what he calls his "duplex micrometer," shown in perspective in fig. 18:—"A plate of glass about $2\frac{1}{2}$ inches square is ruled with twenty-one lines in one direction $\frac{1}{10}$th inch apart, and two lines in the other direction 2 inches apart. The extreme lines of the set therefore form a perfect square of 2 inches. These lines are ruled with exceeding accuracy and care, but provision is left for ascertaining any errors that remain either as to distance or want of perfect squareness. Along one side of the square is mounted a micrometer frame in the ordinary way, actuated by a screw of one hundred threads to the inch. This micrometer frame carries eleven lines corresponding exactly to each alternate line in the glass reticule, so that when the first spider line is made coincident with the first diamond line on the glass the last spider line will be coincident with the last line on the glass, and each of the spider lines will be coincident with all the odd numbers of diamond lines, 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21. Over this glass plate is placed a brass cap in which two eye-pieces are mounted, one sliding in a groove at right angles to the other,—so that, while one has its journey backwards and forwards on the horizontal line, the other has its journey on the vertical line, according to how the cap is placed, for this cap is capable of rotation to meet various circumstances.

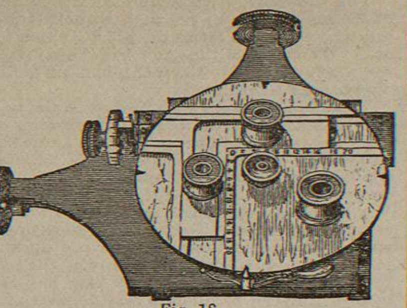
Fig. 18.

"*How to Use the Instrument.*—1. The two stars are brought on the horizontal line, and the distance measured from centre to centre along that line. This distance is measured by counting the number of spaces on the glass, adding the residue as measured by the micrometer screw. Thus the screw is never used for larger measures than $\frac{1}{10}$th inch, and therefore errors of screw and temperature errors are much reduced. In bisecting, one star is brought into the field of one eye-piece, and a bisection is made with one of the diamond lines by moving the micrometer by one or other of its slipping piece screws. Then the other eye-piece is moved till the second star is seen, and a bisection is made with the nearest spider line by moving the micrometer head. Then the eye can be moved back to the first eye-piece, and the bisection checked, and again back to the other eye-piece. When it is seen that both are satisfactory the measure can be read off. 2. The micrometer is turned round till the horizontal line becomes parallel to the path of apparent motion of the star. This is easily found by stopping the clock and allowing the star to run along the horizontal wire. Now the other star will be found to cross the vertical line somewhere, while the first star is on the horizontal line. This second star is then bisected on the vertical line, while the first star is bisected by one of the spider lines; thus the difference in right ascension is found. We then have two sides of a right-angled triangle and of course all the elements are known.

"*To Ascertain the Errors* (*if any*) *of the Distance of the Lines.*—Of course, the usual plan of taking transits can be adopted, and to ascertain if the lines be perfectly at right angles a special additional eye-piece is provided, so that transits can be taken across each diagonal of the square."

This instrument has great advantage over Clark's in ease of adjustment and use, and has done good work at the University Observatory, Oxford (*Mem. R. A. S.*, vol. xlvii. pp. 5–12). Professor Pritchard claims too much when he estimates its work as equal in accuracy with that of the heliometer—at least the published results do not confirm such a view. But it is a very valuable instrument for measuring objects too faint for the limited aperture of most heliometers, and which at the same time are farther apart than the field of view of an ordinary eye-piece.

The accuracy of the duplex micrometer would be very greatly increased if Clark's idea (above mentioned) of viewing both widely separated webs in one eye-piece of high power could be reduced to a convenient practical form.

Method of Webbing the Filar Micrometer

The webbing of a micrometer is a process that should be familiar to all practical astronomers. English opticians usually proceed as follows. A spider (the variety is marked by a cross on the back, and is found in English gardens about decayed wood) is caught, and placed on a wire fork. The insect immediately attaches a web to the wire and begins to lower itself by a web to the ground. This web is wound up on the fork till ten or twelve turns, separated by a convenient space, have been secured. A brush with varnish is then passed along the prongs; the webs are thus securely fixed to the fork. The parallel prongs of the fork must be sufficiently far apart to allow the web-frame of the micrometer to pass between them. The frame to be webbed is placed on a flat dull black surface between the prongs of the fork, the latter being carefully arranged so that one of the webs lies nearly in the furrow ruled in the frame for its reception. As the web-frame is generally thicker than the fork, the web will now be stretched across the former, with a certain amount of tension, and is brought into the furrow with a finely pointed piece of soft wood. If the surface of the frame is well polished, and the furrows sharply cut, without "burr," the web should leap sharply and decidedly into its place. Each end of the web is then secured by a drop of shellac varnish, which should be allowed to harden thoroughly before the frame is touched. The webs can be very readily so handled against a black background, with the aid of a hand lens of 2 or 3 inches focus. In experienced hands this method gives good results, but the following, which is generally followed on the Continent, is preferable.

A web, about 2 inches longer than the width of the frame, is unwound from a cocoon,[1] and small pieces of lead are attached to its extremities by beeswax. One end of the web, with its attached lead, is laid on a piece of cork floating in a tumbler of water; the other end is allowed to hang down in the water, where it becomes thoroughly saturated and untwisted. It is then laid across the fork, and dropped into its furrows in the manner above described, the little lead weights exerting a definite tension. Varnish[2] is immediately applied to secure the webs, and the frame is not touched till it is dry.

The bevel-edge of the web-frame introduced by Repsold (type D) offers great facilities for accurate webbing, and should be employed in all future micrometers.

Illumination of Micrometers.

When micrometer observations are made by night it is necessary to have some mode of rendering the webs visible,—either by rays of light at right angles to the axis illuminating the webs, or by rays nearly coincident with the axis of the telescope. In the former case we get bright webs in a dark field, in the latter dark webs on a bright field.

In the older telescopes bright web illumination is produced by small lamps with nozzles that enter the tubes L, L (fig. 9). The illumination is regulated in colour and intensity by wedges of coloured or darkened glass passing through slides in the nozzles. But it is inconvenient to have lamps so near the observer's eye, and it is at least very difficult to obtain a perfectly dark field when the wires are illuminated in this way.

The Clarks, in their micrometer of the great Washington telescope, have made the end of box T (fig. 15) transparent, and light is thrown on the webs from a lamp held by an assistant. Holden has very recently applied a lamp ingeniously hung so as to preserve its verticality and the constant direction of its light in a similar way, adding a plain silvered mirror inside the box and opposite the lamp, so as to illuminate the webs symmetrically. In the Clarks' and Holden's methods it is only the webs at right angles to the screw that are illuminated.

