

THE CROSSLEY REFLECTOR OF THE LICK OBSERVATORY.*

By JAMES E. KEELER.

The Crossley reflector, at present the largest instrument of its class in America, was made in 1879 by Dr. A. A. Common, of London, in order to carry out, and test by practical observation, certain ideas of his respecting the design of large reflecting telescopes. For the construction of the instrument embodying these ideas, and for some fine astronomical photographs obtained with it, Dr. Common was awarded the gold medal of the Royal Astronomical Society in 1884.

In 1885, Dr. Common, wishing to make a larger telescope on a somewhat similar plan, sold the instrument to Edward Crossley, Esq., F. R. A. S., of Halifax, England. Mr. Crossley provided the telescope with a dome of the usual form, in place of the sliding roof used by its former owner, and made observations with it for some years; but the climate of Halifax not being suitable for the best use of such a telescope, he consented, at the request of Dr. Holden, then Director of the Lick Observatory, to present it to this institution. The funds for transporting the telescope and dome to California, and setting them up on Mount Hamilton, were subscribed by friends of the Lick Observatory, for the most part citizens of California. The work was completed, and the telescope housed in a suitable observatory building, in 1895.¹

On taking charge of the Lick Observatory in 1898, I decided to devote my own observing time to the Crossley reflector, although the whole of my previous experience had been with refracting telescopes. I was more particularly desirous of testing the reflector with my own hands, because such preliminary trials of it as had been made had given rise to somewhat conflicting opinions as to its merits.² The result of my experience is given in the following article, which is written chiefly with reference to American readers. If I have taken occasion to point out what I regard as defects in the design or construction of the instrument, I have done so, not from any desire to look a gift horse in the mouth, but in the interest of future improvement, and to make intelligible the circumstances under which the work of the reflector is now being done and will be done hereafter. The most important improvements which have suggested themselves have indeed already

* Reprinted from *The Astrophysical Journal*, 11, 325, 1900.

¹ For a more complete history of this part of the subject, see Dr. Holden's articles in *Pub. Ast. Soc. Pacific*, 7, 197 *et seq.*, 1895.

² The difficulties here referred to, about which a good deal has been written, seem to have had their origin in the fact that it was impossible, at the time of the preliminary trials, to provide the observer with an assistant, while the Crossley reflector is practically unmanageable by a single person.

been made by Dr. Common himself, in constructing his five-foot telescope. The three-foot reflector is, in spite of numerous idiosyncracies which make its management very different from the comparatively simple manipulation of a refractor, by far the most effective instrument in the Observatory for certain classes of astronomical work. Certainly no one has more reason than I to appreciate the great value of Mr. Crossley's generous gift.

The Crossley dome is about 350 yards from the main Observatory, at the end



DOMES OF THE CROSSLEY REFLECTOR.

of a long rocky spur which extends from the Observatory summit toward the south, and on which are two of the houses occupied by members of the Observatory staff. It is below the level of the lowest reservoir, "Huyghens," which receives the discharge from the hydraulic machinery of the 36-inch refractor, and therefore the water engine furnished by Mr. Crossley for turning the dome can not be used, unless a new water system—overflow reservoir, pump and windmill—is provided. In this respect a better site would have been a point on the south slope of "Kepler,"—the middle peak of Mount Hamilton—just above the Huyghens reservoir. No addition to the present water system would then have been needed. The

slope of the mountain at this place might cut off the view of the north horizon, but since the telescope can not be turned below the pole, this would be a matter of no consequence. Water-power for the dome is not, however, really necessary.

The cylindrical walls of the dome, $36\frac{1}{4}$ feet inside diameter, are double, and provided with ventilators. Opening into the dome, on the left of the entrance, are three small rooms, one of which has been fitted up as a photographic dark room, and another, containing a sidereal clock and a telephone, which communicates with the main Observatory, as a study, while the third is used for tools and storage. There is also a small room for the water engine, in case it should be used. The dome is at present supplied with water from only the middle reservoir, Kepler, which is reserved for domestic purposes and is not allowed to pass through the machinery.

The dome itself, 38 feet 9 inches in diameter, is made of sheet-iron plates riveted to iron girders. It also carries the wooden gallery, ladders, and observing platform, which are suspended from it by iron rods. The apparatus for turning the dome consists of a cast-iron circular rack bolted to the lower side of the sole-plate, and a set of gears terminating in a sprocket-wheel, from which hangs an endless rope. As the dome does not turn easily, it has been necessary to multiply the gearing of the mechanism so that one arm's-length pull on the rope moves the dome only about one inch. In some positions of the telescope the dome can not be moved more than six or eight inches at a time without danger of striking the tube, and this slowness of motion is then not disadvantageous. It is only when the dome has to be moved through a considerable angle, as in turning to a fresh object, or in photographing some object which passes nearly through the zenith, that the need for a mechanical means of rotation is felt.

The observing slit, 6 feet wide, extends considerably beyond the zenith. It is closed by a double shutter, which is operated by an endless rope. The upper part, within the dome, is also closed by a hood, or shield, which serves to protect the telescope from any water that may find its way through the shutter, and which is rolled back to the north when observations are made near the zenith. I have recently fitted the lower half of the slit with a wind-screen, which has proved to be a most useful addition. It is made of tarpaulin, attached to slats which slide between the two main girders, and is raised or lowered by halliards, which belay to cleats on the north rail of the gallery. A more detailed description of the dome has been given in an article by Mr. Crossley,¹ from which the reduced figure in Fig. 1² has been taken.

