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OBSERVATIONS ON THE DEFLECTION OF LIGHT IN PASSING THROUGH
THE SUN'S GRAVITATIONAL FIELD

MADE DURING THE TOTAL SOLAR ECLIPSE OF SEPT. 21, 1922

The observations forming the subject of this paper represent a part of the program of the Wm. H. Crocker Eclipse Expedition to Wallal, Western Australia, of which Mr. Campbell has given a detailed report in another publication.¹ That report also contains a full account of the previous efforts made to determine the light deflection by the Sun's gravitational field during total solar eclipses, and of the results obtained.

Since the British expeditions of 1919 published their measures² on this subject, several physicists and astronomers have pointed out various sources of error that might enter into this problem, which consists in comparing by accurate measures a photograph of the stars surrounding the eclipsed Sun with a photograph of the same stars taken at night several months before or after the eclipse, when the Sun is in another part of the sky and has no disturbing influence on the apparent positions of these stars. The most important of these sources of error are:

1. Distortion in the reproduction of the star field by the optical parts of the instruments. In view of the differential character of the measures such distortions are only to be feared in case they are different for the eclipse photographs and the night comparison plates. This is most likely to occur if the optical parts of the instrument contain mirrors. The experience of the British expedition to Sobral in 1919 has shown such mirrors to be easily deformed in consequence of the inevitable temperature changes during a total eclipse.

¹ *Publ. A. S. P.*, 35, 11, 1923.

² F. W. Dyson, A. S. Eddington, C. Davidson: *A Determination of the Deflection of Light by the Sun's Gravitational Field*, from Observations made at the Total Solar Eclipse of May 29, 1919. *Mem. R. A. S.*, 62, *Appendix*, 1920.

2. Disturbing effect of the uneven illumination of the background,³ the intensity of which is gradually diminishing with increasing distances from the Sun. There may be a physiological effect in bisecting a star image seen on such a background, but there may also be a real shifting of the center of a star's image if this is photographed on a background of uneven intensity. In view of the gentle gradation, hardly noticeable in the field of the measuring microscope, this effect can be but small and may be negligible.

3. Systematic distortion of the photographic film during the process of drying.⁴ According to Ross the blackened part of the plate corresponding to the corona should dry the more rapidly, and we should expect contraction of the film toward the inner corona. Such distortion is favored by the high temperatures encountered by expeditions to tropical countries; it should have the tendency to make the measured light deflections too small.

4. Abnormal refraction in the Earth's atmosphere accompanying the changes of temperature produced by the passing of the Moon's shadow.⁵

It has been stated, also, that other causes than the Sun's gravitational field may be responsible for all or a part of the observed light deflections. As such should be mentioned:

5. Refraction in an extended solar atmosphere.⁶

³ K. F. Bottlinger: *Die astronomischen Prüfungsmöglichkeiten der Relativitätstheorie, Jahrbuch für Radioaktivität und Elektronik*, 17, 149 and 152, 1920.

M. Wolf: *A. N.*, 212, 181, 1920.

⁴ F. Ross: *Image Contraction and Distortion on Photographic Plates. Ap. J.*, 52, 98; Silberstein: *M. N.*, 80, 630, 1920.

⁵ A. Anderson: *Nature*, 104, 354, 372, 393, 436, 468, 563, 1919-20.

⁶ H. F. Newall: *M. N.*, 80, 22, 1919; *The Observatory*, 42, 428, 1919; 43, 145, 1920. W. Anderson: *A. N.*, 218, 251, 1923.

6. The phenomenon observed by Courvoisier,⁷ called "yearly refraction." It consists of an apparent displacement of the stars away from the Sun, but this displacement extends to large angular distances from the Sun. No physical explanation of the yearly refraction has been given as yet, and its amount in the immediate neighborhood of the Sun is not known.

In order to secure high value for the present observations, an attempt was made to eliminate objections based on these points, as far as possible, by taking the following precautions:

To mount the cameras equatorially, thus eliminating the need of any mirrors.

To use wide-angle objectives, allowing us to photograph a relatively large area of sky. A large field is not only desirable in order to increase the number of stars on the plates, but it is most important for a good determination and elimination of the scale value of the plates. This scale value, *i.e.*, the angle on the celestial sphere corresponding to a certain length (unit of measure) on the plate, depends on the focal length of the telescope, and is subject to temperature influences difficult to control. Experimental determinations of this constant do not promise much success under the rapidly varying eclipse conditions. It therefore seemed best to follow the practice, generally accepted in the photographic determination of star positions, of obtaining the scale of the plate from the star images themselves. However, in our problem of comparing the eclipse photographs with the night plates, the effects of the difference of scale of the two plates are mixed up with those of the light deflection; both produce an apparent displacement of the star images radially with reference to the Sun. With increasing distances of the stars from the center of the plate the effect of the scale difference increases proportionately, whereas the light deflection decreases rapidly. It is thus possible to separate the two effects by a least squares solution, and the separation will be the more complete the larger the field of the plate.

An equally important reason for advocating a large field is that it increases the prospects of determining whether the amount of light deflection for any star is inversely proportional to the distance of the star from the Sun's center, as predicted by Einstein's theory. If the observations conform to this law, they will make a much stronger case in favor of the new theory, and some of the other possible causes of such light deflections can the more easily be rejected or isolated.

⁷ *Beob. Ergebn. d. Sternw. Berlin*, 15, 1913; *A. N.*, 211, 305, 1920.

To guard the purely differential character of the measures, the night comparison photographs were taken as nearly as possible under the same conditions, and at the same hour-angle and zenith distance, as those of the eclipse photographs. Unfortunately the arrangements for the expedition did not make it possible to obtain the comparison plates at the eclipse station itself. The selection of Tahiti as the site for the comparison observations necessitated dismantling, transporting and reassembling the telescopes between the two sets of observations to be compared. As a check against any errors that might be introduced on this account, an auxiliary star group was selected with center at R.A. 18^h 5^m5 and Decl. +1° 1' (following the eclipse star field by 6^h 14^m9, but at the same declination). This check field could be photographed at night, in the proper hour-angle, on the island of Tahiti in May, as well as at Wallal in September. At both epochs it was more than 90° distant from the Sun, and therefore unaffected by any light deflections. The expedient of making the exposures of this check field on the same plates and during the same night as the comparison photographs of the eclipse field, and of recording the same check field on the eclipse plates on the nights before and after the eclipse, gives not only a valuable check on the instrumental conditions at both observing stations, but also serves to eliminate any possible effects of errors mentioned in paragraphs 2 and 3, page 41.

It is desirable that the results be based on a number of stars near the Sun, and that these be distributed fairly well in all position-angles, so as to reduce the influence of the plate constants to a minimum. This condition could only be fulfilled by reaching stars slightly fainter than tenth magnitude. The star field of the 1922 eclipse is very poor in bright stars, only two stars brighter than ninth magnitude being situated within 1° from the Sun's center, whereas at the 1919 eclipse seven stars brighter than sixth magnitude were found in a similar field. Every effort therefore had to be made to photograph as faint stars as possible.

