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Autor: Trumpler, Robert J.

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Observational Results on the Light Deflection and on Red-shift in Star Spectra

by ROBERT J. TRUMPLER
(University of California, Berkeley)

1. Light Deflection

The generalized Theory of Relativity published by EINSTEIN in 1916 predicted that light rays passing close to the sun are slightly curved on account of the sun's gravitational field. A star when seen at a small angular distance from the sun should thus appear to the observer somewhat shifted from its true position. This shift is

a) in the direction away from the sun's center
b) by an angle inversely proportional to the angular distance from the sun's center,
c) the amount at the sun's edge being 1″75.

A similar shift of star positions had been predicted by SOLDNER in 1801 on the basis of NEWTONS corpuscular theory of light; but the amount of deflection by this theory is only half as much as required by EINSTEINS theory. According to the classical wave theory of light, however, no deflection was to be expected.

The observational test concerning the existence and amount of light deflection can be made only during total solar eclipses when the scattered sky light is sufficiently reduced to observe stars near the sun. The usual procedure is to take a photograph of the stars surrounding the eclipsed sun and to compare this photograph with a similar photograph of the same stars taken several months before or after the eclipse when the sun is in a different part of the celestial sphere. The second photograph shows the normal positions of the stars.

When coordinates of stars are measured on a photograph and compared with those measured on another photograph, allowance must be made for a difference in the zero point and orientation of the coordinate systems and for a difference in the scale of the plates due to temperature changes or other causes. In our problem, the first two adjustments are easily made if the eclipsed sun is near the center of the plate, and if the stars are symmetrically distributed around it. A difference in the scale of the plates, however, produces an apparent shift in star positions toward or away from the center, and the shift due to scale becomes mixed up with the relativity shift to be determined.

Absolute measures of the light deflection require a direct determination of the scale change between the eclipse photograph and the comparison photograph taken at night several months earlier or later. Since an accuracy of at least 1 part in 10^5 is required this is a very difficult problem particularly under the conditions of a temporary eclipse station.

If, as usual, the eclipsed sun is situated at the center of the plate, the effect of the scale change is directly proportional to the distance from the center, whereas the relativity shift is inversely proportional to this distance. The measured displacement l of each star thus furnishes an equation of condition

$$\frac{1}{r} E + rS = l,$$

where r is the known angular distance of the star from the sun's center measured in units of the sun's radius. Provided the observed stars cover a sufficient range in r, it is possible to determine both the light deflection constant E as well as the scale constant S from the star measures by a least squares solution. We shall designate light deflections derived by this method as *relative*.

In the relative method, used by most of the earlier investigators, the numerous stars near the edge of the plate contribute mainly to the determination of the scale constant; the light deflection constant is essentially based on the relatively few stars near the eclipsed sun. On account of the brightness of the inner corona it is very rarely possible to photograph stars that are less than one solar radius from the sun's edge with deflections of more than $0''9$. The successful application of the relative method thus requires not only measures of highest accuracy, it requires also that the observations cover a large field and extend to a considerable angular distance from the sun; otherwise the light deflection and the scale change cannot be well separated. Both of these requirements can be met by the use of large plates (16–18 inches or 40–45 cm square) and of specially designed triple or quadruple objectives. By means of such wide angle photographs, the Lick Observatory expedition of 1922 was able to test the law of inverse proportionality over the range from 2 to 40 solar radii.

The first attempt to measure absolute values of light deflections was made in 1929 by an expedition of the Potsdam observatory. A reseau was copied by projection on the eclipse photograph as well as on the later night photographs of the same star field. There is, however, some doubt as to whether the reseau copies can by relied upon for the determination of the scale change. If the scale determination by the reseau is rejected, and if the measures are reduced by the relative method, the results are in good agreement with the theory.

Another method for determining absolute values of the light deflections was successfully used by van Biesbroeck at the eclipse of Febr. 15, 1952 in Khartoum. By means of a half transparent mirror in front of the objective he was able to photograph simultaneously the star field around the eclipsed sun as well as an auxiliary star field 90° from the sun. These two star fields were again photographed six months later. The auxiliary star field which at both times was unaffected by light deflection served to determine the scale change.