The mounting of the three-foot reflector has been very completely described and illustrated by Dr. Common,³ so that only a very general description need be

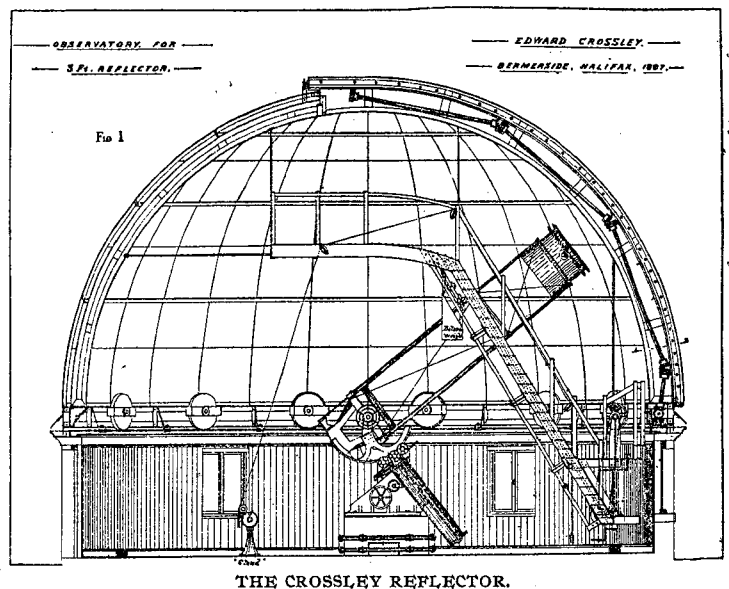
¹ *Mon. Not. R. A. S.*, 48, 386.

² Kindly lent by the Astronomical Society of the Pacific.

³ *Mem. R. A. S.*, 46, 173.

given here. The most important feature of the mounting is that the telescope tube, instead of being on one side of the polar axis, as in the usual construction, is central, so that the axis of the mirror and the polar axis are in the same line when the telescope is directed to the pole. The declination axis is short, and is supported by a massive goose-neck bolted to the upper end of the polar axis. The mirror is placed just *above* the declination axis. Its weight, and the weight of the whole tube and eye-end, are counterpoised by slabs of lead, placed in two iron boxes, between which the goose-neck of the polar axis passes. The great advantage of this arrangement, and the controlling principle of the design, is that the telescope is perfectly free to pass the meridian at all zenith distances. No reversal of the instrument is needed, or is indeed possible.

For long-exposure photography, the advantage above referred to is obvious,



but it is attended by certain disadvantages. One of these is that a very much larger dome is required than for the usual form of mounting. Another is the great amount of dead weight which the axes must carry; for the mirror, instead of helping to counterpoise the upper end of the tube, must itself be counterpoised. When anything is attached to the eye-end (and in astrophysical work one is always attaching things to the eye-end of a telescope), from ten to twenty times as much weight must be placed in the counterpoise boxes below the declination axis. Where room is to be found for the weights required to counterpoise the Bruce spectrograph, is a problem which I have not yet succeeded in solving.

In his five-foot reflector, Dr. Common has caused the telescope tube to swing between two large ears, which project from the upper end of the boiler-like polar axis, the pivots constituting the declination axis being near, but above, the lower end of the tube. The mirror, therefore, helps to counterpoise the upper end of the

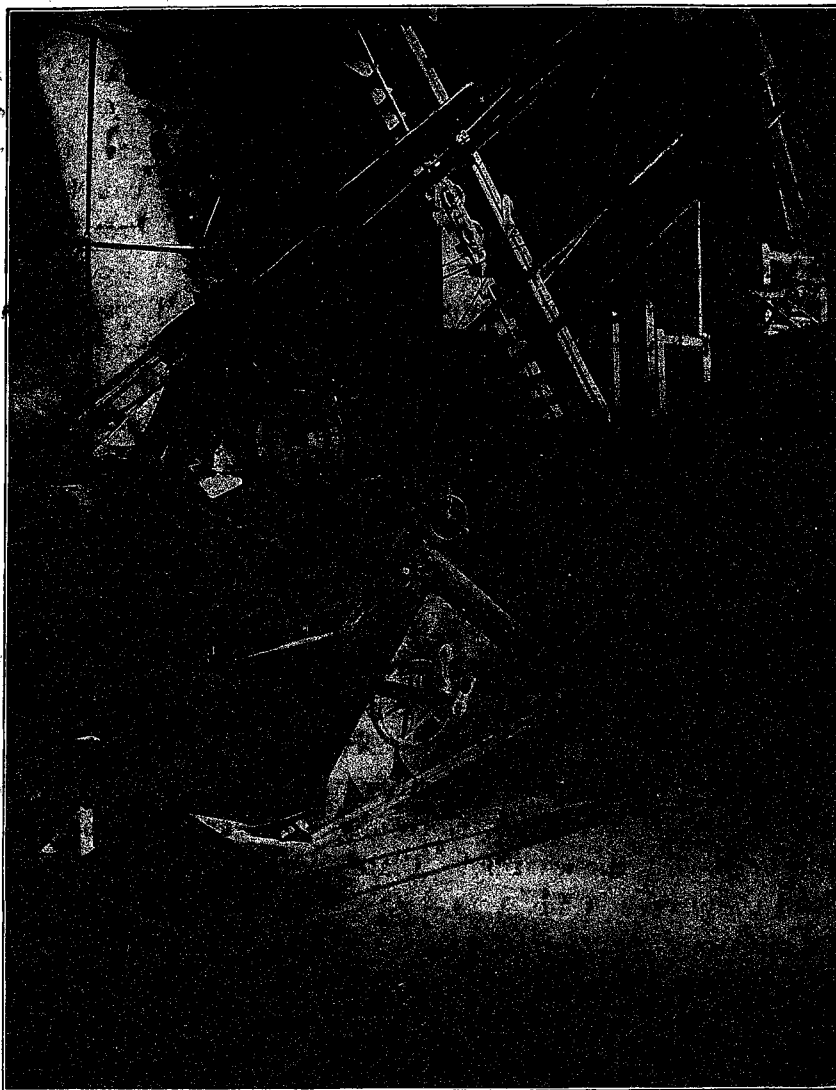
tube. This I regard as a distinct improvement. The danger of large masses of metal near the mirror injuring the definition is, in my opinion, imaginary; at least there is no such danger on Mount Hamilton, where the temperature variations are unusually small. Experience with the Crossley reflector, as well as with the other instruments of the Lick Observatory, shows that the definition depends almost entirely on external conditions.