When photographing stars on an illuminated sky background there is a certain limit of exposure time which gives the best results; an increase of exposure beyond this limit will add very few or no fainter stars, because the blackening of the background of the plate will be intensified at the same rate as the star images; a moderate fogging, on the contrary, would help to bring out the faintest stars. Special experiments on this point were made in preparation for the eclipse by photographing star fields near the full Moon with the Crossley Reflector, with varying exposure times. It was concluded from these tests

that a 2-minute exposure with the 15-foot camera (ratio of aperture 1:36) should not exceed the admissible amount of fogging of the plate. Similar experiments on the best method and duration of development will be referred to later. The procedure decided upon proved correct; the 2-minute exposures during the eclipse show as many faint stars as the 3-minute exposures at night in Tahiti. Stars down to the photographic magnitude 10.5 have measurable images. This is probably the first time that such faint stars have been photographed or observed during a solar eclipse.

INSTRUMENTS

Of the two twin cameras, of 15 feet and 5 feet focal length, respectively, only the observations with the longer cameras form the subject of the present communication. The plates obtained with the other cameras, though quite successful, have not yet been measured. Pictures of the 15-foot cameras and of the observing house are found in Mr. Campbell's report.⁸ The common tube of these cameras, of rectangular cross section, is a framework of channel, tee and angle steel, with two heavy end castings, one carrying the objectives and the other the plate holders. This frame, weighing about 700 lbs., is made light-tight by covering it with one thickness of black cloth and one thickness of rubberized cloth, the latter black inside and white outside. The two halves of the tube are separated optically by a number of steel diaphragms. The 5-inch doublet objectives⁹ are mounted in brass tubes 28 inches long. Several bars on the outside of each objective tube are provided with parts of a screw thread so as to fit into a ring with a complete inside thread. By turning this ring the objective is moved in or out along its optical axis, for focussing; and once the focus is set, the objective tube is clamped. Objective caps, mounted on a wire frame and operated from the plate end of the telescope by means of a string, serve for starting and ending the exposures. This form of shutter, though very light, was not found quite satisfactory, as its operation inevitably led to perceptible vibrations of the telescope. It would be preferable to have a shutter unconnected with the telescope tube. The plate-holders, of aluminum alloy, containing the 17×17 inch plate glass plates, 1/4 inch thick, with Seed 30 emulsion, were held in place in the telescope by three clamping screws pressing against three adjusting screws. The latter screws served to set the plate perpendicular to the optical axis.

⁸ *Publ. A. S. P.*, 35, plate III, p. 18; plate II, p. 11; 1923.

⁹ See R. Trumpler: *Comparative Tests of two Wide-Angle Photographic Objectives*, *Publ. A. S. P.*, 35, 1923.

Following the design of the English equatorial mounting, the camera tubes pass centrally through the polar axis (8 feet long), consisting of a metal framework similar to the camera frames. For the sake of greater rigidity of the polar axis, only a few degrees of motion around the declination axis were allowed. A steel bar connecting the lower end of the polar axis and the plate end of the camera served to clamp the telescope in declination, once it was set. No declination slow motion nor any setting circle was provided. A clock driving arm, 10 feet long, could be clamped to the lower end of the polar axis. The end piece of this arm glided on rollers on a metal plate screwed to a board and inclined so as to be in the plane of the equator. A steel cable released by the drum of a clockwork held this clock arm, allowing it to glide down at the required speed by its own weight, carrying with it the polar axis and cameras properly balanced. The cable was not directly fastened to the driving arm, but to a metal piece, movable on hinges, with a finely-threaded screw which thus furnished a right ascension slow motion. By means of a slender cord the slow motion could be operated by the observer at the eye piece of the guiding telescope.

Piers of solid wood structure supported the roller bearings of the polar axis; their bases were bolted to seven small concrete blocks forming the foundation.

The guiding telescope consisted of a square wooden tube fastened to the cameras by three brackets and carrying a visual 4-inch objective of 15 feet focal length. β *Virginis*, of magn. 3.5, $1\frac{1}{2}^\circ$ north-preceding the center of the eclipsed Sun, was a suitable guiding star, and the guiding telescope had to be set off from the axis of the cameras at the required angle. 70 *Ophiuchi* was selected as guiding star of the auxiliary star field, and the eye piece of the guiding telescope was provided with a declination micrometer to make it possible to set the cross wire on each of the two stars (differing in declination by 19') without changing the declination setting of the cameras. The cross wire was made of very fine metal wire. Projecting it on the slightly extrafocal image of the guiding star it could be used even for the night observations without illumination.

MOUNTING AND ADJUSTMENT OF CAMERAS

For shipping, the instrument was taken to pieces so that no package exceeded 250 lbs. in weight. All parts were properly marked in order to make any interchange impossible. The installation of the instrument at Tahiti and again at Wallal proceeded according to a carefully worked out plan and did not encounter any difficulties.

Among the necessary adjustments of the cameras, the following points should be mentioned:

The objectives demanded accurate centering. A metal plate with a small hole in its center was inserted in one of the plate holders. A polished glass plate outside of this hole, inclined at 45° , allowed us to throw a small bundle of light on the objectives, and to observe its reflections from the different surfaces of the lenses. Each objective was so centered that these reflections fell together.

To adjust the plane of the photographic plate perpendicular to the optical axis, a small telescope with a micrometer was screwed into the hole of the metal plate, used for centering. According to the method of Schlesinger¹⁰ the micrometer wire is set on the edges of the objective diaphragm, the plate is turned 180° in position-angle, and the operation repeated. The micrometer readings in the two positions of the metal plate should show no difference. As perfect adjustment is impossible, the small residual error is finally measured for each plate holder and taken account of by calculation.

Setting and clamping the cameras in declination, and adjusting the guiding telescope so that the guiding star (β *Virginis* at Tahiti, 70 *Ophiuchi* at Wallal) was on the cross wire when its image in one of the cameras fell exactly on a certain mark on the ground glass, were rather trying operations. It was however desirable to have the coördinates of the plate center agree closely with those of the eclipsed Sun (R.A. $11^h 50^m 6$ and Decl. $+1^\circ 1'$, 1922.0) at both observing stations.

The focus was determined at Tahiti and at Wallal by making a series of exposures of a star field on the same plate, changing the focal settings by 1.5 mm. between successive exposures. The images of a number of stars, evenly distributed over the plate, were then examined with the microscope, and for each one the best focal setting was estimated. An average value, about 1 mm. smaller than that of stars at the center of the plate, was adopted. On account of the small ratio of aperture the images thus obtained are sharp and round up to 3° from the plate center.

