Quantitative analyses of conditions in late-type giants and supergiants are possible through a range of opacity-sensitive line ratios. Also, lines of the *C* II ^2P–^4P multiplet near 2325 Ångströms have been shown to provide a valuable method of measuring the electron density in these stars.

Continua Observed with *IUE* in K and M Giants and Supergiants

By D. J. Stickland
Royal Greenwich Observatory

While carrying out a study of spectrograph-scattered light in the short-wavelength, low-resolution mode of *IUE*, I noticed that all of the late K- and M-type giants and supergiants seemed to exhibit rather flat, real, stellar continua between 1200 and 2000 Ångströms. Using the survey data, many of which were secured by Jordan and Brown, and a number of spectra obtained at Goddard by Sanner, I measured the continuum fluxes in fifteen stars at two points (1250 and 1850 Ångströms) assuming a straight-line connection between them in the flux-versus-wavelength plot. Using measured or calculated stellar angular diameters for the programme stars, it was possible to deduce surface fluxes, and these have been compared with the Planck function, assuming a model of pure absorption, to infer 'temperatures of origin'. For all the stars, these range between 4100 and 4800 K at 1250 Ångströms and between 3100 and 3700 K at 1850 Ångströms, with a monotonic change between those wavelengths. According to 'off-the-shelf' model chromospheres and opacity sources, it appears that optical depths of order unity at these wavelengths can be achieved in the chromospheres of these late-type stars, and so it seems that the far-ultraviolet energy distribution can be used as a probe of the region immediately above the temperature minimum in a way complementary to the use of emission lines of neutral and singly-ionized elements. These preliminary results suggest that there is either a slight thickening of the chromosphere or a steepening of the temperature gradient in the M0–M1 giants compared with earlier or later giants.

THE OBJECT GLASS OF THE AIRY TRANSIT CIRCLE AT GREENWICH

By C. M. Lowne
Royal Greenwich Observatory

This article relates the history of the Troughton & Simms object glass of the Airy Transit Circle. A recent examination of its optical properties is described.

Introduction. The need for knowledge of the coördinates of stars and other objects on the celestial sphere has led to the development of many specialized instruments, from the early primitive sighting devices to the modern proposal for an astrometric artificial satellite. A major contributor to the vast accumulation of positional observations has been the type of instrument known as a transit circle, of which the earliest English example was made in 1793 by

Cary to the design of Wollaston[1]. Martin[2] has given a list of the transit circles of the world.

A transit circle is basically a telescope attached to a graduated circle (sometimes two circles) and mounted on an East–West horizontal axis so that the telescope can move only in the plane of the meridian. Right ascensions of objects are derived from the observed times of meridian transit, and their declinations from the zenith distances determined with the graduated circle. Both coördinates are normally observed at each transit.

The Transit Circle at the Royal Observatory, Greenwich, was installed in 1850 to the design of G. B. Airy, Astronomer Royal from 1835 to 1881. In its long working life the instrument was used to observe nearly 700,000 transits, from which 11 star catalogues were compiled. These have been used in combination with results from other observatories to prepare a series of fundamental catalogues; the Fourth Fundamental Catalogue (FK4) is the latest[3]. The local mean time of the Greenwich meridian defined by the transit circle was made[4] the legal time of Great Britain in 1880 and in 1884 the meridian was internationally adopted[5] as the zero of terrestrial longitude.

The last official observations with the instrument were made in 1954. Since then, it has been in the care of the National Maritime Museum, which operates the Observatory as a museum of astronomy. The condition of the object glass had long given cause for concern, and in 1979, at the request of Lt Cdr H. D. Howse (Department of Navigation and Astronomy), the assembly was removed from the telescope and brought to Herstmonceux for cleaning. I took the opportunity of making an examination of the optical properties of the objective.

History of the Object Glass. The transit circle's general history, derived from Reports of the Astronomer Royal to the Board of Visitors[6], has been given by Witchell[7]. The same sources document the history of the objective.

In his 1848 Report Airy writes:

> "An object-glass of 8 inches clear aperture and 11 feet 6 inches focal length, having been placed in my hands by Mr. Simms, I carefully examined it. I found that it shewed some objects not of the closest class (as ε Bootis and ζ Cancri) better, I think, than I had seen them before: that it separated η Coronæ: that it did not separate γ Coronæ (which, having witnessed the difficulty of that star in the great Pulkowa refractor, I was prepared to expect): and that it dispersed light no more than the best object-glasses usually do. At my recommendation, therefore, this object-glass was purchased by the Lords Commissioners of the Admiralty, at the price of £275. . . . I propose to mount it as a Transit Circle. . . ."