My first trials of the reflector, as first mounted at the Lick Observatory, showed that the center of motion was inconveniently high. Among other difficulties arising from this circumstance, the spectroscope projected beyond the top of the dome, so that it had to be removed before the shutter could be closed. In July, 1898, the pier was therefore cut down two feet. This brought the eye-end down nearly to the level of the gallery rail, where it was at a convenient height for the observer when sitting on a camp-stool, and it made all parts of the mounting more accessible. Toward the north and south, the range of the telescope, being limited in these directions by the construction of the mounting, was not affected by the change, but the telescope can not now be used at such low altitudes as formerly, near the east and west points of the horizon. The only occasion likely to call for the use of the reflector in these positions is the appearance of a large comet near the Sun, and, after some consideration, I decided to sacrifice these chances for the sake of increasing the general usefulness of the instrument. Except in rare cases, all observations are made within three hours of the meridian.

To adapt the mounting to the latitude of Mount Hamilton, a wedge-shaped casting, shown in the illustration, had been provided, but through some error, arising probably from the fact that the telescope had been used in two different latitudes in England, the angle of the casting was too great. When the pier was cut down its upper surface was therefore sloped toward the south, in order to compensate the error in the casting. Plate VII shows the instrument very nearly as it is at the present time.

The polar axis of the Crossley reflector is a long, hollow cylinder, separated by a space of about one-eighth of an inch from its concentric casing. The idea was to fill this space with mercury, and float the greater part of the thrust of the axis, the function of a small steel pin at the lower end being merely to steady the axis. But this mercury flotation, as applied to the Crossley telescope, is a delusion, as I think Mr. Crossley had already found. The mercury, it is true, relieves the thrust to some extent, but it greatly increases the already enormous side pressure on the steel pin at the bottom, thus creating a much greater evil than the one it is intended to remedy. The workmen who set up the mounting inform me that the small bearing at the lower end of the polar axis is badly worn, as I should expect it to be. Instead of putting mercury into the space intended for it, I have therefore poured in a pint or so of oil, to keep the lower bearing lubricated. For the reasons indicated above, the force required to move the telescope in right

ascension is perhaps five times greater than it should be. The lower end of the polar axis ought to be fitted with ball bearings to take the thrust, and with a pair of friction wheels on top; but it would be difficult to make these changes now. It should be observed that the disadvantages of the mercury flotation are consider-



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ably greater at Mount Hamilton than at the latitude for which the telescope was designed.

As already stated above, the range of the telescope is limited on the south by the construction of the mounting. The greatest southern declination which can be observed is 25° . In England this would doubtless mark the limit set by atmospheric conditions, but at Mount Hamilton it would be easy to photograph objects 15° farther south, if the telescope could be pointed to them.

The original driving-clock having proved to be inefficient, at least without an electric control, a new and powerful driving-clock was made by the Observatory instrument maker, from designs by Professor Hussey. In its general plan it is like that of the 36-inch refractor. The winding apparatus, contained in the large casting of the original mounting, has no maintaining power, and can not easily be fitted with one. The clock could in no case be wound during a photographic exposure, on account of the tremors attending the operation, but it would be somewhat more convenient to have the stars remain on the plate during the winding. With a little practice, however, one can wind the clock without actually stopping it, though the object must afterwards be brought back to its place by means of the slow motion in right ascension.

Two finders have recently been fitted to the Crossley reflector. One has an object-glass of four inches aperture and eight feet six inches focal length, with a field of about $1^{\circ} 2'$, which is very nearly the photographic field of the main telescope. Its standards are bolted to one of the corner tubes of the reflector. The other finder has a three-inch objective and a large field. It had not been mounted when the photograph for the plate was made.

When a telescope is used for photographing objects near the pole, with long exposures, the polar axis must be quite accurately adjusted, for otherwise the centers of motion of the stars and of the telescope will not agree, and the star images will be distorted. It is true that with a double-slide plate-holder, like the one used with the Crossley reflector, one star—namely, the guiding star—is forced to remain in a fixed position with respect to the plate; but the differential motion of the other stars causes them to describe short arcs, or trails, around this star as a center. A considerable part of the spring of 1899 was spent in efforts to perfect the adjustment of the polar axis, an operation which, on account of the peculiar form of the mounting, offers unusual difficulties.

In the first plan which was tried, the reflector was used as a transit instrument. The inclination of the declination axis was determined with a hanging level which had been provided by Mr. Crossley, the hour circle and polar axis being very firmly clamped. The clock correction being known from the records kept at the Observatory, the collimation and azimuth constants were found by the usual formulæ. This method failed to give satisfactory results, and it was found later that the declination and polar axis were not exactly at right angles.

There is only one part of the sky on which the telescope can be reversed; namely, the pole. A method which promised well, and on which some time was spent, consists in photographing the pole (the declination axis being horizontal) by allowing the stars near it to trail for ten or fifteen minutes, then turning the polar axis 180° and photographing the pole again on the same plate. Half the distance between the images gives the error of the polar axis, which, if the plate is properly oriented, is easily resolved into horizontal and vertical components;

while the distance of each image from the center of the plate is this error increased or diminished by twice the deviation of the telescope axis. In this case the vertical component depends upon the reading of the declination circle, and the horizontal component gives the error of collimation. This method failed, however, to give consistent results, mainly on account of instability of the mirror, and was abandoned.

The use of the large mirror for purposes of adjustment was finally given up, and the axis was adjusted by observations of *Polaris* with the long finder, in the usual manner. In order to reach the star at lower culmination the finder tube had to be thrown out of parallelism with the main telescope.

The base-plate having no definite center of rotation in azimuth, and the wedges and crowbars used for moving it being uncertain in their action, a watch telescope, provided with a micrometer eyepiece, was firmly secured to the mounting throughout these operations, in such manner that a mark on the southern horizon could be observed through one of the windows of the dome. The errors of the polar axis were finally reduced to within the limits of error of observation.