For illumination of the field, in very old telescopes, light was thrown on a small ivory reflector fixed outside the object-glass in the axis of the telescope by an arm fitting on the cell of the lens. This involved the aid of an assistant to direct lamplight on the ivory reflector, or the very frequent change of a lamp support. Afterwards the light from an attached lamp was introduced through a hole in the telescope-tube and thrown upon an elliptical plane (generally dull-gilt) having its centre part cut away sufficiently to avoid interruption of the cone of rays from the object-glass. Many ingenious modes of suspending the lamp have been invented for the purpose of securing a constant direction of its light coupled with verticality of the lamp. One of the best of these, due to Cooke, is shown in fig. 19. L is the lamp, P a prism to reflect

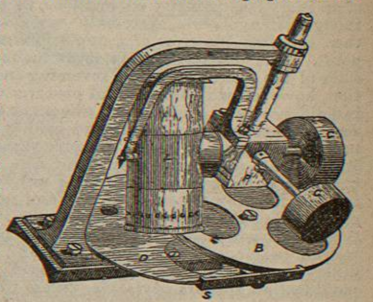

Fig. 19.

its light into the tube, D a disk to regulate the quantity of light, B a disk with glasses to regulate the colour of the light, S a spring to clamp the disks, C the counterpoise of the lamp, G a poise to preserve the horizontality of the axis CL. But astronomers owe to the genius of Grubb the introduction of a more efficient and convenient system, viz., the performance of all necessary illumination of an astronomical telescope by a single lamp, and the perfect control of the illumination of the field or webs, and the regulation of these as to intensity or colour by simple motions from the eye-end. It is impossible to speak too highly of Grubb's efforts in this direction: he has broken the ground in this department of astronomical engineering, and rendered the working of so huge an instrument as the Vienna telescope of 27 inches aperture not only convenient, but easier for a single observer than that of a very small telescope of the older constructions.

But in the illumination of the field wires and scales of a micrometer Grubb's original method has recently been surpassed by one which is due to the Repsolds. We shall therefore describe the latter.

Fig. 20 represents the eye-end of a telescope. The reader will recognize the micrometer (figs. 16 and 17) previously described. L is a paraffin lamp fitting by a bayonet joint into a copper cover *c*. This effectually defends its glass chimney against accident, and protects the lamp from wind. The simple means by which this lamp is made to preserve its verticality in all positions of the telescope is evident from the figure. By this lamp alone the bright wire or bright field illumination is given at pleasure, and with any desired intensity, simply by movement of the small pin *p*.

The position circle and the head of the micrometer are also illuminated, as well as the declination circle, by the same lamp. AB is a cylindrical box, ending in a truncated cone towards A. It is shown, mid-section, in a plane passing through the telescope axis, in fig. 21, where all details unnecessary to the explanation of the illumination are omitted, and proportion of parts is sacrificed to clearness. P is a prism (fig. 21) that rotates with the lamp and reflects its light into AB. The flame of the lamp is in the focus of the lens *ll*, so that the rays become parallel after passing through it. There is a sliding motion to perfect this adjustment. There is a well-polished flat annular reflector of speculum metal *rr* (fig. 21), which reflects light upon the double mirror M (fig. 20), whence it is diverted to the two opposite points on the declination circle that are read by micrometer microscopes from the eye-end (the latter are omitted for sake of clearness).

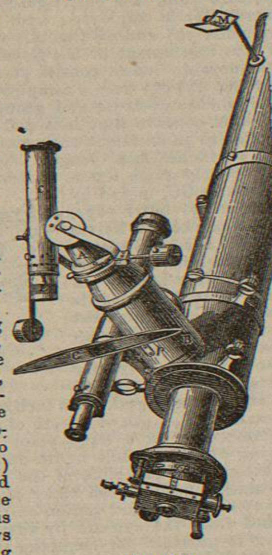

Fig. 20.

The little handle at *p′* and the dotted lines *p′z* represent an iris-diaphragm, very ingeniously constructed, mounted on a plate of transparent glass. There is a flat ring of brass, carrying four pins, which is turned by the handle *p′*, in a plane at right angles to P*n*. These pins work in spiral slots cut in four slides. Thus rotation of the ring causes the four slides to approach or recede from a centre. When the handle *p′* is in the middle of its range, the slides together form a disk as large as the hole in the diaphragm *dd*, and thus prevent all light from entering the telescope tube. When *p′* is pushed to one side of its range the slides move outwards leaving a square opening in the centre so that the light falls on the prism *n*, whence it is diverted to a silvered reflector cemented on the middle of the inner surface of the object-glass, and is then reflected back along the axis of the telescope to illuminate the field at *ω*. When *p′* is pushed to the other side of its range the slides approach and overlap at the centre, excluding light from *n* and allowing it to fall upon the reflector *s* instead. From *s* the light is thrown upon the webs *ω*, *ω* by reflexion from a white papier maché surface laid on the inside of a thin hollow brass truncated cone *xx*. The edge of this cone forms the circle seen within *ττ* in fig. 17. All stray light is prevented by the light-guard tube *mm*, which is attached to and moves with the rotating part of the micrometer. The result is to produce a symmetrical illumination of the whole system of webs in a perfectly dark field. It is also obvious that by placing *p′* at an intermediate position between the centre and the extremes of its range any desired modification of bright wire or bright field illumination can be obtained at pleasure.

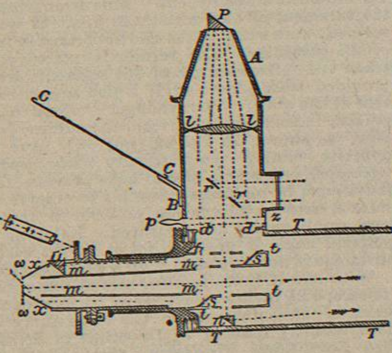

Fig. 21.

The light falling on the papier maché hollow cone is intercepted at three points by prisms, one of which *μ* is shown in section. These prisms are inserted in the cylinder which carries the foundation plate of the micrometer box and rotate with it. Two of them divert light upon the reflectors (seen from different points of view in figs. 16, 17, 20). The third prism after two reflexions (figs. 16, 20) illuminates the micrometer head. The whole arrangement is in the highest degree elegant, and we have found it most simple and convenient in practice. The screen C (figs. 20 and 21)—made of thin copper and attached to AB—effectually protects the observer's eye from stray light from the lamp.