The Mr Simms referred to was William Simms (1793–1860) who[8] had entered into partnership with Edward Troughton (1753–1835) in 1826. The separations in 1848 of the stars mentioned are given in Table I.

TABLE I

Separations of double stars in 1848

Double Star	*Separation*	*Reference*
ε Boo	2″·7	9
ζ Cnc (presumably AB)	0″·9	9
η CrB	0″·66	10
γ CrB (magnitude difference 3·0)	0″·48	11

The Dawes limit[12] for an eight-inch aperture is 0″·57. The "great Pulkowa refractor" (Airy had spent a month there in 1847) was the 15-inch equatorial of 1839, by Merz and Mahler[13]. Clearly Airy had good reason to be satisfied with his new objective.

The firm of Troughton & Simms was responsible for all optical and fine mechanical work in the new transit circle; the main construction work in cast iron was done by Ransomes and May of Ipswich. The telescope was ready for use at the end of 1850 and the first published observation was made on 1851 January 4. A full description of the instrument, with elaborate drawings, is given[14] as an Appendix to Greenwich Observations 1852 and reprinted[15] in 1867. The drawings relating to the objective are reproduced in Fig. 1.

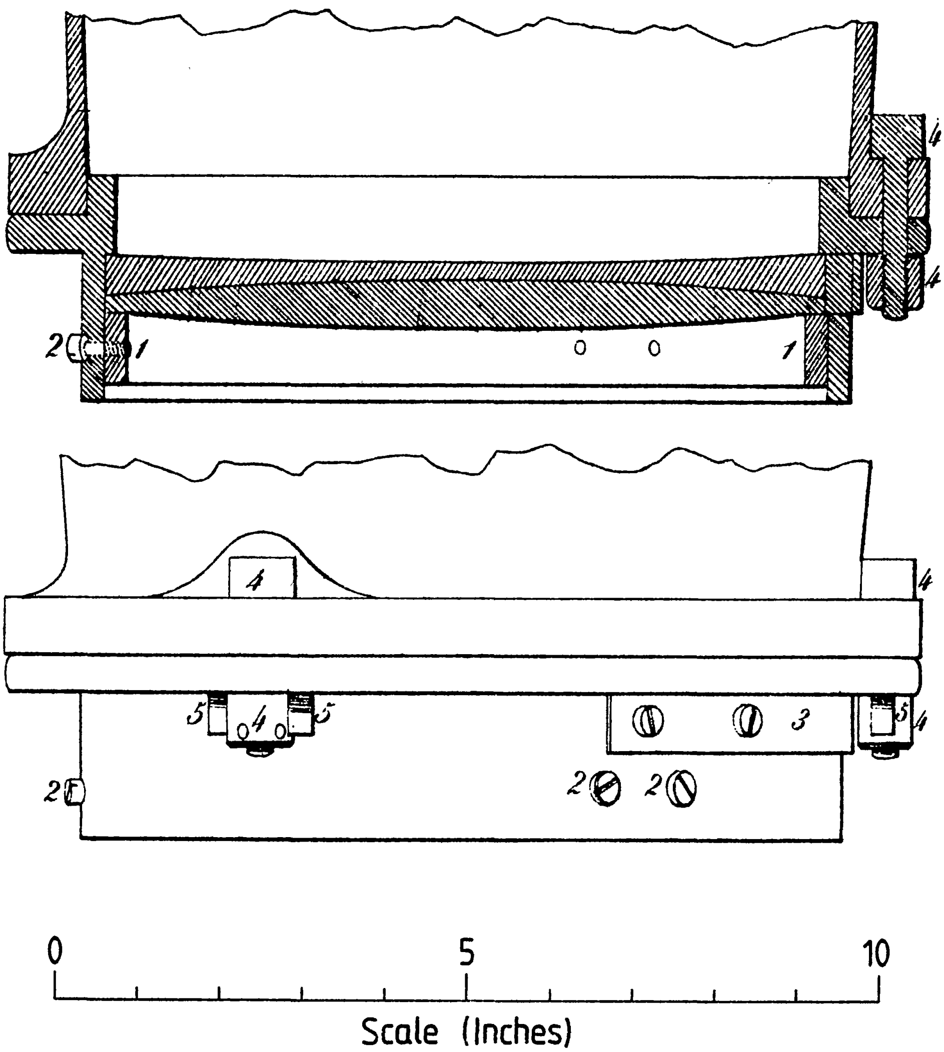

FIG. 1

Details of object-glass assembly, reproduced from the Appendix to *Greenwich Observations 1852*.