Table 1 gives the results for the light deflection at the sun's limb derived by the eclipse expeditions to date. If one considers the various instruments and methods used and the many observers involved, the conclusion seems justified that the observations on the whole confirm the theory.

Table 1. Observations of Light Deflection

Eclipse	Station	Focal lenght	No plates	No stars	Method	Light Deflection at Sun's Limb ″	p. e. ″	Observers
1919 May 29	Sobral	19 feet	7	7	relat.	1·98	±·12	Dyson
	Sobral	11	16	6–12	relat.	(0·86)	±·1	Davidson
	Principe	18	2	5	relat.	1·61	±·3	Eddington
1922 Sept 21	Wallal	15	4	62–85	relat.	1·72	±·11	Campbell
		5	6	134–143	relat.	1·82	±·15	Trumpler
	Wallal	10	2	18	relat.	1·74	±·3	Chant, Young
	Cordillo Downs	5	2	14	relat.	1·77	±·3	Davidson, Dodwell
1929 May 9	Takengon	28	4	17–18	absol.	(2·24)		Freundlich
					relat.	1·75	±·13	v. Klüber, v. Brunn
1947 May 20	Bocaiuva	20	1	51	relat.	2·01	±·18	v. Biesbroek
1952 Febr 25	Khartoum	20	2	9–11	absol.	1·70	±·07	v. Biesbroek

Prediction by Relativity Theory 1·75

2. Red-Shift of Spectral lines

The red-shift of spectral lines due to the gravitational potential at the surface of the sun is small (corresponding to a DOPPLER shift of about 0·6 km/sec). Measures of the solar spectrum at the Mt. Wilson observatory by ST. JOHN did suggest an average red-shift of this order. The discrepancies of various groups of lines and in different parts of the solar surface, however, are considerable, and the confirmation of the theory by the solar observations is not very convincing.

Progress in the study of the constitution of stars, however, has drawn attention to certain cases among the stars where a much larger red-shift may be expected. The gravitational potential at the surface of a star is proportional to M/R, where M is the mass of the star, and R its radius (in units of the sun's mass and radius). There are essentially two classes of stars where M/R becomes large:

a) The so-called white dwarfs, stars of normal mass, but very small radius ($M \sim 1$–2, $R \sim 1/50$).

b) Stars of very large mass and moderate radius. If such stars exists, they must be found among the stars of greatest luminosity and highest temperature.

The main difficulty in determining a gravitational red-shift of spectral lines in stars is to separate the red-shift from the DOPPLER shift due to the motion of the star relative to the solar system.

The companion of Sirius e. g. is a white dwarf which together with Sirius forms a double star system of well determined orbital motion. When the shift of spectral lines is measured both for Sirius and its companion, and when allowance is made for the orbital motion, the white dwarf companion shows a red-shift equivalent to a velocity of 19 km/sec. In this case the mass and radius of the white dwarf are fairly well known, and the red-shift calculated by theory (20 km/sec) is in good agreement with the observed value.

The binary star 40 Eridani also has a companion which is a white dwarf. Its red-shift has recently been measured by D. POPPER at the Mt. Wilson Observatory.

The result $+ 21 \pm 4$ km/sec is very similar to that of the companion of Sirius and is sufficiently close to the theoretical value $+ 17 \pm 3$ km/sec calculated from the mass and radius of the star.

For more than 30 years I have been working on a program of measuring the radial velocities (Doppler shift) of stars in galactic star clusters. The internal motions of stars in such a cluster are usually small, and the physical members of the cluster have nearly the same motion relative to the sun. About 20 years ago I drew attention to the high temperature stars (spectral type 0) of great luminosity contained in many of the clusters. These stars show an appreciable red-shift of spectral lines as compared with the fainter more normal stars of the same cluster, and I suggested that this red-shift is, on the average, probably a relativity red-shift. These stars may have masses of the order of 100 solar masses and radii about 4–5 time that of the sun. The gravitational red-shift would thus be about 20 times greater than on the sun or near 10 km/sec which is about the average value observed.

