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CONTENTS

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RÉSUMÉ OF OBSERVATIONS CONCERNING THE SOLAR ECLIPSE OF MAY 29, 1919, AND THE EINSTEIN EFFECT[1]

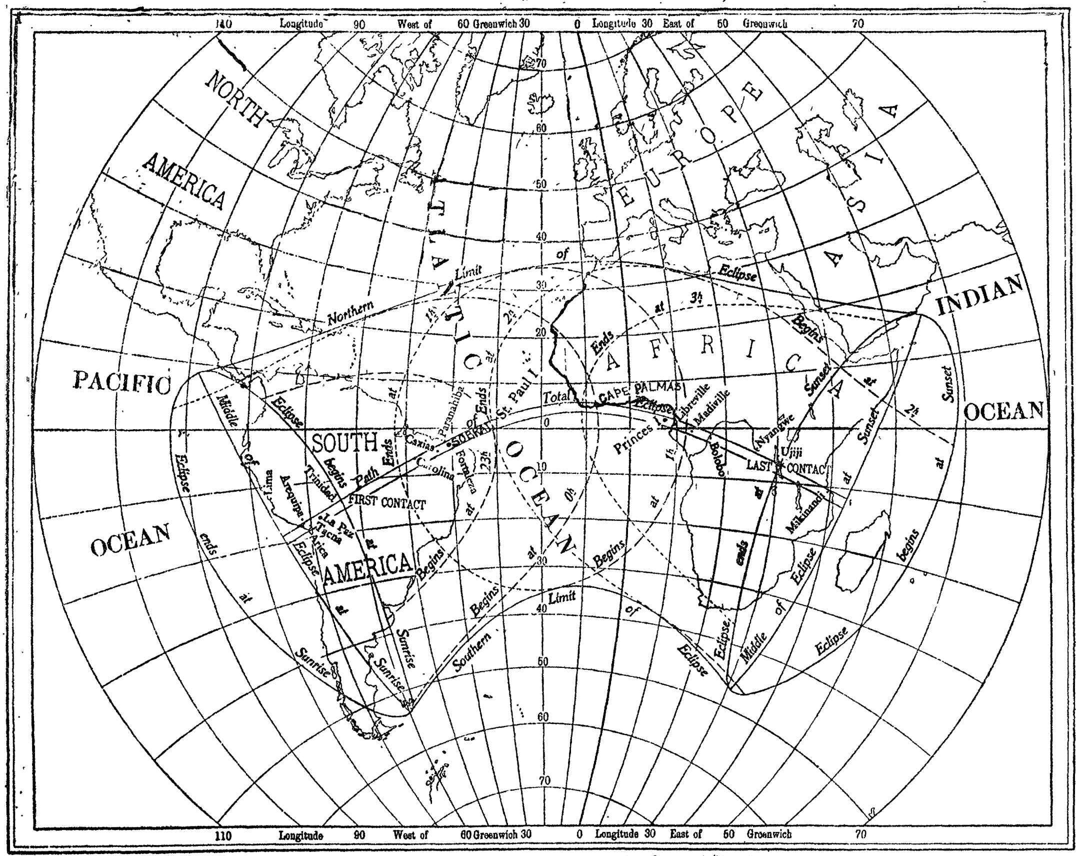
1. A TOTAL eclipse of the sun is of more than passing interest, not merely to the astronomer but also to the geophysicist. Indeed, by reason of the supposed verification of the so-called Einstein effect during the solar eclipse of May 29, 1919, which, in consequence, may make that eclipse the most famous of all eclipses observed thus far, an eclipse of the sun has become of profound interest also to the physicist, to the mathematician, and to the philosopher, in general.

In the following brief account of the chief phenomena observed during the solar eclipse of May 29, 1919, the path of totality for which is shown in Fig. 1, the attempt will be made to bring out succinctly the various points of interest to men of science.

2. To give a personal touch let me first briefly state the results of my own expedition to Cape Palmas, Liberia, where totality was longer (6 minutes and 33 seconds) than at any other accessible station, where the sky was comparatively clear, contrary to all good meteorological predictions, and where totality

[1] Abstract of papers presented before the Philosophical Society of Washington (October 11, 1919 and January 3, 1920), Royal Astronomical Society of Canada, Toronto (December 2, 1919), American Academy of Arts and Sciences, Boston (January 14, 1920), American Philosophical Society, Philadelphia (February 6, 1920) and American Physical Society (New York, February 28). Also basis of public lectures delivered at the following universities: Toronto (December 2, 1919), College of the City of New York (December 4, 1919), Johns Hopkins (January 12), Yale (January 13), Brown (January 15), Columbia (January 16), Swarthmore (February 7) and Middletown Scientific Association of Wesleyan University (March 9).

TOTAL ECLIPSE OF MAY 28-29, 1919.



Note:- The hours of beginning and ending are expressed in Greenwich Mean Time.