It has been found essential, in bright field illumination, when the highest accuracy is desired, to have the illuminating rays parallel with the telescope axis.

In the best telescopes of the future some plan like that of Repsold's, above described, will doubtless be adopted. It is probable also that with the introduction of condensers, in conjunction with the incandescent carbon light in vacuum, electricity will ultimately supersede the oil or paraffin lamp in illuminating astronomical instruments. A small "Swan lamp" can be placed anywhere, is unaffected by wind, and gives off comparatively little heat. These are most valuable qualities for the purpose in question.

The astronomer-royal (Mr Christie) has recently used luminous paint to render the measuring pointer of the Greenwich spectroscope visible at night. This paint, after exposure during the day to sunlight, shines at night with a dull phosphorescence sufficient to make the micrometer pointer, to which it is applied, faintly visible, and, it is stated, with very satisfactory results.

On the use of the filar micrometer consult Struve, *Mensuræ Micrometricæ*, St Petersburg, 1837; Brunnow, *Practical and Spherical Astronomy*; Chauvenel, *Practical and Spherical Astronomy*; Brunnow, *Astronomical Observations and Researches made at Dunsink*, Dublin, 1870, 1873, 1879; Ball, *ibid.*; Kaiser, *Leiden Observations*; and the papers of Dembowski in the *Astronomische Nachrichten.*

Double-Image Micrometers.

The discovery of the method of making measures by double images is stated to have been first suggested by Roemer about 1678. But no such suggestion occurs in the *Basis Astronomiæ* of Horrebow (Copenhagen, 1735), which contains the only works of Roemer that remain to us. It would appear that to Savary is due the first invention of a micrometer for measurement by double image. His heliometer (described in a paper communicated to the Royal Society in 1743, and printed, along with a letter from Short, in *Phil. Trans.*, 1753, p. 156) was constructed by cutting from a complete lens *abcd* the equal portions *aghc* and *acfe* (fig. 22). The segments *gbh* and *efd* so formed were then attached to the end of a tube having an internal diameter represented by the dotted circle (fig. 23). The width of each of the portions *aghc* and *acfe* cut away from the lens was made slightly greater than the focal length of lens × tangent of sun's greatest diameter. Thus at the focus two images of the sun were formed nearly in contact as in fig. 24. The small interval between the adjacent limbs was then measured with a wire micrometer.

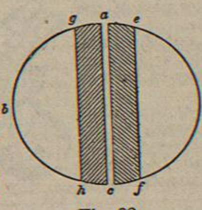

Fig. 22.

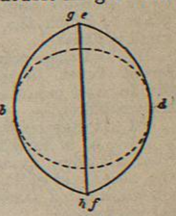

Fig. 23.


Fig. 24.

Savary also describes another form of heliometer, on the same principle, in which the segments *aghc* and *acfe* are utilized by cementing their edges *gh* and *ef* together (fig. 25), and covering all except the portion indicated by the unshaded circle. Savary expresses preference for this second plan, and makes the pertinent remark that in both these models "the rays of red light in the two solar images will be next to each other, which will render the sun's disk more easy to be observed than the violet ones." This

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[1] It is asserted that webs from cocoons are more elastic, better shaped, and more durable than those obtained during an effort of the insect to escape. The best webs we have seen were from a cocoon obtained in Holland, but we have been unable to ascertain the name of the variety of spider.

[2] Argelander used to apply two drops of varnish at each end of his webs. He first fixed each extremity by a drop of shellac varnish, and after that had dried he applied a drop of copal varnish nearer the centre of the frame; the latter took a long time to harden, but gave ultimately a much stronger attachment.

he mentions "because the glasses in these two sorts are somewhat prismatical, but mostly those of the first model, which could therefore bear no great charge" (magnifying power).

A third model proposed by Savary consists of two complete lenses of equal focal length, mounted in cylinders side by side, and attached to a strong brass plate (fig. 26). Here, in order to fulfil the purposes of the previous models, the distance of the centres of the lenses from each other should only slightly exceed the tangent of sun's diameter × focal length of lenses. Savary dwells on the difficulty both of procuring lenses sufficiently equal in focus and of accurately adjusting and centring them.

Fig. 25.

In the *Mém. Acad. de Paris*, 1748, Bouguer describes an instrument which he calls a heliometer. Lalande in his *Astronomie* (vol. ii. p. 639) mentions such a heliometer which had been in his possession from the year 1753, and of which he gives a representation on Plate XXVIII., fig. 186, of the same volume. Bouguer's heliometer was in fact similar to that of Savary's third model, with the important difference that, instead of both object-glasses being fixed, one of them is movable by a screw provided with a divided head. No auxiliary filar micrometer was required, as in Savary's heliometer, to measure the interval between the limbs of two adjacent images of the sun, it being only necessary to turn the screw with the divided head to change the distance between the object-glasses till the two images of the sun are in contact as in fig. 27. The differences of the readings of the screw, when converted into arc, afford the means of measuring the variations of the sun's apparent diameter.

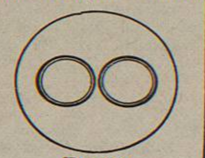
Fig. 26.


Fig. 27.

On the 4th April 1754 Dollond communicated a paper to the Royal Society of London (*Phil. Trans.*, vol. xlviii. p. 551) in which he shows that a micrometer can be much more easily constructed by dividing a single object-glass through its axis than by the employment of two object-glasses. He points out—(1) that a telescope with an object-glass so divided still produces a single image of any object to which it may be directed, provided that the optical centres of the segments are in coincidence (*i.e.*, provided the segments retain the same relative positions to each other as before the glass was cut); (2) that if the segments are separated in any direction two images of the object viewed will be produced; (3) that the most convenient direction of separation for micrometric purposes is to slide these straight edges one along the other as the figure on the margin (fig. 28) represents them: "for thus they may be moved without suffering any false light to come in between them; and by this way of removing them the distance between their centres may be very conveniently measured, viz., by having a vernier's division fixed to the brass work that holds one segment, so as to slide along a scale on the plate to which the other part of the glass is fitted."

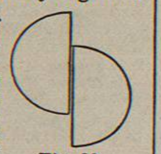
Fig. 28.

Dollond then points out three different types in which a glass so divided and mounted may be used as a micrometer:—

"1. It may be fixed at the end of a tube, of a suitable length to its focal distance, as an object-glass,—the other end of the tube having an eye-glass fitted as usual in astronomical telescopes.