The movable hour circle and driving wheel of the Crossley reflector has two sets of graduations. The driving screw having been thrown out of gear, the circle is turned until the outer vernier indicates the sidereal time, whereupon the driving screw is thrown into gear again. The inner vernier is then set to the right ascension of the object which it is desired to observe. As an inconsistency, of minor importance, in the design of the mounting, I may note that the slow motion in right ascension changes the reading of the outer vernier instead of that of the inner one. In practice, however, no inconvenience is caused by this construction.

In the early experiments and photographic work with the Crossley telescope, irregularities in driving were a source of great annoyance. Dr. Roberts, in laying down the conditions which should be fulfilled by a good photographic telescope, says that a star should remain bisected by a thread in the eyepiece for two minutes at a time. The Crossley telescope was so far from fulfilling this condition that a star would not keep its place for two consecutive seconds; and the greatest alertness on the part of the observer did not suffice to ensure round star images on a photographic plate. It was obvious that the fault did not lie with the driving clock; in fact, many of the sudden jumps in right ascension, if explained in this way, would have required the clock to run backward; nevertheless the clock was tested by causing its revolutions to be recorded on a chronograph at the main Observatory, together with the beats of one of the standard clocks. For this purpose a break-circuit attachment was made by Mr. Palmer. The errors of the clock were in this way found to be quite small.

The principal source of the irregularities was found in the concealed upper differential wheel of the Grubb slow motion. This wheel turned with uncertain

friction, sometimes rotating on its axis, and sometimes remaining at rest. After it was checked the driving was much better, and was still farther improved by repairing some defective parts of the train. Small irregularities still remain. They seem to be partly due to inaccuracies in the cutting of the gears, or of the teeth of the large driving wheel, and partly to the springing of the various parts, due to the very considerable friction of the polar axis in its bearings. The remaining irregularities are so small, however, that they are easily corrected by the screws of the sliding plate-holder, and with reasonable attention on the part of the observer, round star images are obtained with exposures of four hours' duration.

The large mirror, the most important part of the telescope, has an aperture of three feet, and a focal length of 17 feet 6.1 inches. It was made by Mr. Calver. Its figure is excellent. On cutting off the cone of rays from a star, by a knife-edge at the focus, according to the method of Foucault, the illumination of the mirror is very uniform, while the star disks as seen in an ordinary eyepiece are small and almost perfectly round. They are not, I think, quite so good as the images seen with a large refractor; still, they are very good indeed, as the following observations of double stars, made recently for this purpose, will show.

Several close double stars were examined on the night of April 17, 1900, with a power of 620. The seeing was four on a scale of five. The magnitudes and distances of the components, as given in the table, are from recent observations by Professor Hussey with the 36-inch refractor.

Star.	Mag.	<i>d.</i>	Result of Obs.
OΣ 208 (<i>φ Urs. Maj.</i>)	5.0, 5.5	0".35	Not resolved; too bright.
OΣ 249, AB	7.2, 8.0	0 .54	Easily resolved.
OΣ 250	7.7, 8.0	0 .44	Resolved.
OΣ 267	8.0, 8.2	0 .30	Just resolved at best moments.

Although the theoretical limit of resolution for a three-foot aperture is not reached in these observations, I do not think the mirror can do any better.

The small mirror, or flat, at the upper end of the tube, is circular, the diameter being nine inches. Its projection on the plane of the photographic plate is therefore elliptical; but the projection of the mirror and its cell on the plane of the great mirror is very nearly circular.

The small mirror, acting as a central stop, has the effect of diminishing the size of the central disk of the diffraction pattern, at the expense of an increase in the brightness of the system of rings. To this effect may be due, in part, the inferiority of the reflector for resolving bright doubles, as compared with a refractor of the same aperture. For photographic purposes, it is evident that the mirror is practically perfect.

The upper end of the tube can be rotated, carrying with it the flat and the eye-end. Whenever the position is changed, the mirrors have to be re-collimated. In practice it is seldom necessary to touch the adjusting screws of the mirrors

themselves. The adjustment is effected by means of clamping and butting screws on the eye-end, and a change of the line of collimation, with respect to the finders and the circles, is avoided. The operation is generally referred to, however, as an adjustment of the mirrors.

For adjusting the mirrors there are two collimators. One of these is of the form devised by Mr. Crossley.¹ It is very convenient in use, and is sufficiently accurate for the adjustment of the eye-end when the telescope is used for photographic purposes, inasmuch as the exact place where the axis of the large mirror cuts the photographic plate is not then a matter of great importance, so long as it is near the center. Moreover, as stated farther below, the direction of the axis changes during a long exposure. The other collimator is of a form originally due, I think, to Dr. Johnstone Stoney. It consists of a small telescope, which fits the draw-tube at the eye-end. In the focus of the eyepiece are, instead of cross-wires, two adjustable terminals, between which an electric spark can be passed, generated by a small induction machine, like a replenisher, held in the observer's hand. The terminals are at such a distance inside the principal focus of the objective, that the light from the spark, after reflection from the flat, appears to proceed from the center of curvature of the large mirror. The rays are therefore reflected back normally, and form an image of the spark which, when the mirrors are in perfect adjustment, coincides with the spark itself. The precision of this method is very great. It is in fact out of proportion to the degree of refinement attained in other adjustments of the reflector, for a slight pressure of the hand on the draw-tube, or movement of the telescope to a different altitude, instantly destroys the perfection of the adjustment. I have provided these collimators with an adapter which fits the photographic apparatus, so that one can adjust the mirrors without having to remove this apparatus and substitute for it the ordinary eye-end carrying the eyepieces.

For visual observation the Crossley telescope is provided with seven eyepieces, with powers ranging from 620 downward. The lowest power is only 60, and consequently utilizes only 12 inches of the mirror, 9 of which are covered by the central flat. It is therefore of little value, except for finding purposes. The next lowest power utilizes 28 inches of the mirror. The other eyepieces call for no remark.

But, while the Crossley reflector would doubtless be serviceable for various kinds of visual observations, its photographic applications are regarded as having the most importance, and have been chiefly considered in deciding upon the different changes and improvements which have been made.