Fig. 1.

occurred at about one P.M. local mean time. The purpose of my expedition was not to make astronomical but *geophysical* observations, the chief of which were to be observations to detect, or verify, a possible effect on the earth's magnetic field such as has been shown by observations made under my direction, since the solar eclipse of May 28, 1900. Though it is not necessary for the detection of this magnetic effect to have a clear sky, as no layer of cloud could screen it, it has been my good fortune now three times[2] to have a clear sky when others whose work absolutely depended upon clear weather were not so fortunate.

3. When I left Washington early in March, 1919, it had been arranged that I should occupy conjointly with Dr. Abbot of the Smithsonian Institution, La Paz, Bolivia, in order that I might have there the conditions encountered during the eclipse of June 8, 1918, at my station, Corona, Colorado, the elevation of which is 12,000 feet. As Dr. Abbot intended to look after the photographic work, I did not provide myself with appliances for purely astronomical work. Upon arrival in England, it was found impracticable to reach a South American station in time for the eclipse; accordingly, it was

[2] Manua, Samoan Islands, April 28, 1911; Corona, Colorado, June 8, 1918; Cape Palmas, Liberia, May 29, 1919. In addition I made observations at Rocky Mount, North Carolina, of the total solar eclipse, May 28, 1900.

decided to proceed to Cape Palmas, Liberia, instead.

4. The station at Cape Palmas, Liberia, was one of five principal stations at which magnetic and allied observations were carried out by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in connection with the solar eclipse of May 29, 1919. Two of these stations were inside the belt of totality: Sobral, Brazil, in charge of Mr. D. M. Wise, assisted by Mr. A. Thomson; and Cape Palmas, in charge of the author, assisted by Mr. H. F. Johnson. A third station, at Huayao, Peru, north of the totality belt, was in charge of Dr. H. M. W. Edmonds; the fourth station, south of the belt of totality, at Puerto Deseado, Argentina, was assigned to Mr. A. Sterling; and the fifth, about 100 miles north of the belt of totality, at Campo Cameroun, was assigned to Mr. Frederick Brown. Observations were also made at a secondary station, Washington, outside the zone of visibility, by Mr. C. R. Duvall. In addition to these stations, special magnetic observations were made at the Department's magnetic observatory at Watheroo, Western Australia, and at observatories all over the globe, both inside and outside of the region of visibility of the eclipse, according to the department's program.[3] The reports already received from many of the foreign observatories indicate that the magnetic conditions were ideal for the detection of a possible magnetic effect. *There were clear indications at Cape Palmas of a magnetic effect in accordance with the results obtained during previous solar eclipses. Since Cape Palmas was nearly on the magnetic equator, the effect was especially noticeable in the vertical component of the earth's magnetic field intensity, or upon the magnetic dip.*

[3] The general scheme of work consisted in simultaneous magnetic observations of any or all of the elements every minute from May 29, 1919, 9^h58^m A.M. until 4^h32^m P.M., Greenwich civil mean time, thus for an interval of time from 35 minutes before the beginning until 48 minutes after the end of the eclipse on the earth. Similar observations for the same interval of time as on May 29 were to be made, if possible, on May 28 and 30 to afford the necessary means for determining the undisturbed course of the magnetic elements. Special continuous registrations were called for at magnetic observatories. Furthermore, special atmospheric-electric and meteorological observations were included in the program.

5. Our observation program at Cape Palmas (latitude, 4° 22′ N.; longitude, 7° 43′.7 or 30^m55^s West of Greenwich) included magnetic and electric observations, meteorological observations, shadow-band observations, times of contacts and photographs such as could be obtained with a small kodak camera. This comprehensive program was carried out successfully, excepting the atmospheric-electric work which, owing to the deterioration of the dry-cell batteries purchased in England, had to be abandoned. Sir Napier Shaw had kindly loaned us a Benndorf electrograph. Although I had stationed three observers, *no shadow-bands were observed this time, even greater precautions having been taken than at Corona during the eclipse of June 8, 1918, where they were observed.*

The full geophysical program, including complete atmospheric-electric observations, was carried out by our party in charge of Mr. Wise at *Sobral, where shadow-bands were clearly observed* by his assistant, Mr. Thomson.

6. *The eclipse of May 29 as observed at Palmas, was not nearly as dark, in spite of its long duration, as the much shorter one of June 8, 1918,* which I had observed at the mountain station, Corona, Colorado. There was a marked difference in light, both as seen visually and as shown by the photographs, between the inner corona and the outer extensions. The intense brightness of the inner corona may have been the cause of the fact that the eclipse of May 29, 1919, was not as dark as had been expected. Dr. A. C. D. Crommelin, the British astronomer at Sobral, Brazil says:[4] "The darkness during totality was not great; we estimated that the illumination was about the same as that 25 minutes before sunrise. The corona was very brilliant,

[4] *The Observatory*, London, October, 1919, pp. 370–371.

probably at least three times as bright as the full moon."