"2. It may be applied to the end of a tube much shorter than its focal distance, by having another convex glass within the tube, to shorten the focal distance of that which is cut in two.

"3. It may be applied to the open end of a reflecting telescope, either of the Newtonian or the Cassegrain construction."

Dollond adds his opinion that the third type is "much the best and most convenient of the three"; yet it is the first type that has survived the test of time and experience, and which is in fact the modern heliometer

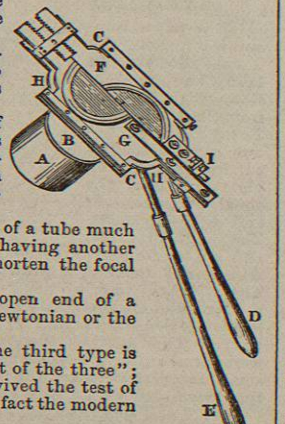

Fig. 29.

Fig. 29 illustrates Dollond's divided object-glass heliometer of the third type. A is the end of the reflecting telescope, upon which the adapter B is fitted. B carries a wheel (not seen in the figure) formed of a ring racked at the outer edge, and fixed to the brass plate CC, so that a pinion moved by the handle D may turn it into any position. Two plates F, G, with the attached semi-lenses, move in slides fixed to the plate CC,—simultaneous motion, in contrary directions, being communicated to them by turning the handle E, which drives a concealed pinion that works in the two racks seen in the highest part of the figure. The amount of separation of the semi-lenses is measured by a scale 5 inches long, subdivided to $\frac{1}{20}$th of an inch, and read by a vernier on the plate F to $\frac{1}{500}$th of an inch. In practical use this micrometer has never given satisfactory results (see Mosotti in the *Efemeride* of Milan for 1821). It must be remembered, however, that when Dollond gave preference to this type he had not invented the achromatic object-glass; his preference was fully justified under these circumstances. So far as we know no heliometer with a divided achromatic object-glass was ever made by the elder Dollond on the principle of his first type. His son, however, made what he called an object-glass micrometer, which was a great improvement on the elder Dollond's second type.

In the older construction the brass mountings of the semi-lenses obstructed the light entering the telescope in proportion to their separation, and the images were so coloured as to prevent the use of any but very low powers. In the later construction the movable segments are formed from a negative achromatic lens of much larger aperture than the object-glass of the telescope with which the micrometer is employed; and, for convenience in mounting, the segments *gbh* and *edf* (fig. 22) are removed. In the fine example of this instrument at the Royal Observatory, Cape of Good Hope, the movable lenses consist of segments of the shape *gach* and *eacf* (fig. 22) cut from a complete negative achromatic combination of 8¼ inches aperture and about 41 feet focal length, composed of a double concave flint lens and a double convex crown. This is applied to an excellent achromatic telescope of 3¼ inches aperture and 42 inches focal length. The instrument is represented in fig. 30; the same letters indicate the analogous parts of fig. 29. The frame CC, moved by teeth on its outer edge, carries one of the halves G of the lens, and a similar frame with teeth carries the other half F. A scale 8½ inches long is fastened like an edge-bar to the frame of the segment G, and each inch is subdivided into twenty parts, which are read off by a vernier to $\frac{1}{1000}$th of an inch, and, by estimation, this can easily be carried to $\frac{1}{2000}$th or $\frac{1}{3000}$th of an inch. The two movable frames are imbedded in a fixed plate HH, screwed to the adapter B, having a circular hole in its middle equal to the diameter of the object-glass. The slide of the segment G is moved by turning the milled head to the right of A, and the other segment F by means of a rack and pinion on the opposite side, the latter being turned from the eye-end by a handle not seen in the figure. A screw is provided for clamping the slide of the segment G, as it is intended that only the segment F shall be moved in making the final bisection. There is an index attached to the slide of G, reading on a rough scale engraved on the plate H, which is obviously intended for setting the optical centre of the segment G approximately as far from the optical axis of the telescope on one side as the optical centre of the segment F will be on the other side during the intended measurement. This arrangement not only permits the measurement of angles twice as great as would be possible if one segment were fixed, but is also important in increasing the symmetry of the measures. The vernier is placed at one end of the scale when the optical centres of the segments are in coincidence, and is provided with screws at I, which are intended for adjusting the zero of the scale. The younger Dollond has in this model retrograded, in some respects, from the admirable example of his father, who, as shown in fig. 29, not only gave the lenses automatic opposite motion symmetrically with respect to the axis of the telescope, but seems also to have provided for entire elimination of index error by making it possible to observe all angles on opposite sides of zero—a precaution possible in the later form only when very small angles are measured. Rotation of the micrometer in position angle is provided for as in the earlier form, but the instrument is not furnished with a position circle.

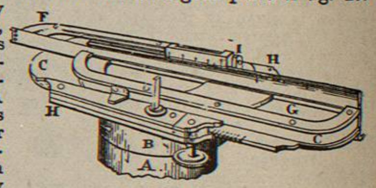

Fig. 30.

With one of these instruments of somewhat smaller dimensions (telescope 2½ inches aperture and 3½ feet focus) Triesnecker made a series of measurements at the observatory of Vienna which has been recently reduced by Dr Schur of Strasburg (*Nova Acta der Ksl. Leop.-Carol. Deutschen Akademie der Natursforscher*, xlv. No. 3). The angle between the stars ζ and g Ursæ maj. (708″·55) was measured on four nights; the probable error of a measure on one night was ± 0″·44. Jupiter was measured on eleven nights in the months of June and July 1794; from these measures Schur derives the values 35″·39 and 37″·94 for the polar and equatorial diameter respectively, at mean distance, corresponding with a compression 1/14·44. These agree satisfactorily with the corresponding values

35″·21, 37″·60, 1/15·69 afterwards obtained by Bessel (*Königsberger Beobachtungen*, xix. 102). From a series of measures of the angle between Jupiter's satellites and the planet, made in June and July 1794 and in August and September 1795, Schur finds the mass of Jupiter $=\frac{1}{1048\cdot55\pm1\cdot45}$, a result which accords perfectly with the received value of the mass derived from modern researches. The probable errors for the measures of one night are ±0″·577, ±0″·889, ±0″·542, ±1″·096, for Satellites I., II., III., and IV. respectively. It is probable that Triesnecker deduced the index error from his measures of the diameter of Jupiter, as, in 1794, the measures of diameter are made on the same nights with those of the measures of distance of the satellites, and it is possible that measures of diameter may have been made in 1795 but not published.