The results which I have now available for 18 stars in 10 clusters are shown in Table 2. Three stars with emission lines (Wolf-Rayet) have been omitted, and for three stars the results are not yet completed. While many of the individual values are somewhat uncertain, the average should be fairly well established.

Table 2. Red-shift of *O*-type Stars in Star Clusters

Cluster	Star	M	Sp. T.	Red-Shift (km/sec)
J. C. 1805	2	—4·5	07	+ 12·4 ± 2·2 S. B.
	3	—4·2	07	+ 2·8 ± 2·0
J. C. 1848	1	—6·0	07	+ 10·4 ± 4·8 S. B.
	1 a	—4·4	08	+ 4·6 ± 5·4
	2	—4·9	09	+ 6·2 ± 3·5
NGC. 2244	9	—5·0	07	+ 6·8 ± 1·3
	15	—4·6	06	+ 13·6 ± 1·7
	8	—4·3	08	+ 6·4 ± 1·6
NGC. 2264	1	—4·6	07	+ 9·8 ± 1·2
NGC. 2353	1	—4·6	09	+ 16·1 ± 1·6 S. B.
NGC. 6231	50	—4·6	08	+ 16·4 ± 2·6
NGC. 6604	1	—6·0	08	+ 13·6 ± 4·1 Var. Vel.
NGC. 6611	1	—5·2	06	+ 9·0 ± 2·1
	2	—4·8	08	+ 4·1 ± 3·7 Var. Vel.
	3	—4·7	08	+ 9·9 ± 2·4
NGC. 6823	1	—4·3	08	+ 11·6 ± 3·4
	2	—4·0	09	+ 7·7 ± 3·6
NGC. 6871	5	—5·4	B0	+ 15·6 ± 1·6
18 stars in 10 clusters				+ 9·8 km/sec

Diskussion – Discussion

W. Baade: For which of the determinations of the light deflection (1922, 1929, 1952) was the star distribution the most favorable one, considering the differential method?

R. J. Trumpler: In the 1929 eclipse the star distribution was decidedly unsymmetrical. In the 1922 eclipse, the distribution was quite symmetrical, and I think the same is true for the 1952 eclipse.

E. Finlay-Freundlich: I would like to say a few words in order to stress the main points:

1) Dr. Trumpler should have mentioned that with regard to the eclipse 1922, when the observations were discussed according to the original plan the result was not 1″·72 but 2″·05, that means 2″·1 (even the tenth of a second is not yet safely established). Hence the result you would have obtained if you had not known Einstein's prediction would have been 2″·1.

2) As to the eclipse of 1919; the value 1″·98, i.e. 2″·0 was chosen as the most probable result. When, however, Eddington reduced his plates he did not take account of the higher order terms in the correction for refraction. Now any distortion of the field other than the relativistic has a very large influence upon the final result; hence the correction for refraction has to be applied with the utmost accuracy. Hopman, as a matter of fact, reduced the plates once more and obtained instead of 1″·98, 2″·16 – that means practically 2″·2.

3) Now with regard to the observations of the eclipse of 1952, reduced according to a method which Professor Trumpler called the absolute method, I must point out that this method is wrong. By using a plane-parallel plate which is partly used as a refracting component of the optical system partly as a reflecting component, one is using two completely different systems. One cannot consequently derive the scale correction by using the stars reflected from the plate and apply this correction to the stars which have passed through the plate.

This is proved by the very simple fact that when van Biesbroeck tried this method for the first time in 1947, the star images which had passed through the plate were measurably good, those stars which had been reflected were so bad that they could not be measured. Michelson has shown that reflecting optical systems have to be four times more accurately figured than refracting systems. Consequently this method may not be used; it is on principle wrong. The fact that in 1952 the star images in both star fields were good enough to be measured does not prove in any way that the scale correction obtained from the one field is accurate within one 10^{-5} th to 10^{-6} th of the focal length as it should be.