The objective was dismounted and taken apart for cleaning six times between 1851 and 1888. On the last occasion the 1889 Report records:

> "The object glass was cleaned and re-centred by Mr Simms . . . and its definition is now much improved."

'Mr Simms' was the nephew of the original maker, also William[16]. Two years later, the 1891 Report reads:

> "The object glass . . . appears to have become permanently stained, probably through damp, and it is proposed to have it repolished."

The work was carried out in the following year; the Report for 1892 says:

> "The object glass was removed for repolishing on August 10 and returned on October 5, Mr Simms having taken great pains in improving the definition and colour correction of this old object glass, as well as in polishing the tarnished surfaces."

Just what improvements were made to the performance cannot now be said. Only slight alterations to the radii of curvature would have been needed to improve the colour correction (within the restraint of maintaining the back focal length at the same value) but in view of Airy's 1848 comments I feel that the improvements could only have been marginal. It is interesting to see the objective referred to as 'old'. By Greenwich standards, at only 44 years old it was a youngster! For example[17], the 5-inch objective made by Peter Dollond in 1793 was used in Troughton's transit instrument from 1816 to 1850, and then transferred to the Reflex Zenith Tube which was in use until 1911.

No further comments relating to the objective appear in the Reports until 1906. The surfaces had by then become badly stained again and another repolishing was undertaken by Troughton & Simms. On this occasion trouble was experienced in controlling the figure, and the objective was used for two months with its aperture reduced to six inches. Further re-figuring was successful in restoring satisfactory performance. The difficulty was attributed to the thinness of the lenses. Fig. 1 (from the 1852 description) clearly shows how thin they are; the maximum thickness of each component is only about one-sixteenth of its diameter.

In 1908 a new on-axis field illumination system was fitted. A small diffusing reflector disk was fixed to the centre of the crown lens at 45° to the axis, and illuminated from the side of the dew-cap by a low-voltage lamp and condenser lens. The original Airy system (consisting of a gold-faced annulus in the central cube, illuminated through the axis) was retained. The new system was altered in 1924 by substituting a 45° mirror and a ground-glass diffuser perpendicular to the axis.

The only remarks concerning the objective in the Reports of later years are complaints of its deteriorating condition. In 1931:

> "The object glass, which is badly stained, is too thin to bear further repolishing."

In 1938, at the conclusion of the telescope's last major programme:

> ". . . the lenses are so thin that a further repolishing, which is now needed, is not possible."

Observations were terminated in 1940 September, but resumed in 1942 owing to the destruction[18] of Pulkova Observatory. The 1946 report notes:

> "The progressive deterioration of the objective through atmospheric corrosion is making observations . . . increasingly difficult."

The telescope was finally retired on 1954 March 30.

Dismantling and Cleaning the Objective. To remove the cell from the telescope, it was only necessary to undo the three long securing bolts (labelled 4 in Fig. 1), leaving the adjacent squaring-on screws untouched. Incidentally, after 25 years of disuse, the low-voltage field-illumination lamp was still alight! As it came off the telescope, the objective was in a sorry condition. Although enclosed in a long dew-cap, the cell was encrusted with Greenwich dirt (and anyone who worked there before the implementation of the 1968 Clean Air Act will know what that means!). There was an interesting pattern of concentric, roughly triangular, white and grey rings between the two components, with patches of white deposit. At the close of its active life, the objective must have absorbed and scattered a considerable amount of the incident starlight.

The screws holding the retaining ring in place were difficult to remove because of corrosion. The front bracket screws were brittle, and three of the six broke off across the line of tommy-bar holes. At some time the inside front of the cell had been coated with matt black paint, most of which had to be scraped out to allow removal of the retaining ring. Spots and streaks of this paint were found on the front lens surface, but were later easily removed with the point of a scalpel held at an acute angle to the glass.

Once the glasses were out of the cell and separated, I found that the contamination between them was due to severe corrosion of the metal edge spacers. The breakdown products had been carried towards the lens centre by repeated condensation and drying-out of moisture, leaving a succession of high-water-marks. Evidently this process had been going on for many years; there is no record of the lenses being separated for cleaning after the 1906 repolishing.

I was agreeably surprised to find that all the dirt washed off easily with detergent and water, leaving only some residual staining around parts of the outer rims, not extending inwards by more than half an inch. These stains are probably similar to those which made repolishing necessary; they show marked interference colours and are resistant to common solvents.