7. The *large crimson prominence*, appearing at Cape Palmas on the southeast limb of the sun, turned out to be the largest prominence thus far photographed; it was a most conspicuous and startling object, projecting about 100,000 miles out from the sun's disk and having a base of 300,000 miles. On the southwest limb was a striking V-shaped rift in the solar corona which showed marked equatorial extensions to the west and east. The corona was approximately of the intermediate type between that which is seen during years of minimum sun-spot activity, when there are great equatorial extensions of the corona, and that shown during years of maximum sun-spot activity, when streamers of about the same length extend from the sun in every direction.

8. I succeeded in obtaining with my small camera, which is provided with an excellent lens, two sharp photographs of 10 and 20 seconds exposure, which when enlarged show well the chief features of the corona and of the prominence.[5] In addition, as the result of the interest aroused by a lecture which I was requested to give in the Methodist Church at Cape Palmas the day before the eclipse, a number of free-hand sketches of the corona were made for me by white merchants and by Americo-Liberians; these sketches, while not one of them is complete, show a number of interesting details.

9. The results of the *meteorological observations* at Cape Palmas will be of interest in connection with one of the theories suggested for the explanation of the bending of light rays, to which reference will be made later. Through the courtesy of Sir Napier Shaw and Colonel H. G. Lyons the British Meteorological Office loaned us a complete outfit of self-recording meteorological instruments, which were kept in operation by my assistant, Mr. Johnston, as long as the conditions permitted during our month's stay at Cape Palmas.[6] On the day of the eclipse there was a steady decrease in temperature from 12^h G.M.T., 0.7 minute after the first contact, to 12.7^h G.M.T., and then a more rapid decrease until the minimum temperature of 79°.4 F. was reached at 14^h G.M.T., which was approximately 0.4^h later than the middle time of totality. *The temperature drop during the time of the eclipse was, accordingly, about 2°.5 to 3°.0 F.* The increase in temperature after 14^h was rapid, the maximum 82°.7 F. being reached at 14.9^h G.M.T. The hygrogram for May 29 showed the following effect: the humidity, which was 71 per cent. at 12^h G.M.T. steadily increased to 78 per cent. at 14^h G.M.T. There was a more rapid decrease from 14^h G.M.T. to 15^h G.M.T., when the humidity was 66 per cent. *The maximum humidity, therefore, occurred at 14^h, or approximately 0.4 hour later than the middle time of totality. The barogram showed nothing marked during the time of the eclipse.*

At Sobral, Dr. Crommelin states:[7]

> The eclipse day opened very unpromisingly, the proportion of cloud at first contact being about 0.9. . . . The cloudiness during the early stages was doubtless the cause of the fall of temperature during totality being unexpectedly small; perhaps this latter fact was connected with the dead calm that prevailed during totality.

COMPLETE SERIES OF PHOTOGRAPHS

10. There was next shown in my lectures a complete series of photographs taken by the various observing parties, namely: C. G.

[5] During the duration of totality it was necessary for the author, (*a*) to take and record the readings of the magnetic-intensity variometer and attached thermometer at one- or two-minute intervals, and to check every fifth minute the Liberian assistant, Professor G. W. Hutchins, who had volunteered to take the declinometer-readings every minute; (*b*) to observe the times of contacts, obtain photographs, and give any required additional directions to the shadow-band observers. Thus though totality lasted at Cape Palmas 6½ minutes, it was none too long for a strenuous program in a tropic region.

[6] Mr. Johnston was also entrusted with the earth-inductor work.

[7] *The Observatory*, London, October, 1919, pp. 370–371.

Abbot, of The Smithsonian Institution, at La Paz, Bolivia; H. Morize, in charge of the Rio de Janeiro Observatory party at Sobral, Brazil; the British Astronomical Party (C. Davidson and A. C. D. Crommelin) at Sobral; L. A. Bauer at Cape Palmas, Liberia; and the British Astronomical Party (A. S. Eddington and Mr. Cottingham) at the Île of Principe in the Bight of Africa. Also slides of the great solar prominence of May 29, 1919, as photographed at the Yerkes Observatory, were exhibited. Grateful acknowledgement is here made to the Astronomer Royal of England, Sir Frank W. Dyson, and to those just mentioned, for copies of the photographs taken by their expeditions, as also to Dr. W. W. Campbell, who supplied slides showing how the corona changes its shape during the sun-spot cycle.

11. The chief features of the solar corona and prominence, as shown by the series of slides exhibited, have already been stated in paragraphs six and seven, where the observations at Cape Palmas were described. Careful measurements have been made between the various prominent features, as shown on the photographs taken along the belt of totality from Bolivia to the French Congo. From all the data supplied it is found that the mean heliographic latitude of the prominence during the time of the eclipse was about 18° south, and on the east limb, whereas the pronounced V-rift was about 45° south, and on the west limb. Practically diametrically opposite the V-rift was a less-pronounced rift, which I have called the U-rift. The solar prominence during the average time (11^h48^m G.M.T., civil) of totality at the two South American stations and the average time (13^h 55^m G.M.T., civil) of the two African stations changed comparatively little, though later in the day, according to the Yerkes Observatory photographs, kindly supplied by Professor Frost and Mr. E. Pettit, very great changes took place; thus, for example, at 20^h23^m G.MT., civil, the prominence had shot up to the height of 472,000 miles from the sun's limb.[8]

[8] See Mr. Edison Pettit's account in the *Astrophysical Journal*, for October, 1919, pp. 206–219.

