GRG Vol.5, No.3 (1974), pp. 757 - 764.

REVIEW ARTICLE

ANALYSIS OF THE OPTICAL DATA ON THE DEFLECTION OF LIGHT IN THE VICINITY OF THE SOLAR LIMB

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Received 2 *February* 1973

ABSTRACT

Analysis of most observations of the deflection of light near the solar limb establishes the validity of general relativity's prediction beyond a certain distance of the sun and the existence of a new effect which is significant in the close vicinity of the solar limb.

It has long been suspected [*1,2*] that the deflection of light (DL) in the vicinity of the sun exceeds the general relativistic (GR) predicted value [*3,4*]. That is, at the limb of the sun instead of the Einstein deflection of 1.75", one obtains, from most eclipse observations and the assumption of the inverse distance law, deflections which exceed the (GR) value by more than 10% [*1,2*].

To check the statistical significance of this deviation we have re-analysed, compared and combined most of the available data on the deflection of optical light in the vicinity of the sun [*5*]. The observations considered are listed in Table I. Our re-analysis of the problem was also motivated by the fact that at distances greater than about 4.5 solar radii, $R_\odot$, ($R_\odot$ = 16' 20"), the (DL) appears to be in good agreement with the (GR) prediction. This is corroborated by the radio light deflection measurements of Seielstad, Sramek, and Weiler [*6*] and Muhleman, Ekers and Fomalont [*7*] and their consistency for $r \geqslant 5R_\odot$ with the optical light deflection observations.

Re-analysing each set of (DL) data we have recalculated the scale correction B by least squares solutions of the equation of

TABLE I

List of Analysed Observations of The Deflection of Optical Light

Eclipse		Number of		γ		B		w
Date	Observatory	Plates	Stars	Observer	Mikhailov	Mikhailov arc-seconds	Present Work arc-seconds	Weight
29 May, 1919	Greenwich (9)	7	7	1.13±0.09	1.18±0.08	-0.0158	-0.0160	2
21 Sept., 1922	Victoria (10)	2	18	1.01	—	—	-0.0080	1
21 Sept., 1922	Lick I (11)	4	62-85	0.98±0.09	1.05±0.10	-0.0170	-0.0170	2
21 Sept., 1922	Lick II (12)	6	145	1.04±0.12	—	—	-0.0010	1
9 May, 1929	Potsdam (13)	4	17-18	1.28±0.06	1.12±0.07	+0.0260	+0.0260	2
19 May, 1936	Sternberg (14)	2	16-29	1.54±0.18	1.53±0.32	-0.0970	-0.0970	2
19 May, 1936	Sendai (15)	2	8	0.97±0.86	—	—	-0.0400	1
20 May, 1947	Yerkes I (16)	1	51	1.15±0.16	1.26±0.32	-0.0470	-0.0480	2
25 Feb., 1952	Yerkes II (17)	2	9-11	0.97±0.06	0.82±0.16	-0.0010	-0.0010	1

condition for each star:

$$\Delta r = 1.75'' \gamma r^{-1} + Br, \tag{1}$$

where Δr is the shift of the stars in a radial direction from the center of the sun in seconds of arc, r the distance from this center in units of $R_\odot$ and γ the deviation factor from the (GR) value 1.75". Our recalculated values of B are nearly identical with those determined by Mikhailov [1,8]. Our evaluations of B along with those of Mikhailov [8] and each corresponding γ at $r = R_\odot$ are given in Table I where values of γ calculated on the basis of the original reduction of each observer are also listed.

As seen in the sixth column of Table I the recalculated values of γ in the Mikhailov reduction, well exceed unity. Their simple mean is 1.16 ± 0.08 (standard deviation) and their weighted mean 1.10 ± 0.04. Consequently if we only assume the inverse distance law of deflection, the data on the (DL) near the sun appears to indicate a deflection excess of about 10-15% and one is confronted with the degree of statistical validity of these results. The radio light deflection measurements data [6,7] being confined — because of uncontrolable background noise — to $r \geqslant 4.6\ R_\odot$ they give no observational information for regions nearer to the solar limb.