The interior of the dome is lighted at night by a large lamp, which is enclosed in a suitable box or lantern, fitted with panes of red glass, and mounted on a portable stand. In order to diffuse the light in the lower part of the dome, where most

¹ *Mon. Not. R. A. S.*, 48, 280, 1888.

of the assistant's work is done, the walls are painted bright red; while to prevent reflected light from reaching the photographic plate, the inner surface of the dome itself, the mounting, and the ladders and gallery are painted dead black. The observer is therefore in comparative darkness, and not the slightest fogging of the plate, from the red light below, is produced during a four-hours' exposure. On the few occasions when orthochromatic plates are used the lamp need not be lighted.

Experiments have shown that the fogging of the photographic plate, during a long exposure, is entirely due to diffuse light from the sky, and is therefore unavoidable. For this reason the cloth curtains which lace to the corners of the telescope tube, enclosing it and shutting out light from the lower part of the dome, have not been used, since their only effect would be to catch the wind and cause vibrations of the telescope. They would probably have little effect on the definition, and at any rate could not be expected to improve it.

For photographing stars and nebulæ the Crossley reflector is provided with a double-slide plate-holder, of the form invented by Dr. Common.¹ This apparatus, which had suffered considerably in transportation, and from general wear and tear, was thoroughly overhauled by the Observatory instrument-maker. The plates were straightened and the slides refitted. A spring was introduced to oppose the right ascension screw and take up the lost motion—the most annoying defect that such a piece of apparatus can have—and various other improvements were made, as the necessity for them became apparent. They are described in detail farther below.

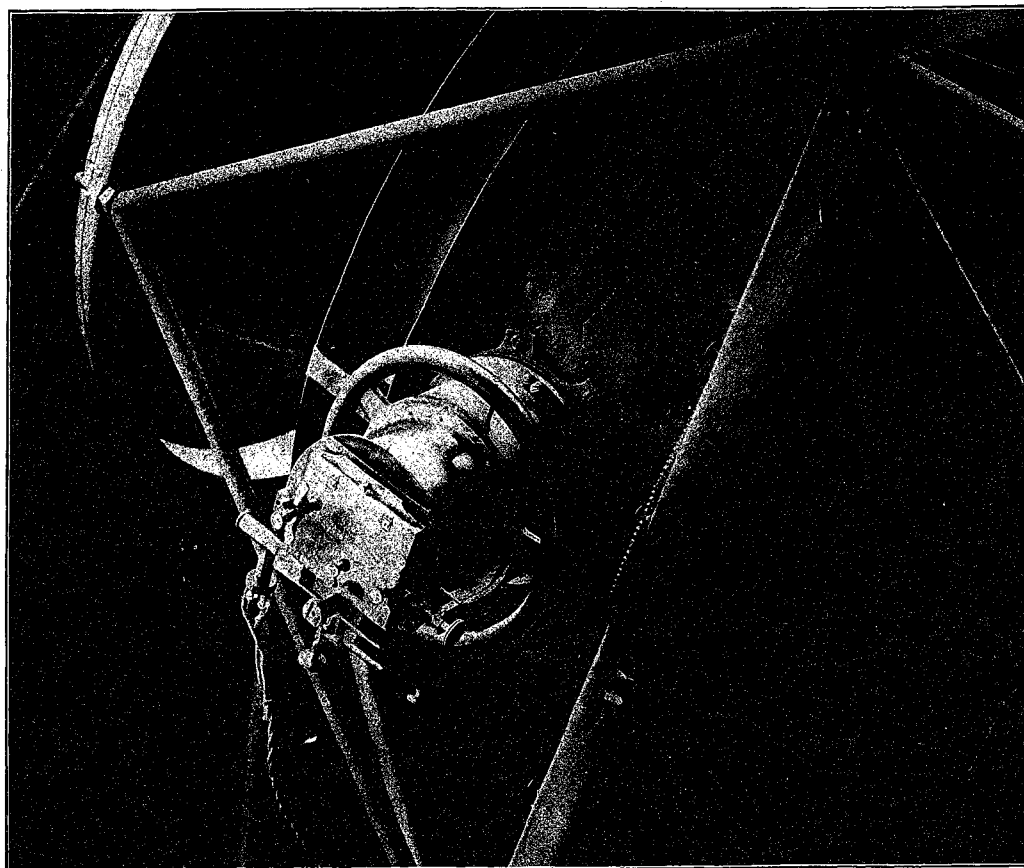
The present appearance of the eye-end is shown in the illustration. The plate-holder is there shown, however, on one side of the tube, and its longer side is parallel to the axis of the telescope. This is not a good position for the eye-end, except for short exposures. In practice, the eye-end is always placed on the north or south side of the tube, according as the object photographed is north or south of the zenith. The right ascension slide is then always at right angles to the telescope axis, and the eye-end can not get into an inaccessible position during a long exposure.

As the original wooden plate-holders were warped, and could not be depended upon to remain in the same position for several hours at a time, they were replaced by new ones of metal, and clamping screws were added, to hold them firmly in place. The heads of these screws are shown in the plate, between the springs which press the plate-holder against its bed.

To illuminate the cross-wires of the guiding eyepiece, a small electric lamp is used, the current for which is brought down from the storage battery at the main

¹ *Mon. Not. R. A. S.*, 49, 297. The construction here described is not followed exactly in the Crossley apparatus. The guiding eyepiece slides freely when not held by a clamp. Pin-holes for preventing fogging are unnecessary when red light is used.

Observatory. The coarse wires have been replaced by spider's webs,¹ and reflectors have been introduced, to illuminate the declination thread. A collimating lens, placed at its principal focal distance from the incandescent filament of the lamp, makes the illumination of the wires nearly independent of their position on the slide, and a piece of red glass, close to the lens, effectually removes all danger of fogging the plate. The light is varied to suit the requirements of



DOUBLE-SLIDE PLATE-HOLDER OF THE CROSSLEY REFLECTOR.

observation by rotating the reflector which throws the light in the direction of the eyepiece.