OBSERVATIONS AT TAHITI AND WALLAL

Mr. Trumpler, in charge of the comparison observations at Tahiti, arrived at this island on April 11, with the necessary equipment. A suitable location for the observations was found in Papeete near the western city limit, close to the beach. The instrument was set up in the garden of a private residence, and on the lower floor of the house a work room was kindly made available, where a temporary dark room

¹⁰ *Publ. Allegheny Obs.*, 3, 63, 1914.

was installed. Mr. P. C. Lieber rendered valuable services as assistant throughout the work at Tahiti.

The observations with the 15-foot cameras were made during the period from May 7 to May 20. The eclipse star-field was photographed at $9^h 40^m$ to $10^h 30^m$ in the evening, the plate holders were left unchanged in the telescope, closing only the slides, and at 4^h to $4^h 50^m$ in the morning the plates were exposed to the check field. The exposures at Tahiti were increased to 3 minutes (as compared with 2 minutes at Wallal) to take account of any difference in the transparency of the air, or of the effect of the fogging of the background during the eclipse in bringing out the fainter stars. Four pairs of plates were secured, three of which had the eclipse and check fields photographed on the same night.

The separate operations for an exposure were: inserting the plate holders, clamping them tightly, and setting the telescope on the guiding star. When the vibrations caused by pulling the slides had subsided, the guiding star was put exactly on the cross wire, and the exposure started by pulling the string of the objective shutter. No guiding was done in declination, and in right ascension not much operation of the slow motion was required during the 3-minute exposures, as the clockwork was well adjusted; but still the few corrections undoubtedly meant a considerable improvement of the star images. Closing the shutter and plateholder slides completed the operation.

The general observing conditions in Tahiti were rather variable, and, as the rainy season was not quite over, considerable cloudiness prevailed on many nights, which was especially a handicap because the exposures had to be made at a specified hour and minute. On a few of the nights the steadiness and definition of the star images were perfect, and some of the Tahiti star images are the best so far obtained with this instrument. On other nights, however, there was noticeable unsteadiness, causing diffused images. The transparency of the air was inferior to that at Mount Hamilton. No trouble was encountered from wind; the night temperatures were remarkably uniform (69° to 74° F); the relative humidity was high; and care had to be taken to prevent fogging of the lenses.

At Wallal Mr. J. B. O. Hosking of the Melbourne Observatory was most helpful during the construction period, and he also assisted in making the instrumental adjustments and the observations. Photographs of the check field were secured on the evening of September 19th to be used in case the evening of the 20th should be cloudy. They were discarded when the weather of the 20th proved favorable, and another pair of plates exposed on the check field at

7^h 45^m on the evening before the eclipse, and left undisturbed in the telescope, was used for the first pair of eclipse photographs. The roof of the observing house was opened about 15 minutes before totality; a small auxiliary finder, set on the crescent of the Sun, helped to point the telescope, while β *Virginis* became visible in the guiding telescope only about 30 seconds before totality, just in time to complete the setting. The image of the guiding star seemed steady and of good definition throughout totality. The first exposure of 2 minutes was started 10 seconds after the beginning of totality; 50 seconds were required to change the plate holders and steady the telescope from the resulting vibrations. The second pair of plates with an exposure of 2 minutes 5 seconds, stopped 10 seconds before the end of totality, received the impression of the cheek field on the evening of the eclipse day.

The night temperatures (70°5 to 72°5) at Wallal recorded during the exposures on the cheek field are very close to those of Tahiti; the temperature in the observing house during totality was about 8° higher (80°0 to 78°5) with a drop of 1°5; the humidity of the air, however, was very low at Wallal during the day and the evening.

DEVELOPMENT AND QUALITY OF STAR IMAGES

In preparation for the eclipse a series of experiments was made to test different developers and different development times in their effects in bringing out the faintest stars on plates with a fogged background (photographs with Crossley reflector of star fields near the full Moon). No doubt was left but that a slow developer is more favorable than a rapid developer, and that the duration should not be much less than that of full development; underdevelopment, though diminishing the fogging of the background, also causes a considerable loss of fainter star images. Rodinal developer diluted 1:50 was selected; all the developing at Tahiti and Wallal had to be done at night and the temperature of the developer was kept close to 70°. At Wallal cooling by evaporation (wrapping the bottles in wet cloth) had to be resorted to.

The Tahiti plates were developed for 10 minutes. At Wallal some bromide of potassium was added and the duration was varied between 5 and 15 minutes. There is a strong psychological tendency to shorten the development when the corona is gaining in intensity so rapidly and when the background of the plate is darkening. After fixing the plate, however, the fogging is generally found much less serious than expected. A rule was therefore set up to extend the development at least 5 times longer than it took the

most intense part of the corona to appear. After two plates (CD22 and AB17), developed according to this rule, had been fixed and examined, this factor was even increased to 10 or 12 times (CD23 and AB18). Despite heavier fogging the longer developed plates show on the average a few more measurable star images.

The corona is strong on all plates and its traces extend to about $1\frac{1}{4}^\circ$ from the Sun's center (see outline on Fig. 1) where the background becomes apparently uniform. The faintest star with a measurable image is of the photographic magnitude 10.8, while in the denser part of the corona (within 30' from the Sun's limb) stars fainter than 9.5 proved very difficult and could be measured only on a few plates.

The star images are generally round and symmetrical, but not as sharp and well defined as on the Tahiti photographs; the fainter stars, especially, appear rather fuzzy and diffuse. It is hardly conceivable that this was produced by a change in focus, which should necessarily have been accompanied by a loss in faint stars. A more adequate explanation seems to be given by the well known fact, that star images on a fogged background become diffused by "creeping." Perhaps the "seeing" during totality may also have had some influence.

The method of measuring as many star images as possible, even faint and poor ones, and of employing a system of weights to take account of their different quality, seemed to make the best use of the available material. During the measures the observers estimated the quality of the image. The weight attributed to it depended entirely on this estimate, according to the following scale, which is in close agreement with the weight system used at the Allegheny Observatory for the parallax photographs:

Quality of image	Weight
Good	1
Fair	.7
Poor, faint, diffuse	.4
Very poor, very faint, very diffuse	.25

MEASUREMENT OF PLATES

From the eight Tahiti plates four were selected to be compared with the four eclipse photographs. In one of the comparison plates (AB10), however, a crack occurred after completing the right ascension measures and another plate (AB9) had to be substituted before the declination measures were made.

To measure the star images differentially an intermediate plate, taken through the glass, was used, following in this the example of the Greenwich expedition of 1919. This intermediate plate had been obtained at Tahiti with objective CD and 4 minutes'

exposure; its star images are remarkably sharp and well exposed even for the faintest stars measured. Eclipse plates as well as night comparison plates were measured by placing them film to film with this intermediate plate, clamping the two plates tightly together by three clamps so that corresponding images fell together with a small offset. As objective AB has a slightly larger focal length, the plates taken with it differ from the intermediate plate in scale, and the distances between corresponding images were somewhat larger for stars near the edge of the plate; in no case, however, did they exceed 2 mm. This cannot introduce any error, since the eclipse plates and the night comparison plates were placed in exactly the same position with respect to the intermediate plate. The first three pairs of plates of TABLE I were measured independently by Campbell and Trumpler, the last one only by Trumpler. The measurement of each plate comprised four series:

- (1) Difference of R.A. (Δx) "direct" : R.A. increasing toward the right hand.
- (2) Difference of R.A. "reversed" : R.A. increasing toward the left hand.
- (3) Difference of Decl. (Δy) "direct."
- (4) Difference of Decl. "reversed."

