry not only the secondary members of the dome but also the shutters and observing platform extend centrally across the dome from side to side separated by a distance of 16 feet. At 6 feet beyond the zenith these ribs are tied together by a cross member which serves to carry the secondary ribs below the shutter opening, the upper end of which is formed by this member. These main ribs are in reality double and of sufficient strength and rigidity to carry the whole weight of the dome and mechanism and in addition to bear the weight of the heavy parts of the telescope mechanism during erection. When the complete polar axis, about 14 tons in weight, was being hoisted, the deflection of these ribs as observed with a transit instrument was less than one-eighth of an inch. The structural frame of the dome is well shown in Fig. 21.

The secondary members of the dome are comparatively light yet rigid in construction, are spaced into a regular polygonal figure of 24 sides and are cross united inside and out by the small angles to which the internal and external coverings separated by an air space of 12 inches are attached. The skirting of the dome which extends below the hemispherical and cylindrical part of the dome, is carried by circular angles with supporting arms riveted to the lower member. This skirting is also double covered and ingeniously arranged in connection with the double weather guards to form a continuous passage for the internal circulating air from the double walls of the building to the double walls of the dome.

The shutters, which are of the usual double separating Warner & Swasey type, give a clear opening of 15 feet extending 6 feet beyond the zenith. They also are double covered with openings at bottom and top to permit circulation of the enclosed air. They move on roller bearing wheels running on horizontal girders at bottom and top of the shutter opening and are actuated by wire cables winding on a motor-operated drum. Canvas wind curtains stretched on tubes extending between the main ribs and rolling on guides attached to the latter can be operated one from the bottom upwards and the other from the top downwards so as to limit the length of the shutter opening to the diameter of the tube when a wind is blowing. These curtains are raised or lowered by the same motor that operates the shutters, clutches serving to connect or disconnect either at will. Motor and clutches are operated from a platform permanently attached to the lower member and right hand main rib of the dome at the level of the lower member. This platform is reached from the observing floor by an iron stairway with handrail also permanently attached to and rotating with the dome.

The main feature of this dome, however, and the principal one which makes it so much superior to previous designs is the observing platform. When the telescope is to be used for direct photography at the principal or Newtonian focus, it is evident that the observer must be able to have convenient access for guiding, etc., to the upper end of the

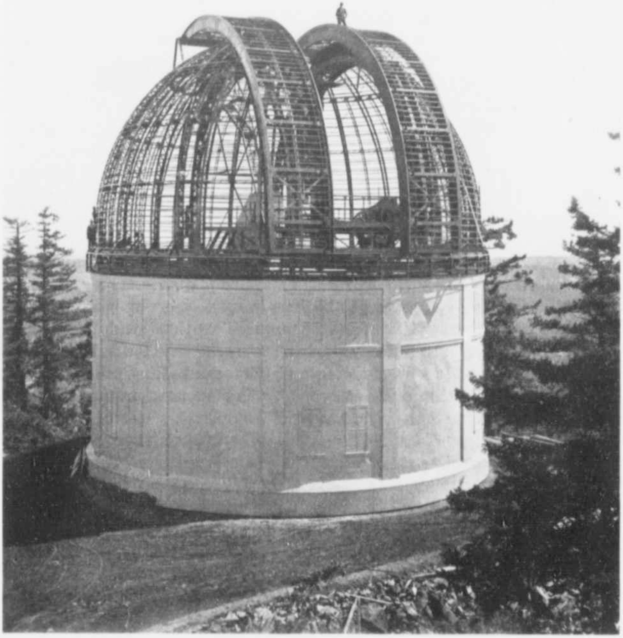

Fig. 21. Framework of Dome from North.

tube in any observing position. For the design of this platform and the perfection with which it fulfills the required purposes, we are indebted to the ingenuity and ability of Mr. E. P. Burrell, works manager of the Warner & Swasey Co. The problem was an especially difficult one owing to the form of mounting of the telescope, as the tube pivoted at one side of the polar axis and moving eccentrically with respect to the dome, made the motions of the upper end more complicated and the corresponding required positions of the platform much more numerous than is required with telescopes like the 60-inch and 100-inch where the axis of tube, the declination axis and the polar axis intersect. The solution of the problem was facilitated by the construction of a model, one-tenth size of telescope, building and dome for exhibition at the Panama Pacific Exposition, as in this model all possible positions and motions could be studied to scale and the design modified to conform to the requirements.