12. A distinct purpose was had in mind in exhibiting first the various features of the solar corona and prominence, which persisted for four rotations of the sun and filled portions of the solar atmosphere with the products of eruptions, in order that one might be the better prepared to pass judgment upon the results concerning the deflection of light rays. For the same reason was given an account, though incomplete, of the results of our geophysical observations. We shall find that all the various phenomena though apparently unrelated have, indeed, an important bearing upon our next topic.

13. Altogether the solar eclipse of May 29, 1919, as observed at Cape Palmas, Liberia, was the most magnificent one of the four[9] it has been my good fortune to observe. Similarly Dr. Abbot with reference to what he saw at La Paz, Bolivia, says:[10]

> Taking into account the great length and beauty of the coronal streamers, the splendid crimson prominence throwing its glory over all, and the fact that the eclipse was observed so near sunrise from so great an elevation as 14,000 feet, with a snow-covered range of mountains upwards of 20,000 feet high as a background for the phenomenon, it seemed to the observers to be the grandest eclipse phenomenon which they had ever seen.

RESULTS OF OBSERVATIONS FOR DEFLECTION OF LIGHT

14. The most important result, undoubtedly, of the observations made by the astronomical parties during the solar eclipse of May 29, 1919, is the disclosing of the fact that the rays of light coming from stars, which appeared on photographs taken of the eclipsed sun and surrounding region, were bent by a measurable amount. No matter what the cause of the bending actually was, the fact is of profound interest and is bound to advance our knowledge. The chief possible causes which have been advanced thus far are:

(*a*) *Newton-Maxwell Effect.—Deflection of the rays of light by the sun's gravitational*

[9] See footnote 2.

[10] Abbot, C. G., and A. F. Moore: "Observations of the Total Solar Eclipse for May 29, 1919," Smithsonian Collections, Vol. 71, No. 5, p. 3, Washington, January 31, 1920.

action, just as the path of a projectile fired into the air is bent by the earth's gravitation pull upon the projectile, the amount of deflection being in accordance with Newtonian mechanics and Maxwell's electromagnetic theory of light. [If we assume, as did Newton, that light consists of corpuscles of matter traveling at great velocity, then it is easy to see why light should be bent under the action of gravity, for a cubic foot of light would in this case differ from a cubic foot of other ponderable material only in matter of *weight.* Newton in fact, had predicted such bending. But as our knowledge of light advanced we were forced to abandon Newton's theory for the undulatory or wave theory of light—a wave motion in the ether supposed to fill all space, the vibrations being electromagnetic ones according to our latest theory (Maxwell's). Light then consisting of some sort of wave motion possesses energy, or the power to do work, and it was furthermore shown about 20 years ago, by a Russian physicist, Lebedew, and by two American physicists, Nichols and Hull, that light exerts a measurable *pressure* when it falls upon a surface just as would material particles when fired at that surface. That light exerts pressure was in fact predicted by Maxwell a half century ago, but it was an open question whether light also had *weight.* The pressure of light resulted from the electromagnetic energy inherent in light, by which it is endowed with inertia just as is a body of material mass. Would gravity act upon something having electromagnetic inertia in the same way as upon a body of material mass? If so, the precise gravitational effect upon light could be predicted.] If a ray of light from a distant star just grazed the sun's edge (limb), it would be bent inwards (towards the sun) by $0''.44$, as viewed by a solar observer. As the ray of light passed out of the sun's gravitational field on its journey to the earth it would suffer another deflection of about $0''.44$, and in such a way that the final and total bending as perceived by an observer on the earth, would be away from the sun $0''.87$—the angle which an object one inch high would subtend at a distance of three and three fourth miles.

(*b*) *Einstein Effect.—Twice the deflection of the rays of light predicted in* (*a*), this time *again by the sun's gravitational action, but according to the principles of Einstein's generalized relativity theory.* (These principles are tersely stated by Professor A. G. Webster):[11]

> First, that of the constancy of the velocity of light with respect to all directions and to any system moving with any velocity whatever with respect to any other system; second, a relation between time and distance such that either of two bodies seem shortened in the direction of their relative motion by an observer attached to the other; third, that it is impossible to distinguish a gravitational field from the acceleration of the frame of reference; and fourth, that everything that has mass, as determined by inertia, has mass of the sort determined by weight or attractability.

According to the Einstein law of gravitation, the deflection of a ray of light which grazed the sun's limb would be away from the sun by $1''.74$[12], as we, or anyone outside the sun's gravitational field, might perceive it.