The results from 1952 have only an apparent accuracy; they are really systematically wrong.

Finally, as far as my own expedition of 1929 is concerned, I made a zero experiment parallel to every exposure on the eclipse field. The whole experiment was made double: one with the telescope pointed towards the star field surrounding the sun and one using a star field about 25 degrees away from the sun.

This second field was reduced similarly with exactly the same optics and gave, indeed, a zero distortion of the starfield. The average absolute difference in the positions of stars was $0''{\cdot}13$; that means it was practically zero, because the mean error of one observation is at least of the order of $0''{\cdot}2$.

To summarize: if the observations had been reduced without knowing the predicted theoretical value, astronomers would have obtained values for the light deflection near to $2''{\cdot}1$ and $2''{\cdot}2$. We have to decide what the observations yield and may not be influenced by the fact that the theory may ask for a different value.

The problem reads: what is the value of the *observed* light deflection?

With regard to the red shift of the sun the situation is the following: it is conclusive that the observed value in the centre of the sun is only about one-third of the predicted value. On principle it would be possible to account for the difference by assuming radial currents in the sun's atmosphere. But then when approaching the sun's limb, the value should converge towards the theoretical value of EINSTEIN, because at the limb the Doppler effects drop out and also pressure effects should become insignificant.

Actually the values go up at the limb to about twice the theoretically predicted value. This has been shown by a great amount of very careful observations by EVERSHED. Moreover, M. G. ADAM has also shown that the necessary current velocities required to compensate the difference between theory and observations are apparently not compatible with the model of the sun's atmosphere.

So actually the situation with regard to the experimental test of the general theory of relativity is by no means favourable.

A lot of work will have to be done before the astronomers really can say what is the value of the observed light deflection and whether the red-shift is in existence at all. It looks at present as if the red-shift we observe is something of a different character and not the relativistic shift.

R. J. TRUMPLER: Prof. FINLAY-FREUNDLICH makes the statement that by another reduction plan the 1922 eclipse observations give the result $2''{\cdot}05$. This statement is misleading in so far as the figure quoted is only a partial result based on four of the ten plates. If all observations of both instruments are treated according to this plan, the result is $1''{\cdot}9$ which still agrees with the theory within the permissible limits of observational error.

H. BONDI: I disagree very strongly with Prof. FINLAY-FREUNDLICH'S view on the reduction of the observations. *Either* one wishes to check General Relativity and then one examines the deviation of the observations from the $1''{\cdot}75/r$ law *or* one approaches the observations with an open mind and then one examines *all* likely laws depending on radius, angle, solar cycle, etc.... I regard it however as wholly unjustifiable to take, as FREUNDLICH does, half the answer of Relativity, taking the law to be of the $1/r$ type, but with an arbitrary coefficient. This is incompatible with the theory and is not suggested by any general considerations.

F. HOYLE: Although the values quoted for Sirius *B* are a classical measurement, their validity seems to me somewhat doubtful. The so-called theoretical value of the red-shift actually depends on an observation of the effective surface temperature. And the effective surface temperature obtained in the measurements seems open to objection since it leads to a quite implausible radius for Sirius *B*.

W. H. MCCREA: I am sorry that Dr. ADAM is not here to describe her latest measurements of line-shifts which she has recently presented to the Royal Astronomical Society. She has measured the shifts for lines of various equivalent widths and, in the range concerned, she finds the departure from the EINSTEIN shift, on the whole, to decrease with increasing equivalent width. Now the lines of greatest equivalent width must in general be those formed nearest to the surface of the photosphere. Although I do not know if Dr. ADAM would agree with the interpretation, it seems to me that her work can therefore be taken as an indication that, the less the line-formation is influenced by the complications mentioned by Prof. FREUNDLICH, the more near the measured shift is to the EINSTEIN value.