The observing platform of the 66-foot dome consists of a substantial structural frame about 22 ft. long and 4 ft. wide with a floor of $\frac{1}{8}$ inch plate. In its normal position when the telescope is used in the Cassegrain form, this platform is at the same level as the stationary platform already described and the observing platform is hence readily accessible. At each end of the platform are movable wings extending out into the dome about 6 ft. from the inner edge of the platform, semicircular in shape on the sides facing each other so as to enable the tube to be about two-thirds encircled when they are moved up to it. They are movable by means of roller bearing wheels longitudinally along the main girders of the platform and the observer by standing on either one of these movable platforms can, by means of a hand wheel, move himself and it with the greatest ease, longitudinally along the observing platform to any desired position and bring himself into a convenient position for guiding. These movable platforms are a great advance and enable the following and guiding to be done in most observing positions with the greatest ease. Both the main platform and the wings are completely enclosed by a tubular railing 30 inches high making it perfectly safe to move around on in the dark. The central section of this railing on the front of the main platform can be lifted out if desired, as is convenient in certain positions of the telescope, but in these positions the tube occupies the place of the railing and the safety character of the railing is preserved.

The platform including of course the movable wings, is pivoted by a rigid rectangular structural framework at each end to trolleys running on curved rails attached to the main ribs of the drum, the greater part of the weight of the platform, 11,000 lbs., being sustained by counterweights on similar trolleys running on an extension on the same curved rails down the main ribs on the opposite side of the dome. The platform is pivoted to the trolley at the upper corner of the rectangular frame work and would not remain horizontal unless it were supported at the upper inner corner of the frame. The horizontality of the platform is maintained without appreciable deviation as it moves in its curved path up the dome by an equalizing cable attached to a drum, on the same shaft as the hoisting drum but of a different diameter. These diameters are so proportioned that, over the 70° arc the platform moves, it remains very nearly horizontal and can be moved up and down to any desired position with the greatest smoothness. This motion is controlled by operating handle and rheostat on the platform itself by which the speed can be varied between 1.5 and 6 ft. per minute.

A pivoted iron stairway whose weight is counterweighted, is attached to the stationary platform and when the observing platform is not in use is drawn up against the roof of the dome entirely out of the way of the telescope. When the observing platform is used this stairway is let down to the bottom of its movement determined by chains attached to the top of the stairway and to the roof of the dome directly above. In this position a handrail attached to the dome is in a suitable position to enable the observer to walk with perfect confidence and safety up and down to the observing platform in any possible position. It is hence not necessary to change the position of the platform in order to get to or from the observing floor and direct photography can be carried on with the greatest possible convenience, ease and safety. A general view of the observing platform and accessories in position for work at the Newtonian focus is shown in Fig. 22.

The dome is revolved at the rate of 60° per minute by means of an endless cable stretched around the interior corner of a circular angle attached to the lower member. This cable is led off by two guiding pulleys over a V-shaped groove in a motor driven wheel, on the ground floor, the correct tension and friction being maintained by a counterweighted idler pulley. The motor is controlled by either one of two operating handles on the auxiliary switchboards on the east and west sides of the south pier directly adjacent to the operating handles for the quick motions of the telescope. Current is led to the shutter-curtain and to the elevator motors by means of two circular trolley wires carried entirely around the dome and attached to the same supports that carry the revolving cable angle, and by trolleys attached to the building conveying the current to these wires.

The whole dome and accessories operate smoothly and comparatively noiselessly, especially since the original steel pinions on the motor shafts have been replaced by Bakelite. Indeed the whole mechanical equipment is so perfected and so convenient in use that it is a constant joy to operate.

CONCLUSION

It suffices to say in conclusion that the test of a year's actual operation of the telescope has shown it to be even more accurate, satisfactory and convenient in operation than had been anticipated. The quality of the optical parts is well shown in the results of the Hartmann tests, in the short exposures required for the spectrograph, and in the remarkable smallness and crispness of the star images in the direct photographs. As previously stated, the driving is perfect and no trace whatever of any period or irregularity in the following has been detected. The arrangements provided for operating the telescope, for setting on the star, work to perfection and I have yet to find any part of the design where any improvement could be suggested. In making exposures on star spectra the average time required in changing from one star to the next, from the end of the exposure on one star to the beginning of the next is less than three minutes and if the stars are not far apart is generally only two minutes. I do not believe that record is excelled by even very small telescopes and, when we consider that the moving parts weigh 45 tons, the ease of handling is a remarkable evidence of the perfection of design and workmanship.

Fig. 22. Telescope and Platform in position for Direct Photography.

Besides being at present the largest telescope in operation, this instrument in optical and mechanical perfection, in convenience and speed of operating, is, in my opinion, unequalled in the world. Canada is to be congratulated on the enterprise which led to the construction and completion, under difficult circumstances of this instrument, a telescope more than twice as large as in any other national observatory, and one from which great advances in astronomical science may be expected. It is in such additions to the cause of pure scientific research that the real progress of a country may be truly judged and if, as has been often said, the degree of civilization of a nation is measured by its support of Astronomy, Canada takes high rank and all Canadians should be proud of the position their country has taken and now holds in astronomical research.

Dominion Astrophysical Observatory, Victoria.
June, 1919.