Considering the accuracy of these measures (an accuracy far surpassing that of any contemporary observations), it is somewhat surprising that this form of micrometer was never systematically used in any sustained or important astronomical researches, although a number of instruments of the kind were made by Dollond. Probably the last example of its employment is an observation of the transit of Mercury (November 4, 1868) by Mr Mann, at the Royal Observatory, Cape of Good Hope (*Monthly Notices R. A. S.*, vol. xxix. p. 197–209). The most important part, however, which this type of instrument seems to have played in the history of astronomy arises from the fact that one of them was in the possession of Bessel at Königsberg during the time when his new observatory there was being built. In 1812 Bessel measured with it the angle between the components of the double star 61 Cygni and observed the great comet of 1811. He also observed the eclipse of the sun on May 4, 1818. In the discussion of these observations (*Königsberger Beobacht.*, Abth. 5, p. iv) he found that the index error of the scale changed systematically in different position angles by quantities which were independent of the direction of gravity relative to the position angle under measurement, but which depended solely on the direction of the measured position angle relative to a fixed radius of the object-glass. Bessel attributed this to non-homogeneity in the object-glass, and determined with great care the necessary corrections. But he was so delighted with the general performance of the instrument, with the sharpness of the images, and the possibilities which a kindred construction offered for the measurement of considerable angles with micrometric accuracy, that he resolved, when he should have the choice of a new telescope for the observatory, to secure some form of heliometer.

Nor is it difficult to imagine the probable course of reasoning which led Bessel to select the model of his new heliometer. Why, he might ask, should he not select the simple form of Dollond's first type? Given the achromatic object-glass, why should not it be divided? This construction would give all the advantage of the younger Dollond's object-glass micrometer and more than its sharpness of definition, without liability to the systematic errors which may be due to want of homogeneity of the object-glass; for the lenses will not be turned with respect to each other, but, in measurement, will always have the same relation in position angle to the line joining the objects under observation. It is true that the scale will require to be capable of being read with much greater accuracy than $\frac{1}{1000}$th of an inch—for that, even in a telescope of 10 feet focus, would correspond with 2″ of arc. But, after all, this is no practical difficulty,—for screws can be used to separate the lenses, and, by these screws, as in a Gascoigne micrometer, the separation of the lenses can be measured; or we can have scales for this purpose, read by microscopes, like the Troughton[1] circles of Piazzi or Pond, or those of the Carey circle, with almost any required accuracy.

Whether Bessel communicated such a course of reasoning to Fraunhofer, or whether that great artist arrived independently at like conclusions, we have been unable to ascertain with certainty. The fact remains that before 1820[2] Fraunhofer had completed one or more of the five heliometers (3 inches aperture and 39 inches focus) which have since become historical instruments. In 1824 the great Königsberg heliometer was commenced, and it was completed in 1829.

To sum up briefly the history of the heliometer. The first application of the divided object-glass and the employment of double images in astronomical measures is due to Savary in 1743. To Bouguer in 1748 is due the true conception of measurement by double image without the auxiliary aid of a filar micrometer, viz., by changing the distance between two object-glasses of equal focus. To Dollond in 1754 we owe the combination of Savary's idea of the divided object-glass with Bouguer's method of measurement, and the construction of the first really practical heliometers. To Fraunhofer, some time not long previous to 1820, is due, so far as we can ascertain, the construction of the first heliometer with an achromatic divided object-glass, *i.e.*, the first heliometer of the modern type

Double-Image Micrometers with Divided Lenses

Various micrometers have been invented besides the heliometer for measuring by double image. Ramsden's dioptric micrometer consists of a divided lens placed in the conjugate focus of the innermost lens of the erecting eye-tube of a terrestrial telescope. The inventor claimed that it would supersede the heliometer, but it has never done anything for astronomy. Dollond claims the independent invention and first construction of a similar instrument (Pearson's *Practical Astronomy*, vol. ii. p. 182). Of these and kindred instruments only two types have proved of practical value. Amici of Modena (*Mem. Soc. Ital.*, xvii. (1815) pp. 344–359) describes a micrometer in which a negative lens is introduced between the eye-piece and the object-glass. This lens is divided and mounted like a heliometer object-glass; the separation of the lenses produces the required double image, and is measured by a screw. Dawes has very successfully used this micrometer in conjunction with a filar micrometer, and finds that the precision of the measures is in this way greatly increased (*Monthly Notices*, vol. xviii. p. 58, and *Mem. R. A. S.*, vol. xxxv. p. 147).

In the improved form[3] of Airy's divided eye-glass micrometer (*Mem. R. A. S.*, vol. xv. pp. 199–209), the rays from the object-glass pass successively through lenses as follows.

Lens	Distance from next Lens.	Focal Length.
a. An equiconvex lens	p	arbitrary $=p$
b. " "	2	5
c. Plano-convex, convex towards *b*	1¾	1
d. Plano-convex, convex towards *c*	...	1

The lens *b* is divided, and one of the segments is moved by a micrometer screw. The magnifying power is varied by changing the lens *a* for another in which *p* has a different value. The magnifying power of the eye-piece is that of a single lens of focus $=\frac{4}{5}p$.

In 1850 Valz pointed out that the other optical conditions could be equally satisfied if the divided lens were made concave instead of convex, with the advantage of giving a larger field of view (*Monthly Notices*, vol. x. p. 160).

The last improvement on this instrument is mentioned in the *Report* of the R. A. S. council, February 1865. It consists in the introduction by Simms of a fifth lens, but no satisfactory description has ever appeared. There is only one practical published[4] investigation of Airy's micrometer that is worthy of mention, viz., that of Kaiser (*Annalen der Sternwarte in Leiden*, iii. pp. 111–274). The reader is referred to that paper for an exhaustive history and discussion of the instrument.[5] It is somewhat surprising that, after Kaiser's investigations, observers should continue, as many have done, to discuss their observations with this instrument as if the screw-value were constant for all angles.

Steinheil's ocular micrometer

Steinheil (*Journal Savant de Munich*, 28th February 1843) describes a "heliomètre-oculaire" which he made for the great Pulkowa refractor, the result of consultations between himself and the elder Struve. It is essentially the same in principle as Amici's micrometer, except that the divided lens is an achromatic positive instead of a negative lens. Struve (*Description de l'Observatoire Central de Pulkowa*, pp. 196, 197) adds a few remarks to Steinheil's description, in which he states that the images have not all desirable precision,—a fault perhaps inevitable in all micrometers with divided lenses, and which is probably in this case aggravated by the fact that the rays falling upon the divided lens have considerable convergence. He, however, successfully employed the instrument in measuring double stars, so close as 1″ or 2″, and using a power of 300 diameters, with results that agreed satisfactorily amongst themselves and with those obtained with the filar micrometer. If Struve had employed a properly proportioned double

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[1] The circles by Reichenbach, then almost exclusively used in Germany, were read by verniers only.