(*c*) *Refraction in the Solar Atmosphere.*—Bending of rays of light by refraction in passing through the sun's atmosphere, which, in more or less attenuated form, is known to extend out so far that the rays from all the stars concerned in the measurements would have to pass through it on their way to the earth.[13] [Such bending of light actually takes place all the time as the rays from the sun and other celestial bodies pass through our own atmosphere; the amount of atmospheric

[11] *The Review*, January 31, 1920, p. 116.

[12] See A. S. Eddington's "Report on the Relativity Theory of Gravitation," London, 1920, p. 55.

[13] See Dr. H. F. Newall's suggestive note in *Monthly Notices of the Royal Astronomical Society*, Vol. LXXX., No. 1, November, 1919. Mr. Jonck-heere (*The Observatory* for August, 1919, Vol. XLI., p. 216) suggested that refractions may be caused by "a hypothetical condensation of ether near the sun." This hypothesis is treated by L. Silberstein in connection with the theory of Stokes-Planck's ether in the *Phil. Mag.*, Vol. 39, pp. 161–170, February, 1920.

refraction of light depends upon the atmospheric conditions (temperature, pressure, humidity) and decreases with altitude of the celestial body above the horizon. Adequate correction of the observed deflections because of this known source of bending in the earth's atmosphere had to be made.]

(*d*) *Terrestrial Refraction Effects*.—Disturbance refraction effects as rays of light from the distant stars passed through the region of the earth's atmosphere affected by the solar eclipse, especially during totality. This cause would give a deflection in the right direction but apparently not of sufficient magnitude to account for the observed effects.[14]

15. The law of decrease in the amount of deflection of light for causes (*a*) and (*b*) is a very simple one, namely, inversely as the distance of the ray from the sun's center when it passes through the solar gravitational field. For cause (*c*) the law may or may not be as simple as that just stated, depending among other things on the variation of the density and distribution of the solar atmosphere with distance from the sun.[15] For our own atmosphere the law of atmospheric refraction is a somewhat complicated one. Sufficient has been said to show how intensely interesting a full discussion of the observed deflections of light will prove to be. Even had no deflections been observed a valuable contribution to science would have resulted.

16. Table I. contains the deflections of light rays observed by the British Astronomical Expedition, equipped and sent to Sobral, Brazil, under the direction of the Astronomer Royal of England, Sir Frank W. Dyson. Let α be the total deflection of a light ray coming from a star, *S*, and passing through the sun's gravitational field and finally reaching the observer on the earth. Suppose α_0 be the value of α if the ray grazed the sun's limb, and ρ, the radius vector or distance from the sun's center to the ray of light passing the sun. (The values of ρ for the various stars are given in units of the sun's radius in the third column of the table.) Then

$$\alpha = \alpha_0/\rho. \qquad (1)$$

As already stated, according to the Newton-Maxwell law, $\alpha_0 = 0''.87$, and according to the Einstein law, $\alpha_0 = 1''.74$. As the observed effects appear to agree better with the Einstein law, the comparison is made in the table with those computed from that law. The main tabular quantities have already been given in various publications. Detailed data were also courteously furnished by the Astronomer Royal for my lectures; these data gave the results separately for each of the seven stars and for each of the seven plates obtained by the observer, Dr. A. C. D. Crommelin, using a 4-inch lens of 19-foot focus and an 8-inch cœlostat. From the detailed data members of my staff computed the probable errors found in the last three columns of the table. From the coordinates furnished we also were able to compute the angle *A*, which the radius vector, ρ, to any star made with the declination axis, counting it from the north end in the direction east or west; these values are contained in the fifth column. The computed effects in right ascension and declination were obtained by multiplying the value of α from (1) by $\sin A$ and $\cos A$, respectively. From the fourth column it will be seen that the photographic magnitudes of the stars ranged from 4.5 to 6.0. The British astronomers were thus exceedingly fortunate in being able to make their observations during a solar eclipse when there was an exceptionally rich field of bright stars, the Hyades, close to the sun.

17. It will be observed that from the figures

[14] This hypothesis was suggested by Dr. J. Satterly at the close of the author's lecture at the University of Toronto, December 2, 1919. It had also occurred to Dr. Alexander Anderson, of the University College, Galway, and has been discussed by him and others (Eddington, Cromelin, Cave, Dines and Schuster) in various issues of *Nature*, December 4, 1919–January 29, 1920.

[15] In the discussion of the author's paper before the American Academy of Arts and Sciences, January 14, 1920, Dr. E. B. Wilson, of the Massachusetts Institute of Technology, suggested that if the density of the solar atmosphere varied inversely as the square of the distance from the sun's center, a refraction law would result similar to the one for causes (*a*) and (*b*).

in the three columns headed O–E (Observed-Einstein value that), relatively, the observed right-ascension deflections depart more markedly from the computed ones than do the observed declinations-deflections. The observed total deflections in every case, except for star 11, exceed the Einstein values.