All the "direct" measures were made with the intermediate plate turned toward the observer and measured through the glass; in the "reversed" measures the eclipse plate or night plate was measured through the glass.

For each series of measures the two plates were oriented in right ascension and declination for equinox 1922.0 by means of a few stars, for which the positions had been taken from the *Astr. Ges. Catalog*. With the filar micrometer of the microscope, magnifying about 15 times, the difference between the two corresponding images (of the eclipse or night plate and the intermediate plate) was measured by making two pairs of bisections on each image. Over 50,000 bisections of star images were thus made by the two observers during the course of the work. While in the eclipse field as many stars as possible were used, only 37 stars of the check field well distributed over the plate and of suitable brightness were selected. The stars of the two fields were measured intermingled without any distinction; two to six of the eclipse stars nearest to the Sun which are of the greatest importance in the present problem were measured at the beginning, in the middle and at the end of each series, to serve as a check on any possible changes as well as to increase the accuracy of their measures. The plates CD23 and CD17 had been measured in one direction (direct) at Broome (Western Australia) immediately after the eclipse; the reversed measures were later made at Mt. Hamilton.

Thanks are due to Miss Howe, Mrs. Campbell and Mrs. Trumpler for their help in recording the measures.

TABLE I

DATA OF THE PLATES MEASURED

Plate		Date 1922	Local M.T.	Expo- sure	Star field	Hour angle W.	Temp. F.	Barom. in.	
CD22	Wallal	Sept. 20	7 ^h 48 ^m .6	2 ^m	Check field	1 ^h 37 ^m .4	72.5	30.28	
		Sept. 21	1 31.2	2 ^m	Eclipse	1 37.8	79.2	30.26	
CD15	Tahiti	May 15	10 8.5	3 ^m	Eclipse	1 50.9	70	30.31	
		May 15	16 23.5	3 ^m	Check	1 52.0	69	30.32	
CD23	Wallal	Sept. 21	1 34.2	2 ^m 5 ^s	Eclipse field	1 40.8	79.2	30.26	
		Sept. 21	7 47.6	2 ^m 5 ^s	Check	1 40.2	70.5	30.31	
CD17	Tahiti	May 20	9 56.8	3 ^m	Eclipse	1 58.8	71	30.33	
		May 20	16 11.8	3 ^m	Check	1 59.9	70	30.31	
AB18	Wallal	Sept. 21	1 34.2	2 ^m 5 ^s	Eclipse field	1 40.8	79.2	30.26	
		Sept. 21	7 47.6	2 ^m 5 ^s	Check	1 40.2	70.5	30.31	
AB12	Tahiti	May 20	9 56.8	3 ^m	Eclipse	1 58.8	71	30.33	
		May 20	16 11.8	3 ^m	Check	1 59.9	70	30.31	
AB17	Wallal	Sept. 20	7 48.6	2 ^m	Check field	1 37.4	72.5	30.28	
		Sept. 21	1 31.2	2 ^m	Eclipse	1 37.8	79.2	30.26	
AB10	Tahiti	May 15	10 8.5	3 ^m	Eclipse	1 50.9	70	30.31	} R.A.
		May 15	16 23.5	3 ^m	Check	1 52.0	69	30.32	
AB9	Tahiti	May 12	10 17.2	3 ^m	Eclipse	1 47.7	74	30.31	} Decl.
		May 14	16 25.4	3 ^m	Check	1 49.9	72	30.17	

(All photographs taken by Trumpler.)

REDUCTION OF MEASURES

Subtracting the Δx and Δy (mean of "direct" and "reversed" measures) of the night comparison plate from the corresponding measures of the eclipse plate, we obtain the differences eclipse plate minus night plate (E — N) expressed in revolutions of the micrometer screw; the intermediate plate is thus completely eliminated. The screw value was determined repeatedly during the measuring period by means of two pairs of stars (98–99 and 102–103). Another method of evaluating this constant was to read on the setting scales how many mm. the microscope had to be shifted to make a star image move over an interval of 20 or 30 revolutions of the screw. Combining this with the known scale value of the plate (45''075 per mm. for objective AB; 45''30 for CD) the screw value in seconds of arc was obtained. Both methods gave satisfactory agreement: 7''18 was used for plates CD22 and CD23; 7''30 for AB18; 7''32 for AB17.

The observed (E — N) were then corrected for the effects of proper motion and annual parallax of the stars, differential refraction and aberration, and inclination of the plate to the optical axis. Terms of the second order in x and y had to be included in these corrections. Ten stars of the eclipse field and three of the check field had determined proper-motions of sensible amount. One star (β *Virginis*) has a measured parallax and for three other stars hypothetical parallaxes derived from their spectral classes and proper-motions were taken into account.

For the check field a reduction formula:

$$\left. \begin{aligned} \Delta x(\text{E—N}) &= a + bx + cy + dx^2 + exy + fy^2 \\ \Delta y(\text{E—N}) &= a' + b'x + c'y + d'x^2 + e'xy + f'y^2 \end{aligned} \right\} \begin{array}{l} (12 \text{ con-} \\ \text{stants}) \end{array}$$

containing all terms of the second order was first used and the plate constants $a, b, \dots, a', b', \dots$ were determined by least squares solutions. It was, however, found that in all cases the second order terms could be confined to those produced by an error in the inclination of the plate to the optical axis:

$$f = 0, d' = 0, d = e' = p, e = f' = q.$$

The further condition that the scale and orientation constants of both coördinates be the same:

$$a = b' = r, c = -b' = s$$

was satisfied for the two plates CD22 and CD23. For AB17 the two coördinates, of course, had to be treated separately because different comparison plates had been used in the two coördinates. For AB18 a small change in the adjustment of the microscope between the R.A. and Decl. measures was sufficient explanation of the non-fulfillment of this condition. The final reduction of the check field was therefore made with the following simplified formulae:

$$\begin{aligned} \text{CD22} & \left\{ \begin{array}{l} \Delta x = a + rx + sy + px^2 + qxy \\ \Delta y = a' - sx + ry + pxy + qy^2 \end{array} \right\} (6 \text{ constants}) \\ \text{CD23} & \\ \text{AB18} & \left\{ \begin{array}{l} \Delta x = a + bx + cy + px^2 + qxy \\ \Delta y = a' + b'x + c'y + pxy + qy^2 \end{array} \right\} (8 \text{ constants}) \\ \text{AB17} & \left\{ \begin{array}{l} \Delta x = a + bx + cy + px^2 + qxy \\ \Delta y = a' + b'x + c'y + p'xy + q'y^2 \end{array} \right\} (10 \text{ constants}) \end{aligned}$$

and a second set of least squares solutions supplied the numerical values of the constants.