[2] The diameter of Venus was measured with one of these heliometers at the Observatory of Breslau by Brandes in 1820 (*Berlin Jahrbuch*, 1824, p. 164).

[3] For description of the earliest form see *Cambridge Phil. Trans.*, vol. ii., and *Greenwich Observations*, 1840.

[4] We understand that a very thorough investigation of Airy's double-image micrometer used by Dr Copeland at Mauritius on Lord Lindsay's expedition has been made by him, and will soon be published.

[5] Dawes (*Monthly Notices*, January 1858, and *Mem. R. A. S.*, vol. xxxv. p. 150) has suggested and used a valuable improvement for producing round images, instead of the elongated images which are otherwise inevitable when the rays pass through a divided lens of which the optical centres are not in coincidence, viz., "the introduction of a diaphragm having two circular apertures touching each other in a point coinciding with the line of collimation of the telescope, and the diameter of each aperture *exactly equal* to the semidiameter of the cone of rays at the distance of the diaphragm from the focal point of the object-glass." Practically the difficulty of making these diaphragms for the different powers of the *exact* required equality is insuperable: but, if the observer is content to lose a certain amount of light, we see no reason why they may not readily be made slightly less. Dawes found the best method for the purpose in question was to limit the aperture of the object-glass by a diaphragm having a double circular aperture, placing the line joining the centres of the circles approximately in the position angle under measurement. Dawes successfully employed the double circular aperture also with Amici's micrometer. The present writer has successfully used a similar plan in measuring position angles of α Centauri with the heliometer, viz., by placing circular diaphragms on the two segments of the object-glass.

circular diaphragm, fixed symmetrically with the axis of the telescope in front of the divided lens and turning with the micrometer, it is probable that his report on the instrument would have been still more favourable. This particular instrument has historical interest, having led Struve to some of those criticisms of the Pulkowa heliometer which ultimately bore such valuable fruit (see below).

Ramsden (*Phil. Trans.*, vol. xix. p. 419) has suggested the division of the small speculum of a Cassegrain telescope and the production of double image by micrometric rotation of the semi-specula in the plane passing through their axis. Brewster (*Ency. Brit.*, 8th ed., vol. xiv. p. 749) proposes a plan on a like principle, by dividing the plane mirror of a Newtonian telescope. Again, in an ocular heliometer by Steinheil double image is similarly produced by a divided prism of total reflexion placed in parallel rays. But practically these last three methods are failures. In the last the field is full of false light, and it is not possible to give sufficiently minute and steady separation to the images; and there are of necessity a collimator, two prisms of total reflexion, and a small telescope through which the rays must pass; consequently there is great loss of light.

Micrometers Depending on Double Refraction.

To the Abbé Rochon (*Jour. de Phys.*, liii., 1801, pp. 169–198) is due the happy idea of applying the two images formed by double refraction to the construction of a micrometer. He fell upon a most ingenious plan of doubling the amount of double refraction of a prism by using two prisms of rock-crystal, so cut out of the solid as to give each the same quantity of double refraction, and yet to double the quantity in the effect produced. The combination so formed is known as Rochon's prism. Such a prism he placed between the object-glass and eye-piece of a telescope. The separation of the images increases as the prism is approached to the object-glass, and diminishes as it is approached towards the eye-piece.

Arago (*Comptes Rendus*, xxiv., 1847, pp. 400–402) found that in Rochon's micrometer, when the prism was approached close to the eye-piece for the measurement of very small angles, the smallest imperfections in the crystal or its surfaces were inconveniently magnified. He therefore selected for any particular measurement such a Rochon prism as when fixed between the eye and the eye-piece (*i.e.*, where a sunshade is usually placed) would, combined with the normal eye-piece employed, bring the images about to be measured nearly in contact. He then altered the magnifying power by sliding the field lens of the eye-piece (which was fitted with a slipping tube for the purpose) along the eye-tube, till the images were brought into contact. By a scale attached to the sliding tube the magnifying power of the eye-piece was deduced, and this combined with the angle of the prism employed gave the angle measured. If p'' is the refracting angle of the prism, and n the magnifying power of the eye-piece, then p''/n will be the distance observed. Arago made many measures of the diameters of the planets with such a micrometer.

Dollond (*Phil. Trans.*, 1821, pp. 101–103) describes a double-image micrometer of his own invention in which a sphere of rock-crystal is substituted for the eye-lens of an ordinary eye-piece. In this instrument (figs. 31, 32) a is the sphere, placed in half-holes on the axis bb, so that when its principal axis is parallel to the axis of the telescope it gives only one image of the object. In a direction perpendicular to that axis it must be so placed that when it is moved by rotation of the axis bb the separation of the images shall be parallel to that motion. The angle of rotation is measured on the graduated circle C. The angle between the objects measured is $= r \sin 2\theta$, where r is a constant to be determined for each magnifying power employed,[1] and θ the angle through which the sphere has been turned from zero (*i.e.*, from coincidence of its principal axis with that of the telescope). The maximum separation is consequently at 45° from zero. The measures can be made on both sides of zero for eliminating index error. There are considerable difficulties of construction, but these have been successfully overcome by Dollond; and in the hands of Dawes (*Mem. R. A. S.*, xxxv. p. 144 *sq.*) such instruments have done valuable service. They are liable to the objection that their employment is limited to the measurement of very small angles, viz., 13″ or 14″ when the magnifying power is 100, and varying inversely as the power. Yet the beautiful images which these micrometers give permit the measurement of very difficult objects as a check on measures with the parallel-wire micrometer.

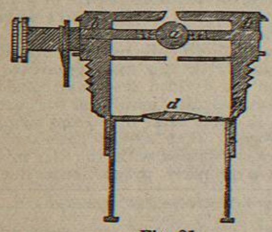

Fig. 31.

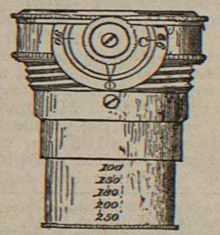

Fig. 32.

The Modern Heliometer.