TABLE I

Comparison of Deflections of Light Rays Observed by the British Astronomical Expedition at Sobral, Brazil, May 29, 1919, with Values Computed according to the Einstein Theory

(*Instruments:* 4-inch lens of 19-foot focus and 8-inch coelost at. *Observer:* A. C. D. Crommelin)

No.	Star	Dist. in Sun's Radii	Phot. Mag.	Angle A	Right Ascension Obs'd	Right Ascension Einstein	Right Ascension $O-E$	Declination Obs'd	Declination Einstein	Declination $O-E$	Total Obs'd	Total Einstein	Total $O-E$	Probable Error R. A.	Probable Error Dec.	Probable Error Tot.
				°	″	″	″	″	″	″	″	″	″	″	″	″
3	κ_2 Tauri	1.99	5.5	8.2W	−0.20	−0.12	−0.08	+1.00	+0.87	+0.13	1.02	0.88	+0.14	.02	.02	.02
2	Pi. IV. 82	2.04	5.8	96.2E	+0.95	+0.85	+0.10	−0.27	−0.09	−0.18	0.99	0.86	+0.13	.04	.05	.04
4	κ_1 Tauri	2.35	4.5	8.6W	−0.11	−0.10	−0.01	+0.83	+0.74	+0.09	0.84	0.75	+0.09	.03	.03	.03
5	Pi. IV. 61	3.27	6.0	144.8W	−0.29	−0.31	+0.02	−0.46	−0.43	−0.03	0.54	0.53	+0.01	.04	.05	.05
6	υ Tauri	4.34	4.5	6.3E	−0.10	+0.04	−0.14	+0.57	+0.40	+0.17	0.58	0.40	+0.18	.04	.04	.04
10	72 Tauri	5.19	5.5	14.9E	−0.08	+0.09	−0.17	+0.35	+0.32	+0.03	0.35	0.34	+0.01	.04	.05	.05
11	56 Tauri	5.38	5.5	86.6W	−0.19	−0.32	+0.13	+0.17	+0.02	+0.15	0.25	0.32	−0.07	.06	.02	.05

18. From the observational results in Table I., the resulting value of the deflection, α_0, at the sun's limb, as published by Dr. Crommelin, is 1″.98,[16] thus agreeing with the Einstein predicted value, 1″.74, within 14 per cent. The result from the astrographic plates taken by the other British observer at Sobral, Mr. C. Davidson, using the astrographic object glass of the Greenwich Observatory in conjunction with a 16-inch cœlostat, was not so satisfactory, the star-images being diffuse on account of a probable change in figure of the cœlostat mirror; the discordance between the mean results from the individual plates was said to be rather large, but from the whole series an outward deflection reduced to the limb, of 0″.93, or 0″.99, according to the method of treatment, was found, with a probable error of about 0″.3.[16]

19. The plates taken by Dr. A. S. Eddington and Mr. Cottingham, the second British Astronomical Expedition, at the Ile of Principe, west coast of Africa, where the weather conditions were unfortunately not as favorable as at Sobral, showed only a few stars and the scale could not be directly determined as it was not possible to remain at Principe the required time. Instead, plates of another region of the sky taken at the same altitude were used and compared with plates of the same region and of the eclipse-field obtained previously at Oxford. The determination of scale was therefore somewhat weak, though the uniformity of temperature at Principe was in its favor. The final result of the discussion of the plates gave an outward deflection of 1″.61 with a probable error of 0″.3.[17]

20. *Except then for the unsatisfactory Sobral astrographic plates, the general conclusion to be drawn is that deflections of light were observed by the British astronomers that agree better with the Einstein law of gravitation (Cause b) than with the Newton-Maxwell law (Cause a).* This is well shown by Fig. 2, constructed by the Department of Terrestrial Magnetism, giving a graphical representation of the law of variation with distance followed by the observed deflections for each star, as well as by the computed ones on the basis of causes *a* and *b*. It is seen at once that, excepting the most distant star (56 Tauri), each star shows a deflection agreeing better with the Einstein value than with the Newton-Maxwell

[16] See *Nature*, November 13, 1919, p. 281. The probable error as given by Dr. Crommelin is 0″.12, whereas Dr. H. Spencer Jones, of the Greenwich Observatory, in his summary (*Science Progress*, January, 1920, p. 372) gives 0″.06.

[17] See reference to Dr. Jones's article in previous footnote.

one. Though the result from 56 Tauri is discordant, it still is about midway between the two computed curves (Causes *a* and *b*). It should be noted also that the probable error of observation, as shown by the size of the circle around each star, is largest for 56 Tauri, so