From the resulting residuals in x and y the radial component in the direction away from the plate center was calculated. The mean radial residuals for all the plates measured by each observer are plotted in Fig. 3 as a function of the star's angular distance from the plate center.

It seemed desirable to effect the reduction of the eclipse field without determining too many constants from the measures themselves, for these constants would necessarily be mixed up with the light deflections; it was desirable also to avoid making any *a priori* assumptions about the light deflections and about the law according to which they diminish with increasing angular distance of the stars from the Sun's center. The first point was facilitated by the way in which the exposures on the check field had been made; this allowed the adoption for the eclipse region of the second order terms determined by the solution of the check field. The second desideratum could be secured, thanks to the large field of the plate, by using the stars more distant than 2° from the Sun's center (28 to 38) as reference stars for the determination of the linear correction terms (zero point, orientation and scale). Neglecting the light deflections of these stars (0''14 to 0''23 according to Einstein's theory) would cause a sensible error only in the scale value thus determined. A revision of this correction will have to be made later, when the law of light deflection has been established.

The linear plate constants of the eclipse field were obtained by least squares solutions according to Turner's formula:

$$\left. \begin{aligned} \Delta x &= a + bx + cy \\ \Delta y &= a' + b'x + c'y \end{aligned} \right\} (6 \text{ constants})$$

The agreement of the scale and orientation constants of both coördinates

$$b = c' = r, c = -b' = s$$

was satisfactory for the plates CD22 and CD23 for which another solution, made with the formula:

$$\left. \begin{aligned} \Delta x &= a + rx + sy \\ \Delta y &= a' - sx + ry \end{aligned} \right\} (4 \text{ constants})$$

was finally used. For the plates AB17 and AB18 the six-constant formula had to be retained for the reasons stated above in describing the reduction of the check field.

RESULTS

The residuals, after application of these plate corrections, represent the observed star displacements due to light deflection. We shall call them the *relative* displacements, because they are derived by comparing the stars near the Sun with the reference stars of the outer portions of the plate, and the plate constants

are so determined as to make the average displacements of the reference stars zero. To convert the relative values into absolute ones an additional scale correction is needed.

In forming the means of the results of both observers for each plate the weight of any measure made only by one observer (plate AB17) was reduced

Fig. 1. Star chart of the total solar eclipse of Sept. 21, 1922, containing the 92 stars actually measured. The observed relative displacements are marked by a full line for weights 2.0 to 3.9, by a dotted line for weights 1.0 to 2.0, displacements of smaller weight are omitted. The dotted circle is of 2° radius and gives the inner limit of the reference stars, for which the average displacement has been made zero. The outline of the brighter parts of the corona as well as the limit of the faintest traces of coronal light is drawn in. The border line represents the edge of the plate.

by multiplication with 0.9. This factor was derived according to the theory of errors from the accidental "measuring error" and the "plate error" common to the measures of both observers. The four plates were then combined according to their weights. The resulting mean values of the observed relative dis-

placements are given in TABLE II (seventh and eighth columns) together with their total weights (ninth column); they are also plotted, 2250 times enlarged, in Fig. 1. A remarkably large residual is shown by star 110; perhaps this may be accounted for by the situation of the star close to the edge of the plate.

TABLE II
OBSERVED RELATIVE STAR DISPLACEMENTS

No.	B. D.	Phtgr. magn.	X	Y	Distance fr. Sun.	Ecl.—Night		Weight	Radial comp. D ₁	Corr. rad. comp. D ₂	Theory
						Δx	Δy				
2	-0° 2479	10.4	-2.00	-1.58	2.55	+ .12	+ .24	1.13	- .24	- .26	-.06
3	+3 2544	9.2	-1.92	+1.99	2.76	+ .29	+ .28	1.5	.00	.00	-.08
4	+3 2545	10.1	-1.91	+1.42	2.38	+ .47	+ .33	.66	- .18	- .23	-.03
5	+0 2831	8.3	-1.92	- .88	2.11	+ .01	- .06	3.9	+ .02	- .04	+ .01
6	-0 2482	10.4	-1.92	-1.12	2.22	- .15	+ .16	.87	+ .05	.00	-.01
7	+2 2474	10.3	-1.90	+ .80	2.06	- .28	+ .05	1.27	+ .28	+ .24	+ .02
8	+1 2608	9.8	-1.90	+ .26	1.91	+ .08	- .12	2.46	- .10	- .13	+ .04
9	+3 2548	9.2	-1.82	+1.65	2.46	+ .06	+ .14	1.5	+ .05	+ .02	-.04
10	+3 2549	8.7	-1.78	+1.79	2.52	- .06	+ .11	2.46	+ .12	+ .11	-.05
11	+2 2477	10.0	-1.67	+ .77	1.84	+ .26	+ .21	1.61	- .15	- .18	+ .05
12	+0 2833	9.6	-1.67	- .60	1.77	- .41	- .19	2.88	+ .45	+ .44	+ .07
14	+1 2610	10.3	-1.61	- .18	1.62	- .24	- .22	1.79	+ .26	+ .29	+ .10
16	-0 2490	9.3	-1.52	-1.77	2.34	- .06	- .11	2.31	+ .12	+ .08	-.03
17	+2 2480	10.2	-1.49	+ .74	1.66	- .42	- .06	1.94	+ .35	+ .36	+ .09
18	+0 2836	10.0	-1.47	- .59	1.58	+ .10	- .02	2.39	- .09	- .07	+ .11
19	+0 2837	10.4	-1.45	- .38	1.50	- .26	+ .07	1.06	+ .23	+ .28	+ .13
20	+2 2481	9.3	-1.43	+1.14	1.83	- .31	+ .07	2.73	+ .28	+ .26	+ .06
21	+3 2553	10.4	-1.43	+1.86	2.34	+ .36	- .02	1.12	- .23	- .25	-.03
22	+0 2839	10.4	-1.36	- .73	1.55	- .47	- .04	1.39	+ .43	+ .45	+ .12
23	+2 2483	10.2	-1.33	+1.17	1.77	+ .23	+ .25	1.06	- .01	- .01	+ .07
25	+0 2843	6.9	-1.11	- .72	1.33	- .12	- .01	3.9	+ .11	+ .16	+ .17
26		10.8	-1.10	- .74	1.33	- .30	+ .12	.72	+ .18	+ .24	+ .17
27	+1 2617	9.4	-1.02	+ .02	1.02	- .21	- .02	2.61	+ .21	+ .32	+ .28
28	+3 2560	8.2	- .96	+1.32	1.63	- .12	+ .01	3.9	+ .08	+ .08	+ .10
29	+1 2618	10.2	- .96	+ .04	.97	+ .01	- .02	1.27	- .01	+ .10	+ .31
30	+2 2486	10.4	- .96	+ .79	1.24	- .67	- .13	1.76	+ .43	+ .51	+ .20
31	+3 2561	10.2	- .96	+1.42	1.71	+ .01	- .02	1.56	- .02	- .03	+ .08
32	+3 2562	10.3	- .87	+1.74	1.95	- .01	+ .24	.44	+ .22	+ .19	+ .04
33	-0 2498	9.7	- .84	-1.47	1.69	- .11	+ .14	2.46	- .06	- .07	+ .09
35	+1 2619	10.1	- .83	+ .34	.90	- .51	- .09	1.31	+ .44	+ .56	+ .34
36	β Virginis	4.3	- .80	+ .95	1.24	- .09	+ .32	2.73	+ .30	+ .38	+ .20
37	+2 2490	9.7	- .69	+ .96	1.18	- .23	+ .29	3.18	+ .37	+ .46	+ .22
41	+1 2621	10.0	- .47	- .27	.54	- .64	- .35	1.31	+ .73	+ .80	+ .64
43	+3 2566	9.1	- .43	+2.01	2.06	+ .24	+ .15	2.58	+ .10	+ .05	+ .02
46	-0 2501	9.7	- .33	-1.48	1.52	+ .07	- .05	2.88	+ .03	+ .07	+ .12
47	+0 2853	10.2	- .20	- .72	.75	+ .07	- .56	1.2	+ .52	+ .63	+ .44
48	+1 2623	9.4	- .20	+ .40	.44	+ .27	+ .68	.22	+ .47	+ .48	+ .80
51	-0 2507	9.4	- .12	-1.30	1.30	+ .08	- .21	3.6	+ .20	+ .28	+ .18
52	+0 2854	10.2	- .12	- .88	.89	+ .03	- .38	1.2	+ .37	+ .49	+ .34
55	+0 2855	10.4	- .06	- .52	.52	-1.18	- .58	.44	+ .72	+ .74	+ .67
56	+2 2492	10.6	+ .02	+ .74	.74	- .40	+ .69	.55	+ .68	+ .77	+ .44
57	+0 2856	10.6	+ .02	- .79	.79	- .09	+ .53	.66	- .53	- .45	+ .41
58	-0 2510	8.4	+ .05	-1.62	1.62	+ .26	- .18	3.75	+ .19	+ .21	+ .10
59	+0 2858	8.3	+ .08	- .91	.91	+ .07	- .35	3.75	+ .36	+ .46	+ .33
60	+2 2493	9.4	+ .09	+ .59	.60	+ .24	+ .58	2.06	+ .61	+ .69	+ .57