The Königsberg heliometer is represented in fig. 33. No part of the equatorial mounting is shown in the figure, as it resembles in every respect the usual Fraunhofer mounting. An adapter h is fixed on a telescope-tube, made of wood, in Fraunhofer's usual fashion. To this adapter is attached a flat circular flange h. The slides carrying the segments of the divided object-glass are mounted on a plate, which is fitted and ground to rotate smoothly on the flange h. Rotation is communicated by a pinion, turned by the handle c (concealed in the figure), which works in teeth cut on the edge of the flange h. The counterpoise w balances the head about its axis of rotation. The slides are moved by the screws a and b, the divided heads of which serve to measure the separation of the segments. These screws are turned from the eye-end by bevelled wheels and pinions, the latter connected with the handles a', b'. The reading micrometers e, f also serve to measure, independently, the separation of the segments, by scales attached to the slides; such measurements can be employed as a check on those made by the screws. The measurement of position angles is provided for by a graduated circle attached to the head. There is also a position circle, attached at m to the eye-end, provided with a slide to move the eye-piece radially from the axis of the telescope, and with a micrometer to measure the distance of an object from that axis. The ring which carries the supports of the handles a', b', c is capable of a certain amount of rotation on the tube. The weight of the handles and their supports is balanced by the counterpoise z. This ring is necessary in order to allow the rods to follow the micrometer heads when the position angle is changed. Complete rotation of the head is obviously impossible because of the interference of the declination axis with the rods, and therefore, in some angles, objects cannot be measured in two positions of the circle. The object-glass has an aperture of 6½ inches, and 102 inches focal length.

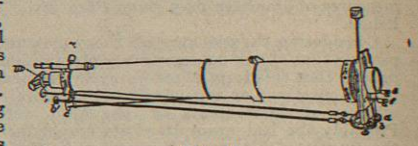

Fig. 33.

There are three methods in which this heliometer can be used.

First Method.—One of the segments is fixed in the axis of the telescope, and the eye-piece is also placed in the axis. Measures are made with the moving segment displaced alternately on opposite sides of the fixed segment.

Second Method.—One segment is fixed, and the measures are made as in the first method, excepting that the eye-piece is placed symmetrically with respect to the images under measurement. For this purpose the position angle of the eye-piece micrometer is set to that of the head, and the eye-piece is displaced from the axis of the tube (in the direction of the movable segment) by an amount equal to half the angle under measurement.

Third Method.—The eye-piece is fixed in the axis, and the segments are symmetrically displaced from the axis each by an amount equal to half the angle measured.

Of these methods Bessel generally employed the first because of its simplicity, notwithstanding that it involved a resetting of the right ascension and declination of the axis of the tube with each reversal of the segments. The chief objections to the method are that, as one star is in the axis of the telescope and the other displaced from it, the images are not both in focus of the eye-piece,[2] and the rays from the two stars do not make the same angle with the optical axis of each segment. Thus the two images under measurement are not defined with equal sharpness and symmetry. The second method is free from the objection of non-coincidence in focus of the images, but is more troublesome in practice from the necessity for frequent readjustment of the position of the eye-piece. The third method is the most symmetrical of all, both in observation and reduction; but it was not employed by Bessel, on the ground that it involved the determination of the errors of two screws instead of one. On the other hand it is not necessary to reset the telescope after each reversal of the segments.[3]

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[1] Dollond provides for changing the power by sliding the lens d nearer to or farther from a.

[2] The distances of the optical centres of the segments from the eye-piece are in this method as 1 : secant of the angle under measurement. In Bessel's heliometer this would amount to a difference of $\frac{1}{1000}$th of an inch when an angle of 1° is measured. For two degrees the difference would amount to nearly $\frac{1}{16}$th of an inch. Bessel confined his measures to distances considerably less than 1°.

[3] In criticizing Bessel's choice of methods, and considering the loss of time involved in each, it must be remembered that Fraunhofer provided no means of reading the screws or even the heads from the eye-end. Bessel's practice was to unclamp in declination, lower and read off the head, and then restore the telescope to its former declination reading, the clockwork meanwhile following the stars in right ascension. The setting of both lenses symmetrically would, under such circumstances, be very tedious.

When Bessel ordered the Königsberg heliometer, he was anxious to have the segments made to move in cylindrical slides, of which the radius should be equal to the focal length of the object-glass. Fraunhofer, however, did not execute this wish, on the ground that the mechanical difficulties were too great.

Wichmann states (*Königsb. Beobach.*, xxx. p. 4) that Bessel had indicated, by notes in his handbooks, the following points which should be kept in mind in the construction of future heliometers:—(1) The segments should move in cylindrical slides;[1] (2) the screw should be protected from dust;[2] (3) the zero of the position circle should not be so liable to change;[3] (4) the distance of the optical centres of the segments should not change in different position angles or otherwise;[4] (5) the points of the micrometer screws should rest on ivory plates;[5] (6) there should be an apparatus for changing the screen.[6]

The elder Struve, in describing the Pulkowa heliometer,[7] made by Merz in 1839 on the model of Bessel's heliometer, submits the following suggestions for its improvement:[8]—(1) to give automatically to the two segments simultaneous equal and opposite movement;[9] and (2) to make the tube of brass instead of wood; to attach the heliometer head firmly to this tube; to place the eye-piece permanently in the axis of the telescope; and to fix a strong cradle on the end of the declination axis, in which the tube, with the attached head and eye-piece, could rotate on its axis.

Both suggestions are important. The first is originally the idea of Dollond (fig. 29); its advantages were overlooked by his son (description of fig. 30), and it seems to have been quite forgotten till resuggested by Struve. But the method is not available if the separation is to be measured by screws; it is found, in that case, that the direction of the final motion of turning of the screw must always be such as to produce motion of the segment against gravity, otherwise the "loss of time" is apt to be variable. Thus the simple connexion of the two screws by cog-wheels to give them automatic opposite motion is not an available method unless the separation of the segments is independently measured by scales.

Struve's second suggestion has been adopted in nearly all succeeding heliometers. It permits complete rotation of the tube and measurement of all angles in reversed positions of the circle; the handles that move the slides can be brought down to the eye-end, inside the tube, and consequently made to rotate with it; and the position circle may be placed at the end of the cradle next the eye-end where it is convenient of access. Struve also points out that by attaching a fine scale to the focussing slide of the eye-piece, and knowing the coefficient of expansion of the brass tube, the means would be provided for determining the absolute change of the focal length of the object-glass at any time by the simple process of focussing on a double star. This, with a knowledge of the temperature of the screw or scale and its coefficient of expansion, would enable the change of screw value to be determined at any instant. Or, if we suppose the temperature of the instrument to be the same in all its parts, the changed scale value becomes simply a function of the reading of the focal scale.