In long exposures it is important for the observer to know at any moment the position of the plate with reference to its central or zero position. For this purpose scales with indexes are attached to both slides; but as they can not be seen in the dark, and, even if illuminated with red light, could not be read without removing the eye from the guiding eyepiece, I have added two short pins, one of

¹It so happens that the tension of the vertical thread is such that it begins to slacken when the temperature falls to within about 2° of the dew point. The thread thus forms an excellent hygrometer, which is constantly under the eye of the observer. When the thread becomes slack, it is time to cover the mirrors.

which is attached to the lower side of the right ascension slide, and the other to its guide, so that the points coincide when the scale reads zero. These pins can be felt by the fingers, and with a little practice the observer can tell very closely how far the plate is from its central position. It would not be a very difficult matter to improve on this contrivance, say by placing an illuminated scale, capable of independent adjustment, in the field of the eyepiece, but the pins answer every purpose. The declination slide is changed so little that no means for indicating its position are necessary.

In this apparatus, as originally constructed, the cross-wires of the guiding eyepiece were exactly in the plane of the photographic plate. The earlier observations made with the Crossley reflector on Mount Hamilton showed that this is not the best position of the cross-wires. The image of a star in the guiding eyepiece, which, when in the middle of its slide, is nearly three inches from the axis of the mirror, is not round, and its shape varies as the eyepiece is pushed in or drawn out. In the plane of the photographic plate (assumed to be accurately in focus), it is a crescent, with the convex side directed toward the center of the plate. This form of image is not suitable for accurate guiding. Outside this position the image changes to an arrow-head, the point of which is directed toward the axis, and this image can be very accurately bisected by the right ascension thread. As the construction of the apparatus did not allow the plane of the cross-wires to be changed, the wooden bed of the plate-holder was cut down, so as to bring the wires and the plate into the proper relative positions.

After some further experience with the instrument, still another change was made in this adjustment. It was found that the focus often changed very perceptibly during a long exposure, and while the arrow-head image above described was suitable for guiding purposes, its form was not greatly affected by changes of focus. Between the crescent and the arrow-head images there is a transition form, in which two well-defined caustic curves in the aberration pattern intersect at an acute angle. The intersection of these caustics offers an excellent mark for the cross-wires, and is at the same time very sensitive to changes of focus, which cause it to travel up or down in the general pattern. The bed of the plate-holder was therefore raised, by facing it with a brass plate of the proper thickness.

Why the focus of the telescope should change during a long exposure is not quite clear. The change is much too great to be accounted for by expansion and contraction of the rods forming the tube, following changes of temperature, while a simple geometrical construction shows that a drooping of the upper end of the tube, increasing the distance of the plate from the (unreflected) axis of the mirror, can not displace the focus in a direction normal to the plate, if it is assumed that the field is flat. The observed effect is probably due to the fact that the focal surface is not flat, but curved. During a long exposure, the observer keeps the guiding star, and therefore, very approximately, all other stars, in the same posi-

tions relatively to the plate; but he has no control over the position of the axis of the mirror, which, by changes of flexure, wanders irregularly over the field. The position of maximum curvature, therefore, also varies, and with it the focus of the guiding star relatively to the cross-wires, where the focal surface is considerably inclined to the field of view. It is certain that the focus does change considerably, whatever the cause may be, and that the best photographic star images are obtained by keeping the focus of the guiding star unchanged during the exposures. This is done by turning the focusing screw of the eye-end.

In making the photographs of nebulae for which the Crossley telescope is at present regularly employed, it was at first our practice to adjust the driving-clock as accurately as possible to a sidereal rate, and then, when the star had drifted too far from its original position, on account of changes of rate or of flexure, to bring it back by the right-ascension slow motion, the observer either closing the slide of the plate-holder or following the motion of the star as best he could with the right-ascension screw. Lately a more satisfactory method, suggested by Mr. Palmer, has been employed. The slow motion in right ascension is of Grubb's form,¹ and the telescope has two slightly different rates, according to whether the loose wheel is stopped or allowed to turn freely. The driving-clock is adjusted so that one of these rates is too fast, the other too slow. At the beginning of an exposure the wheel is, say, unclamped, and the guiding star begins to drift very slowly toward the left, the observer following it with the screw of the plate-holder. When it has drifted far enough, as indicated by the pins mentioned farther above, the wheel is clamped. The star then reverses its motion and begins to drift toward the right; and so on throughout the exposure. The advantages of this method over the one previously employed are, that the star never has to be moved by the slow motion of the telescope, and that its general drift is in a known direction, so that its movements can be anticipated by the observer. In this way photographs are obtained, with four hours' exposure, on which the smallest star disks are almost perfectly round near the center of the plate, and from 2" to 3" in diameter.

The star images are practically round over a field at least 1 inch or 16' in diameter. Farther from the center they become parabolic, but they are quite good over the entire plate, $3\frac{1}{4}$ by $4\frac{1}{4}$ inches.

From these statements it will be seen that small irregularities in driving no longer present any difficulties. But certain irregular motions of the image still take place occasionally, and so far it has not been possible entirely to prevent their occurrence.

It was found that the declination clamp (the long slow-motion handle attached to which is shown in the illustration) was not sufficiently powerful to hold the telescope firmly during a long exposure. A screw clamp was therefore added, which

¹*Mon. Not. R. A. S.*, 48, 352.

forces the toothed-declination sector strongly against an iron block just behind it, thus restoring, I think, the original arrangement of the declination clamp as designed by Dr. Common. This clamp holds the tube very firmly.

The irregularities to which I have referred consist in sudden and unexpected jumps of the image, which always occur some time after the telescope has passed the meridian. These jumps are sometimes quite large—as much as one-sixteenth of an inch or 1. They are due to two causes: flexure of the tube, and sliding of the mirror on its bed. When the jump is due to sudden changes of flexure, the image moves very quickly, and vibrates before it comes to rest in its new position, and at the same time there is often heard a slight ringing sound from the tension rods of the tube. There seems to be no remedy for the sudden motions of this class. The tension rods are set up as tightly as possible without endangering the threads at their ends or buckling the large corner tubes. A round telescope tube, made of spirally-wound steel ribbon riveted at the crossings, would probably be better than the square tube now in use.