TABLE II (Continued)

No.	B. D.	Phtgr. magn.	X	Y	Distance fr. Sun.	Ecl.—Night		Weight	Radial comp. D ₁	Corr. rad. comp. D ₂	Theory
						Δx	Δy				
63	+1° 2628	7.3	+ .16	+ .41	.44	+ .24	+ .68	3.9	+ .72	+ .76	+ .81
64	+3 2572	9.1	+ .16	+1.36	1.37	+ .15	+ .15	3.75	+ .17	+ .23	+ .16
65	-0 2511	10.3	+ .20	-1.32	1.33	+ .14	- .49	2.13	+ .51	+ .58	+ .17
66	+0 2859	10.2	+ .21	- .53	.57	- .78	- .90	.25	+ .55	+ .64	+ .62
68	-0 2512	8.8	+ .28	-1.62	1.64	+ .16	- .16	3.48	+ .19	+ .20	+ .10
70	+0 2860	10.2	+ .30	-1.11	1.14	+ .26	- .33	1.94	+ .39	+ .49	+ .24
72	+3 2576	9.4	+ .47	+1.46	1.54	+ .04	- .25	2.31	- .23	- .19	+ .12
73	+1 2631	9.6	+ .49	+ .03	.49	- .14	- .47	.69	- .17	- .12	+ .73
75	+3 2577	10.1	+ .56	+1.97	2.05	+ .03	+ .14	1.05	+ .14	+ .10	+ .02
76	+0 2864	10.5	+ .56	- .37	.67	+1.18	-1.08	.22	+1.58	+1.64	+ .50
77	+0 2865	10.6	+ .61	- .61	.86	+ .47	+ .16	.44	+ .22	+ .30	+ .36
78	+1 2633	8.4	+ .72	+ .23	.76	+ .49	+ .09	3.75	+ .49	+ .60	+ .43
79	+1 2635	10.3	+ .79	+ .23	.82	+ .48	+ .09	1.39	+ .49	+ .60	+ .39
80	-0 2515	10.3	+ .83	-1.29	1.54	+ .27	- .18	1.86	+ .30	+ .33	+ .12
81	+1 2636	7.5	+ .89	- .04	.89	+ .32	+ .07	3.9	+ .32	+ .43	+ .34
82	+2 2498	10.3	+ .89	+ .82	1.21	+ .06	+ .01	1.86	+ .05	+ .14	+ .21
84	+0 2870	9.6	+ .94	- .45	1.04	+ .47	+ .07	2.88	+ .39	+ .49	+ .28
85	+0 2872	10.2	+ .95	- .60	1.12	+ .21	- .13	1.2	+ .25	+ .34	+ .24
86	+2 2499	8.0	+ .96	+1.00	1.38	+ .04	- .16	3.9	- .09	- .02	+ .16
87	+3 2583	10.4	+ .97	+1.84	2.08	+ .32	+ .15	.87	+ .28	+ .23	+ .01
88	+0 2874	10.0	+ .99	- .34	1.04	+ .13	- .07	1.71	+ .15	+ .26	+ .28
89	-1 2600	8.3	+ .99	-2.00	2.23	+ .16	+ .29	3.18	- .19	- .24	- .01
90	+1 2637	10.4	+1.06	+ .26	1.09	+ .22	+ .10	.73	+ .24	+ .35	+ .26
91	+2 2501	9.7	+1.07	+ .50	1.18	+ .39	+ .05	2.28	+ .37	+ .47	+ .22
92	+0 2875	9.6	+1.16	-1.02	1.55	+ .30	- .02	2.88	+ .24	+ .27	+ .12
93	+2 2502	10.0	+1.20	+ .58	1.33	+ .11	- .23	1.68	.00	+ .06	+ .17
94	+3 2586	10.5	+1.21	+1.46	1.90	+ .75	- .12	.77	+ .38	+ .35	+ .05
95	+2 2505	9.6	+1.27	+1.03	1.64	- .13	- .48	2.81	- .40	- .39	+ .10
96	-0 2520	7.8	+1.28	-1.88	2.28	+ .13	+ .08	3.9	+ .01	- .04	- .02
97	-0 2521	10.3	+1.29	-1.74	2.17	- .21	+ .09	1.35	- .20	- .25	.00
98	+0 2877	9.3	+1.37	- .76	1.57	+ .42	- .15	3.0	+ .44	+ .46	+ .11
99	+0 2878	9.0	+1.37	- .77	1.57	+ .29	+ .11	3.33	+ .20	+ .23	+ .11
100	+3 2588	9.5	+1.37	+1.42	1.98	+ .33	- .15	2.55	+ .12	+ .08	+ .03
101	+1 2639	10.0	+1.43	- .04	1.43	+ .13	- .35	2.09	+ .14	+ .19	+ .15
102	+0 2880	8.2	+1.47	- .38	1.52	+ .24	+ .06	3.75	+ .21	+ .26	+ .13
103	+0 2881	9.5	+1.47	- .40	1.52	+ .26	- .11	2.88	+ .28	+ .32	+ .13
104	+1 2641	9.3	+1.55	- .01	1.55	- .06	- .06	3.03	- .06	- .03	+ .12
105	+0 2883	8.8	+1.58	- .43	1.64	+ .12	- .04	3.03	+ .13	+ .14	+ .10
106	+2 2507	10.4	+1.59	+ .83	1.80	- .06	- .41	.47	- .24	- .26	+ .06
107	-0 2524	10.2	+1.65	-1.61	2.30	+ .25	+ .23	1.3	+ .02	- .02	- .02
108	-0 2526	10.2	+1.73	-1.77	2.47	+ .43	+ .15	.87	+ .19	+ .15	- .05
109	-0 2527	10.4	+1.80	-1.16	2.14	+ .23	.00	1.16	+ .19	+ .14	.00
110	+2 2509	7.8	+1.92	+ .70	2.05	- .64	- .21	3.75	- .67	- .72	+ .02
112	+1 2645	10.0	+1.97	+ .09	1.98	- .79	+ .43	.76	- .76	- .80	+ .03
113	+2 2510	10.1	+1.98	+1.13	2.28	- .52	- .11	.66	- .51	- .54	- .02
117	+1 2647	10.1	+2.00	+ .14	2.01	.00	- .28	.33	- .02	- .07	+ .02
118	+1 2648	9.9	+2.01	- .29	2.03	- .96	+ .96	.25	-1.09	-1.13	+ .02