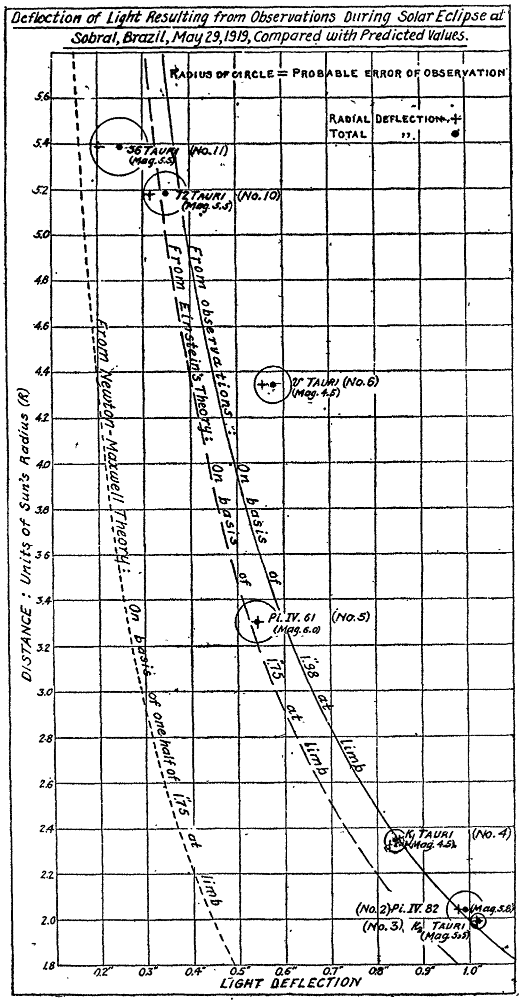


FIG. 2.

that no wholly safe inference as to cause of its departure from the Einstein value may be made.

In view of the recognized difficulties of the observations and the conditions under which they had to be made, and recalling, furthermore, that the preparations and securing of the requisite instrumental equipments were undertaken during the stress of the great war, every one will surely agree that the Astronomer Royal of England and the British observers are heartily to be congratulated upon the splendid results of their labors.

ANALYSIS OF OBSERVED LIGHT DEFLECTIONS

21. In conclusion an analysis was sketched of the observed light deflections and some evidences were pointed out showing that while the simple law (1) was followed to the greater extent, the effects in addition to varying inversely as the distance from the sun's center also apparently depended in some measure upon the heliographic latitude, ϕ, of the star. As a consequence the observed effects are not strictly radial, the departures from radiality occurring in a strikingly systematic manner, and not in the accidental manner that would be the case if the non-radial effects were attributable wholly to errors of observations. When such trigonometric functions are added to law (1) as would arise from forces similar in effect to centrifugal ones, the additional effects are largely accounted for. This possible additional cause, whatever it turns out to be, is designated as *e*. In complete allowance for differential atmospheric refraction effects in the earth's atmosphere may also be the cause of non-radial effects. Resolving the observed actual deflections into two components, radial (along radius vector) and the other non-radial (perpendicular to radius vector), preliminary computations were made with the aid of the expanded law.

$$\alpha = \frac{\alpha_0}{\rho} + f(\rho, \phi). \tag{2}$$

A value resulted for α_0 agreeing better with the Einstein value of $1''.74$, than the value $1''.98$ stated in paragraph 18. A future paper will give further account of this interesting matter.[18] I must not fail to record here

[18] The possibility of non-radial effects arising from cause *e* was announced at the meeting of the American Philosophical Society, Philadelphia, Feb-

the assistance received in the construction of diagrams and in the computational work from members of my staff, viz., W. J. Peters, H. B. Hedrick, C. R. Duwall and C. C. Ennis.

22. It is, of course, impossible without further analysis to state at present just what portion of the observed effects may be accounted for by the various causes described in paragraphs 14 and 21. Dr. Newall, for example, see reference in footnote 13, is ready to accept an effect from cause *a* (the Newton-Maxwell effect), but prefers considering the possibility of accounting for the greater portion of the remaining effect by cause *c* (Refraction in the Solar Atmosphere).

23. If it should prove to be the case that the observed light deflections are the result of a combination of the causes mentioned, the way may be open to explain the *results obtained by Dr. W. W. Campbell's eclipse expedition of June 8, 1918, at Goldendale, Washington.* Using two 4-inch photographic objectives photographs were taken of the sun and its surroundings, the exposures being 110 seconds, 50 stars to the ninth magnitude being recorded. He states his results as follows:[19]

The measurement of photographs, 14 inch × 17 inch in size, is a difficult problem even with suitable apparatus: we found it necessary to construct a special measuring machine, and this was made in our own shops. Duplicate photographs of the eclipse field were secured at Mount Hamilton seven months after the eclipse. As the difference of latitude between Mount Hamilton and the eclipse station is only a few degrees, no errors were introduced by not obtaining the comparison field at the eclipse station. These were taken at the proper altitude to avoid the chief refraction troubles in the comparison with the eclipse plates, so that second differences of differential refraction alone entered into the comparison. The plates were measured right and left. The same scale-divisions were used for corresponding pairs of stars. As far as possible the measures were freed from any known source of error. The corrected differences of position were measured along radii from the sun to each star and were arranged in order of distance from sun to star. Dr. Curtis was not able to say that there was anything systematic about these differences, which showed no change of the order required by Einstein's second hypothesis. The probable error of one star position was the order of 0″.5, regrettably large when we are dealing with the differences of small quantities—the difference between the expected displacements of the nearest and furthest stars only being 0″.26. A telescope of great focal length would have been of great help in this work. For the one we used the stars were too faint and in the long exposure required we suffered from the increased extent of coronal structure. Curtis divided his stars into inner and outer groups. The differential displacement between the two groups should have been 0″.08 or 0″.15, according to which of Einstein's hypotheses was adopted. The mean of the results came out at 0″.05 and of the right sign. After getting this result Curtis looked over the collection of 40-foot coronal plates. In the 1900 eclipse there were six stars fairly bright, but not well distributed. It is useless to take a duplicate photograph now owing to uncertainty in the values of the proper motions. Reference has been made to the Paris plate in the Carte du Ciel, but Curtis was unable to say from the comparison that the innermost star showed a displacement due to the Einstein effect.