Jumps due to shifting of the mirror are characterized by a gentle, gliding motion. They can be remedied, in part, at least, by tightening the copper bands which pass around the circumference of the mirror within its cell. This will be done the next time the mirror is resilvered.

All that the observer can do when a jump occurs is to bring back the image as quickly as possible to the intersection of the cross-wires. If all the stars on the plate are faint, no effect will be produced on the photograph; but stars of the eighth magnitude or brighter will leave short trails. The nebula, if there is one on the plate, will, of course, be unaffected.

Before beginning an exposure the focus is adjusted by means of a high-power positive eyepiece. An old negative, from which the film has been partially scraped, is placed in one of the plate-holders, and the film is brought into the common focus of the eyepiece and the great mirror. The appearance of the guiding star, which varies somewhat with the position of the guiding eyepiece on its slide, is then carefully noted, and is kept constant during the exposure by turning, when necessary, the focusing screw of the eye-end. For preliminary adjustments a ground-glass screen is often convenient. On it all the *DM.* stars, and even considerably fainter ones, as well as the nebulae of Herschel's Class I, are easily visible without a lens.

Plates are backed, not more than a day or two before use, with Carbutt's "Columbian backing," which is an excellent preparation for this purpose. During the exposure the observer and assistant exchange places every half hour, thereby greatly relieving the tediousness of the work, though two exposures of four hours each, in one night, have proved to be too fatiguing for general practice. At the end of the first two hours it is necessary to close the slide and wind the clock.

The brightness of the guiding star is a matter of some importance. If the star is too bright, its glare is annoying; if it is too faint, the effort to see it strains the eye, and changes of focus are not easily recognized. A star of the ninth magnitude is about right. In most cases a suitable star can be found without difficulty.

In such an apparatus as that described above, the amount by which the plate may be allowed to depart from its zero position is subject to a limitation which has not, I think, been pointed out, although it is sufficiently obvious when one's attention has been called to it. It depends upon the fact that the plate necessarily moves as a whole, in a straight line which is tangent to a great circle of the sphere, while the stars move on small circles around the pole. The compensation for drift, when the plate is moved, is therefore exact at the equator only.

Let the guiding star have the declination δ_1 , and let a star on the upper edge of the plate (which, when the telescope is north of the zenith, and the eye-end is on the north side of the telescope, will be the southern edge) have the declination δ_2 . Then if the guiding star is allowed to drift from its zero position through the distance d , the other star will drift through the distance $d \frac{\cos \delta_2}{\cos \delta_1}$. If the guiding star is followed by turning the right-ascension screw, the upper edge of the plate, as well as the guiding eyepiece, will be moved through the distance d . Hence there will be produced an elongation of the upper star, represented by

$$e = d \left(\frac{\cos \delta_2}{\cos \delta_1} - 1 \right)$$

$$\text{from which } d = \frac{e \cos \delta_1}{\cos \delta_2 - \cos \delta_1}.$$

Now, in the Crossley reflector, the upper edge of the plate and the guiding eyepiece are just about $3\frac{2}{3}$ inches, or 1° , apart. If e is given, the above formula serves to determine the maximum range of the slide for different positions of the telescope.

It has been stated farther above that the smallest star disks, on a good photograph, are sometimes not more than $2''$ in diameter, or in a linear measure, about $\frac{1}{16}$ mm. An elongation of this amount is therefore perceptible. There are many nebulae in high northern declinations, and there are several particularly fine ones in about $+70^\circ$. If, therefore, we take $\delta_2 = 70^\circ$, $\delta_1 = 71^\circ$, $e = 0.05$, and substitute these values, we find $d = 1.0$ mm, which is the greatest permissible range of the plate in photographing these nebulae. Before I realized the stringency of this requirement, by making the above simple computation, I spoiled several otherwise fine negatives by allowing the plate to get too far from the center, thus producing elongated star images.

There is a corresponding elongation in declination, the amount of which can

be determined by an adaptation of the formula for reduction to the meridian, but it is practically insensible.

On account of the short focal length of the three-foot mirror, the photographic resolving power of the telescope is much below its optical resolving power. For this reason the photographic images are less sensitive to conditions affecting the seeing than the visual images. On the finest nights the delicate tracery of bright lines or caustic curves in the guiding star is as clear and distinct as in a printed pattern. When the seeing is only fair these delicate details are lost, and only the general form of the image, with its two principal caustics, is seen. A photograph taken on such a night is not, however, perceptibly inferior to one taken when the seeing is perfect. When, however, the image is so blurred that its general form is barely distinguishable, the photographic star disks are likewise blurred and enlarged, and on such nights photographic work is not attempted.

The foregoing account of the small changes which have been made in the Crossley telescope and its accessories may appear to be unnecessarily detailed, yet these small changes have greatly increased the practical efficiency of the instrument, and, therefore, small as they are, they are important. Particularly with an instrument of this character, the difference between poor and good results lies in the observance of just such small details as I have described.

At present the Crossley reflector is being used for photographing nebulae, for which purpose it is very effective. Some nebulae and clusters, like the great nebula in *Andromeda* and the *Pleiades*, are too large for its plate ($3\frac{1}{4} \times 4\frac{1}{4}$ in.), but the great majority of nebulae are very much smaller, having a length of only a few minutes of arc, and a large-scale photograph is required to show them satisfactorily. It is particularly important to have the images of the involved stars as small as they can be made.

Many nebulae of Herschel's I and II classes are so bright that fairly good photographs can be obtained with exposures of from one to two hours; but the results obtained with full-light action are so superior to these, that longer exposures of three and one half or four hours are always preferred. In some exceptional cases, exposures of only a few minutes are sufficient. The amount of detail shown, even in the case of very small nebulae, is surprising. It is an interesting fact that these photographs confirm (in some cases for the first time) many of the visual observations made with the six-foot reflector of the Earl of Rosse.

Incidentally, in making these photographs, great numbers of new nebulae have been discovered. The largest number that I have found on any one plate is thirty-one. Eight or ten is not an uncommon number, and few photographs have been obtained which do not reveal the existence of three or four. A catalogue of these new objects will be published in due time.