The first two columns of TABLE II designate the star; the third contains the photographic magnitudes, derived from diameter measures of the star images and based on the photographic magnitude scale of the *Henry Draper Catalogue*. The next three columns (4 to 6) give the rectangular coördinates of each star

and its distance from the Sun's center expressed in units of 100 mm. = 4508". From the mean observed relative displacements Δx and Δy in columns 7 and 8, the component in the radial direction D₁, (positive if away from the Sun) was calculated (column 10). This observed radial component represents the effect

of light deflection and may be compared with the corresponding values predicted by Einstein's theory (last column of TABLE II). The theoretical values given are not the full predicted star displacements, but the *relative* displacements derived from them by the scale correction: $-.079 d$ (d = distance from

Sun's center). This coefficient is the mean of the scale corrections of the four plates as obtained from the least squares solutions mentioned below.

Arranging the stars according to their distance from the Sun's center the group means of TABLE III were formed:

TABLE III
GROUP MEANS OF OBSERVED RELATIVE RADIAL DISPLACEMENTS

Group	Stars	Weight	Mean dist. from Sun	Obs. rad. displ.	Corrected rad. displ.	Theory
1	8	9.09	0.64	+".64	+".69	+".70
2	11	19.42	1.06	+".35	+".46	+".37
3	10	20.15	1.40	+".30	+".39	+".24
4	8	22.41	1.66	+".16	+".22	+".17
5	9	21.10	1.90	+".17	+".21	+".13
6	8	24.67	2.00	+".15	+".17	+".11
7	11	21.32	2.22	+".08	+".08	+".08
8	13	21.37	2.55	-.09	-.14	+".02
9	14	22.78	2.97	-.04	-.08	-.03

Reserving the data in the next to the last column (corrected rad. displ.) of TABLES II and III for comment on a later page, one may note here that the *observed* radial displacements given in these tables are in remarkably good agreement with the values predicted on the basis of Einstein's theory. Even the stars between 1°25 and 2°25 from the Sun's center, lying entirely outside of any trace of the corona, show the light deflection well marked, an effect that would be hard to explain by an extended solar atmosphere.

A graphical representation of the coincidence between the observed and the predicted light deflections is given in Fig. 2, where the observed radial displacement D_1 of each star is plotted as a function of the star's angular distance from the Sun's center. Stars with weights 2.0 to 3.9 are marked by large dots, those with weights 1.0 to 2.0 by small dots, stars with weight below 1.0 being omitted. The group means (D_1) of TABLE III are joined by the broken line, while the dotted curve shows the prediction by Einstein's theory. A new base line B has been constructed illustrating the scale correction needed to convert the

relative displacements into absolute ones. All plots if measured vertically from base line B give absolute displacements. As far as it is referred to the original base A, the figure represents the relative radial displacements actually observed and is independent of any assumption about the light deflection (except that it be radial and independent of the position angle of the star).

Adopting Einstein's prediction that the displacements are inversely proportional to the distance d from the Sun's center, and keeping in mind that the scale value needs correction, the radial displacements (Δr) observed are represented by a formula

$$\Delta r = \alpha d + \beta \frac{R}{d}$$

where:

α = correction of scale value

β = light deflection at Sun's limb

R = radius of Sun's disk = 0°2661.

For each plate and each set of measures α and β were determined from the measured radial displacements of all stars by least squares solutions.

TABLE IV
LIGHT DEFLECTION AT THE SUN'S LIMB

Plates	Campbell	No. of stars	Trumpler	No. of stars	Plate mean
CD22—CD15	*1.72±.32	62	*1.88±.27	69	1.80
CD23—CD17	1.35±.22	77	*1.62±.22	81	1.48
AB18—AB12	*1.78±.22	80	*1.91±.19	84	1.85
AB17—AB10/9			1.76±.22	85	1.76 (weight .9)
Mean for each observer	1.60±.14		1.78±.11		
			Mean from four plates		1.72±.11
			Einstein's predicted value		1.745

* These five values, very slightly modified, were the only ones available when the preliminary announcement of our results for the Einstein eclipse problem was made through the press associations and otherwise, on April 11, 1923. At that date we had also determined from measures of the check-region star images, that any corrections suggested or demanded by existing small plate errors could not operate to diminish any of the five values of the Einstein coefficient.

The agreement with the prediction is again very satisfactory, only one of the seven results differing from it by more than its probable error. The plate means were formed by giving equal weight to both observers. The means for each observer are based on the weights of the separate least squares solutions. When taking the mean of the four plates, the first three plates received weight 1, the last plate, measured only once, weight 0.9 (see page 48).