"*It is my own opinion,*" concludes Dr. Campbell, "*that Dr. Curtis's results preclude the larger Einstein effect, but not the smaller amount expected according to the original Einstein hypothesis.*"

24. It will be observed that although Dr. Campbell was not so fortunate as the British astronomers in the matter of bright stars close to the sun, he obtained an effect at more than twice the distance from the sun of the farthest star (56 Tauri), shown in Fig. 2, in the right direction and of about the same amount as that given by cause *a* (Newton-Maxwell Effect). It is of interest to note here that the farthest star, 56 Tauri, in Fig. 2, also gave a deflection approaching that given by cause *a*, though since that star gave the largest probable error, not much weight is to be attached

ruary 6, 1920, and slides were shown exhibiting the systematic character of these effects. The matter was gone into more fully at the New York meeting of the American Physical Society, February 28, 1920.

[19] *The Observatory*, London, Vol. XLII., No. 542, August, 1919 (298–300).

to the fact. It would be of great importance to know, of course, whether as the distance of a star from the sun greatly increases, the deflections of light will correspond more and more closely with that given by cause *a*. There is no possibility that the Einstein effect with increased distance will merge into the Newton-Maxwell effect, since theoretically the former should always be twice the latter. However, if the main cause of light deflections should prove to be *a, c* and *e,* or *a* and *e,* or similar ones in effect, it may be possible, as already stated, to harmonize Dr. Campbell's results with those of the British observers. As a caution it may be well to bear in mind that Dr. Campbell unfortunately was obliged to get his results from very distant stars and hence had to look for quantities very much smaller than those concerned in the British observations of the solar eclipse of May 29, 1919.

OUTSTANDING MOTION OF MERCURY'S

25. As a further proof of the Einstein theory of gravitation has been cited the very satisfactory way[20] in which the theory accounts for the outstanding motion of the perihelion of mercury, characterized by the late Professor Simon Newcomb as one of the greatest of astronomical puzzles. Dr. Charles L. Poor, of Columbia University, at the close of my lecture there on January 16 suggested that the outstanding motion of Mercury's perihelion could also be fully accounted for if the equatorial radius of the sun were found to exceed the polar radius by $0''.5$, so that the sun would not be truly spherical. Seeliger advanced the hypothesis[21] "that the scattered zodiacal-light materials, if condensed into one body might have a mass fairly comparable to that of the little planet Mercury, " and he has concluded that the attractions of the zodiacal light materials upon the planet Mercury could explain the deviation of that planet from its computed orbit. This problem can not yet be regarded as definitely settled."

[20] See A. S. Eddington's *Report on The Relativity Theory of Gravitation,* London, 1920, p. 52.

[21] W. W. Campbell, "The Solar System," published in *The Adolfo Stahl Lectures,* p. 10, San Francisco, 1919.

EINSTEIN DISPLACEMENT OF LINES OF SPECTRUM

26. Dr. Einstein appears to regard as essential to this theory the verification of the shifting towards the red of the lines of the spectrum of light from the sun and stars. However, Sir Joseph Larmor, according to a paper presented before the Royal Society on November 20, 1919, does not apparently agree with him. The predicted effect has not yet been successfully observed, or, as Professor Joseph S. Ames in his concluding remarks at the end of my lecture at the Johns Hopkins University put it, "has not yet been disentangled from the various possible other causes for shifts of the spectrum lines."

CONCLUDING REMARKS

27. The endeavor has been to set forth impartially all the facts pro and con with reference to the question of the verification of the Einstein theory of gravitation by the recent astronomical observations, so as to enable the reader to form an independent judgment and reach his own decision. Though we may differ as to whether the Einstein theory has been definitely verified, or not, one result of fundamental importance appears to have been established with fair certainty, upon which perhaps chief emphasis should be laid, viz.: that *light has weight*—just how much depends upon whether the Newtonian or the Einstein principles will ultimately be found correct. Possibly the best attitude to take is that of open-mindedness and to let no opportunity pass by for further experimental tests. The British astronomers are already zealously preparing to make observations during the solar eclipse of September, 1922, which will occur in Australia. Perhaps one of the most satisfactory results of the discussion aroused by the subject has been the stimulus imparted to further research in many fields, which is bound to bear fruit.

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