After a final wipe with isopropanol, the lenses were re-assembled in the cleaned cell, with new spacers of aluminium foil. It seems ironic that, after all the complaints about the deterioration of the objective in its final years, all it needed was a good wash! In fact, apart from a few scratches and the edge staining mentioned above, the glasses are in very good condition.

Description and Optical Performance. A photograph of the objective in its present condition is given in Plate I. The cell is cast brass and carries the makers' inscription 'Troughton and Simms London 1850'. As we have seen, this is the date of the telescope, the lenses having been made at least two years earlier. Possibly they were supplied to Airy for testing in a temporary cell. The two glasses are held in place laterally by pressure from the two springs visible in Plate I, acting through a loose block in the cell wall. A front retaining ring holds the lenses back against three steps in the base of the cell. This ring is secured by three pairs of screws through the cell side wall, and also by the three brackets with pressure screws attached to the front of the cell. These brackets are not original equipment; they were added at some

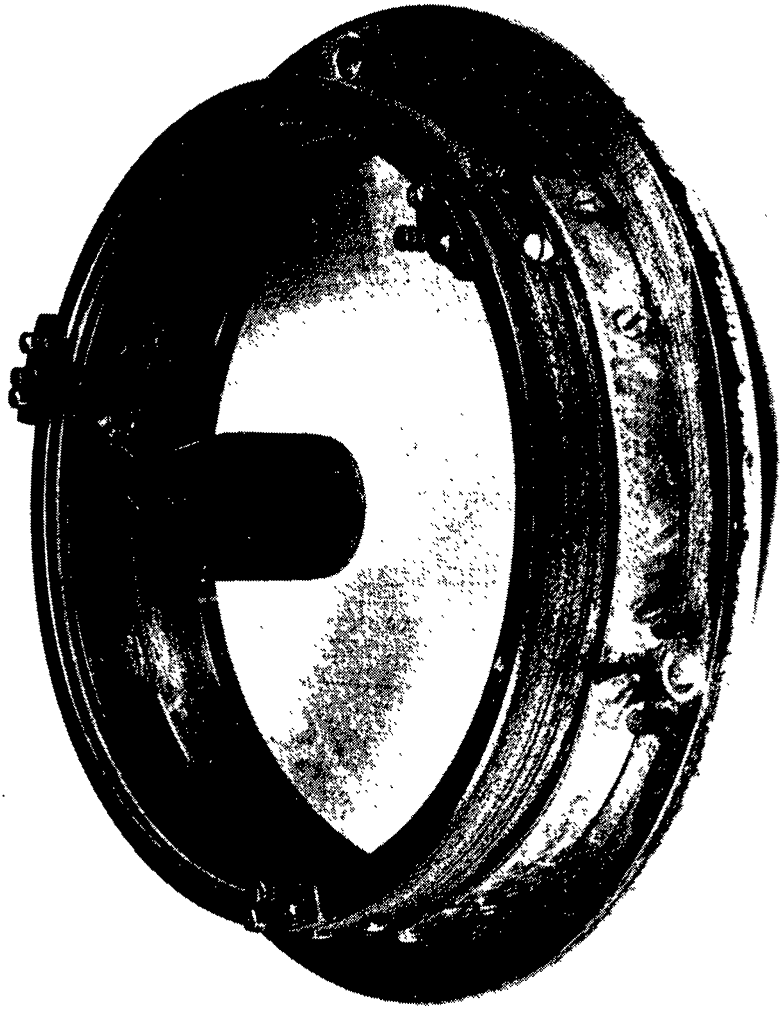

PLATE I
The object glass of the Airy Transit Circle.

Facing p. 47]

unrecorded time, presumably as a "belt and braces" precaution against the glasses moving forward when the telescope was inverted to observe the nadir (and stars) by reflection in a trough of mercury. The 45° reflector in the centre for field illumination is not original either; this is the 1924 version with a specular reflector and ground-glass diffuser on the front lens surface.

In view of the age and historic associations of the objective, I was interested to examine its optical properties, of which nothing was known. Although the lenses have been repolished and refigured twice, it does not seem likely that the optical performance has been significantly altered.

The clear aperture is 8·05 inches (204 mm) and the back focal length is 138·6 inches (3·52 m). The focal ratio of $f/17$ is quite typical for the period.