For every plate the measures of the two observers were reduced independently, even as to the weighting of the stars according to the estimates of each observer, and as to all the plate constants determined from the measures. No measures once entered in the observing book were rejected during the reductions, except when a remark suggesting that this be done had been made during the measures (two cases), or if the star image

on one of the plates was within 10 mm. from its edge, and further in two cases of measures of very faint and uncertain images, giving residuals exceeding $1''.5$.

The star field was further divided into four quadrants so situated that the Sun's equator passed through the middle of two of the quadrants and the Sun's axis of rotation through the middle of the other two. For the stars of each quadrant a separate least squares solution with the formula of page 51 was made, using the mean radial displacements D_1 of TABLE II.

Quadrant	No. of stars	Light deflection at Sun's limb
Preceding Sun's equator	24	$1''.61 \pm .28$
Following Sun's equator	29	$1.68 \pm .25$
At Sun's North pole	18	$1.76 \pm .26$
At Sun's South pole	21	$1.73 \pm .24$
Mean of equatorial quadrants	53	$1''.63 \pm .15$
Mean of polar quadrants	39	$1.76 \pm .18$

Fig. 2. Observed radial displacements as a function of the star's angular distance from the Sun's center. Large dots represent stars with weights 2.0 to 3.9, small dots those with weights 1.0 to 2.0; stars of smaller weight are omitted. The broken line connects the group means of the observed radial displacements, the asterisks mark the group means of the observations corrected on the basis of the residuals of the check stars. The dotted curve gives the values predicted by Einstein's theory. If the displacements are measured vertically from base line B they are absolute, if measured from base line A they are relative to the reference stars (as actually measured).

The agreement of the four quadrants is better than we should expect from the probable errors. This shows that the light deflections are practically identical in all position angles, and it proves also that the determination of the plate constants is very satisfactory and can have no appreciable influence on our results. The slight difference between the light deflections at the Sun's equator and those at the poles is probably accidental; at least it is well within the limits of the errors of observation.

The probable errors of a differential measure ($E - N$) of weight 1 (good) on one pair of plates are on the average:

	Campbell	Trumpler
Check field	$\pm .19$	$\pm .16$
Eclipse field, radial	$\pm .20$	$\pm .19$
Eclipse field, pos. angle	$\pm .18$	$\pm .18$

These data are derived from the residuals of all the stars. Comparing the radial residuals of both observ-

ers for the eclipse stars of two plates, the "accidental measuring error" is found to be only $\pm .08$. From this we conclude that the preponderant part of the above probable errors is an actual "plate error" in the star images, not reduced by increasing the number of measures. The effects of the corona and of the fogging of the sky background, not only in increasing the difficulty of the measures, but probably also in influencing the grouping of the silver grains in the star images, have to be considered when judging these probable errors.

The probable error is slightly smaller in position-angle than in radial direction. The observations, therefore, give no evidence of star displacements in any other direction than radially away from the Sun's center, and the deviations from the radial direction shown by the observations plotted in Fig. 1 are entirely accounted for by the accidental errors of observation.

Fig. 3. Radial residuals of check stars as a function of their angular distance from the plate center. Large dots represent stars with weights larger than 2.0, small dots those with weights smaller than 2.0. The asterisks give the group means of the residuals; the dotted curves show the corrections derived therefrom and applied to the stars of the eclipse field.

We have still to examine the residuals of the check stars for the existence of any systematic errors that might have affected the observed light deflections. Arranging the check stars according to their distance

from the plate center and forming group means of the radial components of the residuals we obtain the following table:

TABLE V
RADIAL COMPONENT OF RESIDUALS OF CHECK STARS

Group	Stars	Campbell			Trumpler		
		Weight	Dist. fr. center	Radial resid.	Weight	Dist. fr. center	Radial resid.
1	7	11.75	0.76	-.16	15.15	0.76	-.05
2	6	16.8	1.24	-.15	23.1	1.24	-.09
3	6	16.5	1.79	-.10	22.2	1.79	-.02
4	6	15.6	2.17	-.01	21.3	2.17	+.01
5	6	15.0	2.72	+.16	19.2	2.71	+.04
6	6	12.75	3.08	+.02	17.55	3.12	+.01

This table corresponds to TABLE III, except that the measures of the two observers are treated separately. In a similar way Fig. 3 is to be compared with Fig. 2. The large star displacements near the Sun found in the eclipse field have no counterpart in the check field and can therefore not have their source in any instrumental errors, nor can they be due to the peculiar method of measuring and reducing the plates. Some small systematic deviations in the check stars, however, are indicated for both observers, and if their causes affect the stars of the eclipse field in the same manner, our results for the light deflections will be too small.

There may be some doubt as to whether corrections based on the residuals of the check stars should be applied to the observed displacements of the eclipse stars. Temperature and other conditions during the eclipse were of course not identical with those prevailing at night when the check field was photographed; the check stars are also on the average a little brighter than the eclipse stars; and, finally, a part of the grouping in the residuals of the check stars may be accidental. On the other hand the most reasonable explanations of the observed deviations of the check stars seem to be offered by the sources of error mentioned on page 41 under 1, 2, and 3, which should have affected alike both star fields photographed on the same plate. The contraction of the photographic film during the process of drying, mentioned under 3, would explain the sign of the deviation. The fact that the two observers differ in its amount, rather suggests that a personal measuring error is involved. This personal difference is reflected in exactly the same way in the results of TABLE IV, where the light deflections measured by Campbell are consistently smaller than those by Trumpler; and the improvement in the agreement of the results of the two observers, achieved by the use of the corrections mentioned, is undoubtedly in their favor.

If such corrections, read from the dotted curves drawn in Fig. 3, are applied with opposite sign to the observed radial displacements D_1 of the eclipse stars, we obtain the "corrected" values D_2 of the column next to the last in TABLES II and III. The group means of D_2 are also represented in Fig. 2 by asterisks, and a new least squares solution with the formula of page 51, using the corrected data D_2 of TABLE II, gives for the deflection at the Sun's limb: $2''.05$.

This result is 17% in excess of the prediction, but it should be kept in mind that it is derived by extrapolation. A closer examination of the last two columns of TABLE III and of Fig. 2 shows that it is not the stars nearest to the Sun that differ in their corrected displacements from the theoretical values; it is only for the stars between one and two degrees distant from the Sun's center that the corrections have introduced a marked excess in light deflection (slightly indicated even in the original displacements D_1). If the corrections are justified, our observations suggest the existence of an effect additional to that of Einstein's theory. This additional effect should be small at the Sun's limb and rise gradually to a maximum of about $0''.4$ at 2° to 3° from the Sun's center, in order, when combined with a new determination of the scale value to agree with the corrected displacements D_2 . It could then be considered as representing Courvoisier's "yearly refraction" in the immediate neighborhood of the Sun. It is however inadvisable to pursue this problem any further at the present moment, as the plates of the 5-foot cameras, with a larger field, will shortly supply material much better suited to its investigation.

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