Bonn
helio-
meter.

It is probable that the Bonn heliometer was in course of construction before these suggestions of Struve were published or discussed, since its construction resembles that of the Königsberg and Pulkowa instruments. Its dimensions are similar to those of the former instrument. Bessel, having been consulted by the celebrated statesman Sir Robert Peel, on behalf of the Radcliffe trustees, as to what instrument, added to the Radcliffe Observatory, would probably most promote the advancement of astronomy, strongly advised the selection of a heliometer. The order for the instrument was given to the Repsolds in 1840, but "various circumstances, for which the makers are not responsible, contributed to delay the completion of the instrument, which was not delivered before the winter of 1848."[10] The building to receive it was commenced in March 1849 and completed in the end of the same year. This splendid instrument has a superb object-glass of 7½ inches aperture and 126 inches focal length. The makers availed themselves of Bessel's suggestion to make the segments move in cylindrical slides, and of Struve's to have the head attached to a brass tube; the eye-piece is set permanently in the axis, and the whole rotates in a cradle attached to the declination axis. They provided a splendid, rigidly mounted, equatorial stand, fitted with every luxury in the way of slow motion, and scales for measuring the displacement of the segments were read by powerful micrometers from the eye-end.[11] It is somewhat curious that, though Struve's second suggestion was adopted, his first was overlooked by the makers. But it is still more curious that it was not afterwards carried out, for the communication of automatic symmetrical motion to both segments only involves a simple alteration previously described. But, as it came from the hands of the makers in 1849, the Oxford heliometer was incomparably the most powerful and perfect instrument in the world for the highest order of micrometric research. It so remained, unrivalled in every respect, till 1873; it remains still, optically, the most powerful heliometer in the world; and, with a few alterations, it might almost rival the most recent instruments in practical convenience and accuracy. These alterations, all of which could be made without great difficulty, are the following:—

(*a*) Beyond the automatic symmetrical motion above-described, the instrument should be fitted with means for adjusting the screens from the eye-end (see footnote 6 in last column).

(*b*) The arrangement of the scales should be changed. At present both scales are read separately by separate micrometers, each relative to a separate fiducial line. What the observer requires is the difference of the readings of the two scales, and this can obviously be most quickly and accurately obtained if the edges of the two scales are brought together, and both are read, relatively to each other, by the same micrometer.

(*c*) The unsatisfactory motion in position angle should be replaced by the action of a pinion (attached to the cradle) in the teeth of a wheel (attached to the tube).[12]

(*d*) The position circle should be read by telescopes or microscopes attached to the cradle, and accessible from the eye-end.

(*e*) It would add greatly to the rapidity of work and the ease of the observer if a small declination circle were attached to the cross-head, capable of being read from the eye-end.

As the transit of Venus of 1874 approached, preparations were set on foot by the German Government in good time; a commission of the most celebrated astronomers was appointed, and it was resolved that the heliometer should be the instrument chiefly relied on. The four long-neglected small heliometers made by Fraunhofer were brought into requisition. Fundamental alterations were made upon them:—their wooden tubes were replaced by tubes of metal; means of measuring the focal point were provided; symmetrical motion was given to the slides; scales on each slide were provided instead of screws for measuring the separation of the segments, and both scales were read by the same micrometer microscope; a metallic thermometer was added to determine the temperature of the scales. These small instruments have since done admirable work in the hands of Schur, Hartwig, Kustner, and Elkin.

Russian
helio-
meters.

The Russian Government ordered three new heliometers (each of 4 inches aperture and 5 feet focal length) from the Repsolds, and the design for their construction was superintended by Struve, Auwers, and Winnecke, the last-named making the necessary experiments at Carlsruhe. Fig. 34 represents the type of instrument which re-

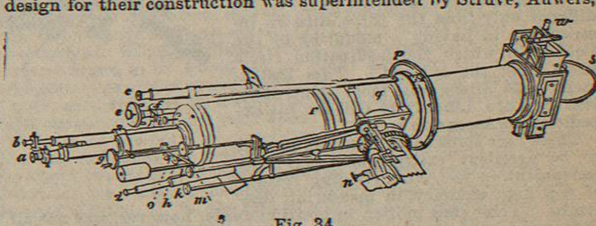

Fig. 34.

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[1] This most important improvement would permit any two stars under measurement each to be viewed in the optical axis of each segment. The optical centres of the segments would also remain at the same distance from the eye-piece at all angles of separation. Thus, in measuring the largest as well as the smallest angles, the images of both stars would be equally symmetrical and equally well in focus. Modern heliometers made with cylindrical slides measure angles over two degrees, the images remaining as sharp and perfect as when the smallest angles are measured.

[2] Bessel found, in course of time, that the original corrections for the errors of his screw were no longer applicable. He considered that the changes were due to wear, which would be much lessened if the screws were protected from dust.

[3] The tube, being of wood, was probably liable to warp and twist in a very uncertain way.

[4] We have been unable to find any published drawing showing how the segments are fitted in their cells.

[5] We have been unable to ascertain the reasons which led Bessel to choose *ivory* planes for the end-bearings of his screws. He actually introduced them in the Königsberg heliometer in 1840, and they were renewed in 1848 and 1850.

[6] A screen of wire gauze, placed in front of the segment through which the fainter star is viewed, was employed by Bessel to equalize the brilliancy of the images under observation. An arrangement, afterwards described, has been fitted in modern heliometers for placing the screen in front of either segment by a handle at the eye-end.

[7] This heliometer resembles Bessel's, except that its foot is a solid block of granite instead of the ill-conceived wooden structure that supported his instrument. The object-glass is of 7·4 inches aperture and 123 inches focus.

[8] *Description de l'Observatoire central de Pulkowa*, p. 208.

[9] Steinheil applied such motion to a double-image micrometer made for Struve. This instrument suggested to Struve the above-mentioned idea of employing a similar motion for the heliometer.

[10] Manuel Johnson, M.A., Radcliffe observer, *Astronomical Observations made at the Radcliffe Observatory, Oxford, in the year* 1850, Introduction, p. iii.

[11] The illumination of these scales is interesting as being the first application of electricity to the illumination of astronomical instruments. Thin platinum wire was rendered incandescent by a voltaic current; a small Swan light and condenser would probably now be found more satisfactory.

[12] This has been recently carried out by Stone, the present Radcliffe observer, on Gill's suggestion.