Examination of the focussed image formed in a beam of collimated white light showed that the on-axis image is quite good, with a well-defined diffraction pattern. There is a little astigmatism, possibly the remnant of the trouble at the time of repolishing in 1906; the longitudinal difference of focus between the line foci is about 0·9 mm. Under high magnification, some spherical aberration is detectable. The visual chromatic correction is very good: to quote Airy, the lens disperses light no more than the best object-glasses usually do. In fact, the most noticeable chromatic effect is in the first diffraction ring, which shows radial colour due to the change of scale with wavelength. The measured minimum image (diameter of first dark ring) is about 30 μm; the theoretical value at $\lambda = 560$ nm is 24 μm.

A knife-edge test showed some zonal effects; the main feature is that the centre and edge have longer focal length than do the intermediate zones. The figure is quite smooth, with no discontinuities or fine structure. A plot of the zonal aberrations determined from knife-edge focus readings is given in Fig. 2. This confirms the presence of the spherical aberration noted in the examination of the image.

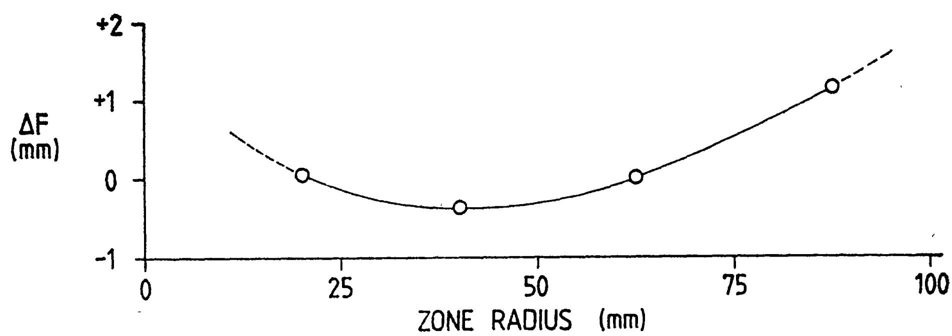

FIG. 2

Zonal aberrations derived from knife-edge focus measures at $\lambda = 560$ nm.

The colour curve plotted in Fig. 3 was derived from differential knife-edge focus measures made in the wavelengths passed by interference filters. It shows typical colour correction, and demonstrates clearly that (contrary to the statements made in many text books) the best achromatism for visual use is not achieved by bringing the C and F wavelengths to coincident focus. As is pointed out by Bell[19], this would take the minimum focus too far towards the blue end of the spectrum.

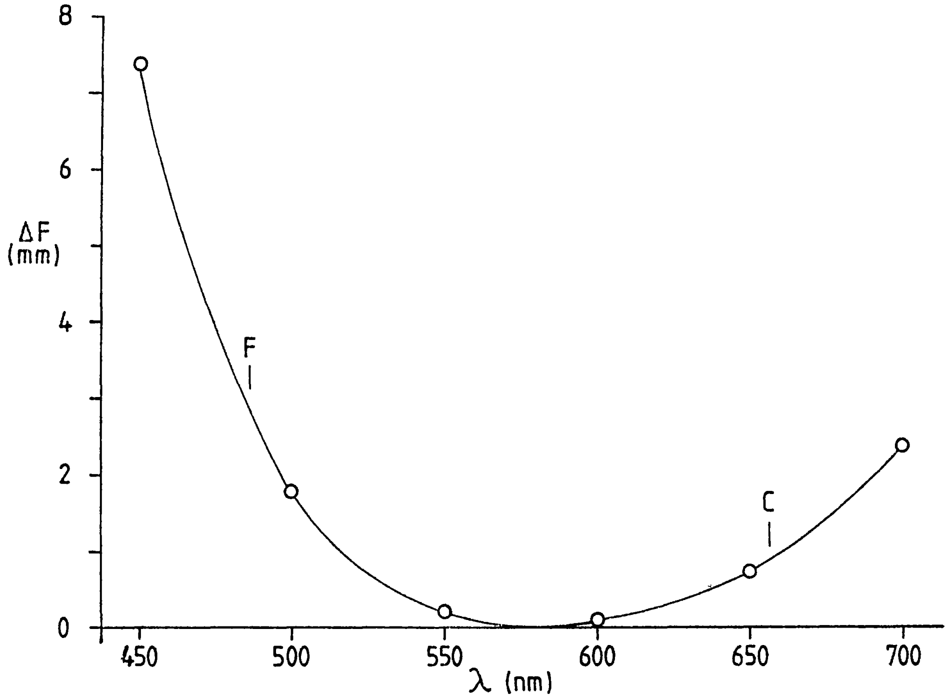

Fig. 3
Chromatic differences of focus.