Some of the results obtained with the Crossley reflector, relating chiefly to

particular objects of some special interest, have already been published.¹ The photographs have also permitted some wider conclusions to be drawn, which are constantly receiving further confirmation as the work progresses. They may be briefly summarized as follows:

1. Many thousands of unrecorded nebulae exist in the sky. A conservative estimate places the number within reach of the Crossley reflector at about 120,000. The number of nebulae in our catalogues is but a small fraction of this.

2. These nebulae exhibit all gradations of apparent size, from the great nebula in *Andromeda* down to an object which is hardly distinguishable from a faint star disk.

3. Most of these nebulae have a spiral structure.

To these conclusions I may add another, of more restricted significance, though the evidence in favor of it is not yet complete. Among the objects which have been photographed with the Crossley telescope are most of the "double" nebulae figured in Sir John Herschel's catalogue (*Phil. Trans.*, 1833, Plate XV). The actual nebulae, as photographed, have almost no resemblance to the figures. They are, in fact, spirals, sometimes of very beautiful and complex structure; and, in any one of the nebulae, the secondary nucleus of Herschel's figure is either a part of the spiral approaching the main nucleus in brightness, or it can not be identified with any real part of the object. The significance of this somewhat destructive conclusion lies in the fact that these figures of Herschel have sometimes been regarded as furnishing analogies for the figures which Poincaré had deduced, from theoretical considerations, as being among the possible forms assumed by a rotating fluid mass; in other words, they have been regarded as illustrating an early stage in the development of double star systems. The actual conditions of motion in these particular nebulae, as indicated by the photographs, are obviously very much more complicated than those considered in the theoretical discussion.

¹The following list includes all papers of interest:

"Photographic Observations of Comet I, 1898 (Brooks), made with the Crossley Reflector of the Lick Observatory." *A. J.* No. 451, **19**, 151; see also *Ap. J.*, **8**, 287.

"The Small Bright Nebula near *Meropé*," *Pub. A. S. P.*, **10**, 245.

"On Some Photographs of the Great Nebula in *Orion*, taken by means of the Less Refrangible Rays in its Spectrum," *Ap. J.*, **9**, 133. See also *Pub. A. S. P.*, **11**, 70; *Ap. J.*, **10**, 167; *A. N.*, 3601.

"Small Nebulae discovered with the Crossley Reflector of the Lick Observatory," *Mon. Not. R. A. S.*, **59**, 537.

"The Ring Nebula in *Lyra*," *Ap. J.*, **10**, 193.

"The Annular Nebula H. IV. 13 in *Cygnus*," *Ap. J.*, **10**, 266; see also *Pub. A. S. P.*, **11**, 177.

"On the Predominance of Spiral Forms among the Nebulae," *A. N.*, 3601.

"The Distribution of Stars in the Cluster *Messier 13* in *Hercules*" (by H. K. Palmer), *Ap. J.*, **10**, 246.

"The Photographic Efficiency of the Crossley Reflector," *Pub. A. S. P.*, **11**, 199; *Observatory*, **22**, 437.

"New Nebulae discovered photographically with the Crossley Reflector of the Lick Observatory," *Mon. Not. R. A. S.*, **60**, 128.

"The Spiral Nebula, H. I., 55 *Pegasi*," *Ap. J.*, **11**, 1.

"Photographic Observations of Hind's Variable Nebula in *Taurus*, made with the Crossley Reflector of the Lick Observatory," *Mon. Not. R. A. S.*, **60**, 424.

"Use of the Crossley Reflector for Photographic Measurements of Position," *Pub. A. S. P.*, **12**, 73.

"Discovery and Photographic Observations of a New Asteroid 1899 FD.," *A. N.*, 3635.

"Elements of Asteroid 1899 FD." (by H. K. Palmer), *A. N.* 3635.

While I must leave to others an estimate of the importance of these conclusions, it seems to me that they have a very direct bearing on many, if not all, questions concerning the cosmogony. If, for example, the spiral is the form normally assumed by a contracting nebulous mass, the idea at once suggests itself that the solar system has been evolved from a spiral nebula, while the photographs show that the spiral nebula is not, as a rule, characterized by the simplicity attributed to the contracting mass in the nebular hypothesis. This is a question which has already been taken up by Professor Chamberlin and Mr. Moulton of the University of Chicago.

The Crossley reflector promises to be useful in a number of fields which are fairly well defined. It is clearly unsuitable for photographing the Moon and planets, and for star charting. On the other hand, it has proved to be of value for finding and photographically observing asteroids whose positions are already approximately known.

One of the most fruitful fields for this instrument is undoubtedly stellar spectroscopy. Little has been done in this field, as yet, with the Crossley reflector, but two spectrographs, with which systematic investigations will be made, have nearly been completed by the Observatory instrument-maker. One of these, constructed with the aid of a fund given by the late Miss C. W. Bruce, has a train of three 60° prisms and one 30° prism, and an aperture of two inches; the other, which has a single quartz prism, will, I have reason to expect, give measurable, though small, spectra of stars nearly at the limit of vision of the telescope.

The photogravure* of the Trifid nebula, which accompanies this article, was made from a photograph taken with the Crossley reflector on July 6, 1899, with an exposure of three hours. It was not selected as a specimen of the work of the instrument, for the negative was made in the early stages of the experiments that I have described, and the star images are not good, but rather on account of the interest of the subject. At the time the photogravures were ordered no large scale photograph of the Trifid nebula had, so far as I am aware, ever been published.¹ The remarkable branching structure of the nebula is fairly well shown in the photogravure, though less distinctly than in the transparency from which it was made. The enlargement, as compared with the original negative, is 2.9 diameters ($1 \text{ mm} = 13''$). The fainter parts of the nebula would be shown more satisfactorily by a longer exposure.

*Footnote added in 1908: This concluding paragraph, retained in the present publication for completeness, loses point in some particulars, because the photogravure referred to is not reproduced here. The heliogravure reproduction of the Trifid nebula is No. 55.

¹Since then a photograph by Dr. Roberts has appeared in *Knowledge*, 23, 35, February, 1900.