The measured radii of curvature of the lenses are given in Table II.

Table II

Radii of lens surfaces of the Airy Transit Circle

Surface	*Radius* *inches*	*Radius* *mm*	*Form*
1	41·3	1049	convex
2	74·8	1900	convex
3	70·6	1793	concave
4	166·3	4224	concave

The bi-concave form of the flint element is quite unusual. The focal length and colour curve of the objective can be accurately reproduced by using simple thin-lens formulae and assuming the glass parameters shown in Table III.

Table III

Probable properties of the Airy Transit Circle glasses

Component	n_d	$(n_d-1)/(n_F-n_C)$
Crown	1·519	60
Flint	1·609	37

Such glasses were known in later years as "hard crown" and "dense flint"; modern equivalents are still in the catalogues. The origin of the glasses is unknown.

The off-axis image given by the objective is dominated by ferocious coma which appears at the rate of $0''\cdot 22$ per arc-minute off-axis angle. In the transit circle the field of view[20] was $\pm 15'$, so at the edge of the field the total image-spread (coma plus diffraction) was nearly $5''$. I have found no comments on this in any of the Reports or catalogues. The presence of this coma makes the concept of other off-axis aberrations quite meaningless, and I have not attempted to determine them.

The problem of coma had been investigated and solved by Fraunhofer (1787–1826), who had made objectives which were essentially coma-free[21]. Fraunhofer left no account of his methods, but the necessary design criterion was re-discovered by Abbe in 1879 and formulated as the well-known sine condition[22]. Nevertheless, objectives with excessive coma were made until comparatively recently. The original Cooke, Troughton & Simms objective of the Reversible Transit Circle installed at Greenwich in 1932 suffered from "a large amount of off-axis coma"[23]. It was replaced in 1952 with a coma-free objective by Cox, Hargreaves and Thomson.

Acknowledgements. I am grateful to Lt Cdr Howse and the Director and Trustees of the National Maritime Museum for giving me the opportunity to examine this historic objective. Thanks are also due to Mr M. J. Waite who assisted at the telescope and in dismantling the objective, and to Mr C. W. Taylor for his painstaking duplication of damaged parts. Dr R. G. Bingham made valuable comments on the manuscript.

References

(1) H. C. King, *The History of the Telescope* (Charles Griffin, London), 1955, p. 172.
(2) E. G. Martin, *The Observatory*, **69**, 140, 1949.
(3) W. Fricke *et al.*, *Veröff. astr. Rechen Inst. Heidelberg*, **10**, 1963.
(4) D. H. Sadler, *Q.J.*, **19**, 290, 1978.
(5) *Report of the International Meridian Conference*, Washington, 1884. A summary of the resolutions is given by H. M. Smith, *Vistas*, **20**, 219, 1976.
(6) *Reports of the Astronomer Royal to the Board of Visitors*, 1848 to 1954 (not individually referenced).
(7) W. M. Witchell, *Occ. Not. R.A.S.*, **2**, 147, 1952.
(8) Report of the Council, *M.N.*, **21**, 105, 1861.
(9) S. W. Burnham, *A General Catalogue of Double Stars within 121° of the North Pole* (Carnegie Institute of Washington, Washington, D.C.), 1906.
(10) W. Doberck, *A.N.*, **141**, 153, 1896.
(11) W. Doberck, *A.N.*, **169**, 133, 1905.
(12) W. R. Dawes, *Mem. R.A.S.*, **35**, 158, 1867.
(13) H. C. King, *op. cit.*, p. 206.
(14) *Astr. Results Observ. Greenwich*, Appendix, 1852.
(15) *Astr. Results Observ. Greenwich*, Appendix, 1867.
(16) H. C. King, *op. cit.*, p. 238.
(17) H. D. Howse, *Greenwich Observatory, Volume 3: The Buildings and Instruments* (Taylor & Francis, London), 1975.
(18) W. M. Witchell, *op. cit.*, p. 157.
(19) L. Bell, *The Telescope* (McGraw–Hill, New York), 1922, p. 90.
(20) W. M. Witchell, *op. cit.*, p. 151.
(21) L. Bell, *op. cit.*, p. 82.
(22) M. Born & E. Wolf, *Principles of Optics* (second edition) (Pergamon Press, Oxford), 1964, p. 167.
(23) *Report of the Astronomer Royal to the Board of Visitors*, 1950.