In order to verify the above discrepancy is statistically significant we have made this attempt to compare and combine most of the available data on the deflection of the optical light. Owing to more or less favorable general physical conditions at the time of the eclipse and also to the differences in techniques and instruments used for the recording and measurement process, results obtained by different observers for the (DL) by the sun are of uneven quality.

In order to allow for this we have used the procedure of attributing weights to each set of observational data. The available factual information on the nature and quality of many sets of deflection observations and the corresponding reductions being rather laconic, we have chosen the most simple double valued weighting system of ratio 2 to 1. The weights attributed to each set of data are given in Table I. Combining these weights with those given within a given set to each star by the observers, we have normalized the weights to a system ranging from 0.10-4.00.

We arranged all the stars of the observations listed in Table I according to their distance from the sun's center and used our normalized weights, to form the group means of Table II around integer distances ranging from 2-12 solar radii. Although the actual number of stars is somewhat inferior, our data comprises a total of 297 star deflections resulting from nine groups of observations during six total solar eclipses. The only cut off introduced concerns the second set of the Lick observations. The cut off is taken at the distance of 13 $R_\odot$ beyond which no deflection data from any other presently considered set of observations exists. This

TABLE II

Mean Deviations from General Relativistic (GR) Light Deflection Prediction (9 *samples)*

$\bar{r}$	w	n	$\bar{\phi}$
Weighted mean distance of each sample in $R_{\odot}$ units	Relative weight of each sample	Number of star deflections in each sample	Mean deviation of each sample from the (GR) prediction (arc-seconds)
2.09	7	15	+0.18 ± 0.11
3.12	10	21	+0.11 ± 0.08
4.02	21	40	+0.14 ± 0.04
5.10	11	31	+0.06 ± 0.07
6.06	25	45	+0.12 ± 0.04
7.11	22	46	+0.06 ± 0.04
7.84	16	33	+0.02 ± 0.04
9.51	15	37	+0.02 ± 0.06
11.60	10	29	+0.01 ± 0.03

cut off is consistent with the conclusions of the present analysis and those of the radio source observations [6,7] inasmuch as for $5\ R_{\odot} \leqslant r < 13\ R_{\odot}$ the observational data is already in close agreement with the (GR) prediction. Our regroupings of the data around $9.5\ R_{\odot}$ and $11.6\ R_{\odot}$ are imposed by the necessity of having a larger sample of star deflections in each group.

The mean of observed minus (GR) predicted deflections with the standard deviations, the number of stars, the relative weights and the weighted mean distances from the center of the sun in $R_{\odot}$ units, for each corresponding sample are given in Table II.

The values of $\bar{\phi}$ with the corresponding standard deviations illustrate the deviation from the (GR) effect which begins to be statistically significant at distances $r < 5\ R_{\odot}$. We can therefore conclude that the values of $\bar{\phi}$ for $r > 5\ R_{\odot}$ are in agreement with the radio deflection (RD) observations $\gamma = 1.01 \pm 0.11$ as determined by Seielstad et al. [6] or $\gamma = 1.04^{+0.15}_{-0.10}$ as measured by Muhlman et al. [7] which – as already stated – are confined to $r \geqslant 4.6\ R_{\odot}$, while for $r < 5R_{\odot}$, deviations from the Einstein prediction begin to become statistically significant.

In figure 1 we compare the $\bar{\phi}$ results given in Table II with two least squares fits:

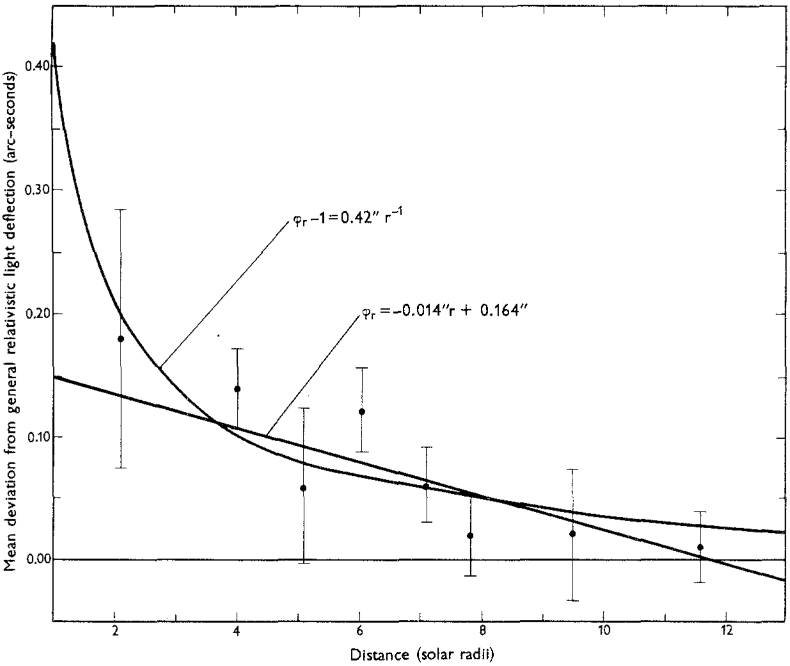

Figure 1 - Mean deviations of observed optical light deflection from the general relativistic prediction. Nine samples grouped near nine integer distances from the center of the sun ranging from 2 to 12 solar radii. The horizontal line represents the Einstein prediction. The slanted line and the curve represent least squares fits corresponding respectively to equations (2,3).

$$\phi_r - 1 = \frac{\delta}{r}, \qquad \delta = 0.42''\ {}^{+\,0.21''}_{-\,0.27''}, \tag{2}$$

$$\phi_r = \alpha r + \beta, \quad \alpha = -\,0.014'' \pm 0.003'', \quad \beta = +\,0.164'' \pm 0.075'', \tag{3}$$

For equation (2) the sum of the weighted squares of the residuals is $\sum p_i v_i v_i = 0.125$ while for the straight line (3) $\sum p_i v_i v_i = 0.098$ This points to the possibility that the deviation from the Einstein prediction may be different from an inverse distance law.

Table III in which the whole star deflection data is assembled into four samples and where calculated deviations of the radio light deflections [7] from the (GR) prediction are also given, is

TABLE III

Mean Deviations from General Relativistic (GR) Light Deflection Prediction (4 samples)

$\bar{r}$	w	n	$\bar{\phi}$	ϕ_r
Weighted mean distance of each sample in $R_\odot$ units	Relative weight of each sample	Number of star deflections in each sample	Mean deviation of each sample from the (GR) prediction (arc-seconds)	Calculated deviations of radio light deflections [7] from the (GR) prediction (arc-sec)
3.43	3.8	76	$+0.139 \pm 0.033$	$+0.020^{+0.078}_{-0.050}$
6.14	6.6	122	$+0.081 \pm 0.024$	$+0.014^{+0.042}_{-0.028}$
8.65	3.1	70	$+0.023 \pm 0.032$	$+0.008^{+0.030}_{-0.020}$
11.60	1.0	29	$+0.013 \pm 0.029$	$+0.006^{+0.022}_{-0.015}$

more illustrative of the concordance of our combined optical deflection reduction with the (RD) measurements [6,7] and the (GR) prediction for $r > 5\ R_\odot$ and its statistically significant deviations from (GR) prediction for $r < 5\ R_\odot$.

The disposition of the three first values of the $(\bar{r},\bar{\phi})$ pair — as listed in Table III — on the straight line:

$$\phi_r = -\ 0.022''\, r\ +\ 0.215'', \qquad (4)$$

is illustrated in figure 2. We notice that the deviation from the (GR) deflection as indicated by equation (4) being opposed to the scale corrections it cannot be accounted for by these and any attempt to eliminate the deviation represented by equation (4) from the (GR) prediction by scale corrections will at greater distances throw the observational data, on light deflection, far below the Einstein prediction.

To conclude, we have analysed most of the available eclipse measurements of the deflection of light to check the statistical significance of the suspected discrepancy between the observed deflection and the Einstein prediction. Our analysis shows the validity of the general relativistic prediction at great distances — which is corroborated by the recent radio lights deflection measurements [6,7] — and the existence from the optical light deflection measurements, of a mean significant deflection excess of $(8 \pm 2)\%$ over the Einstein prediction at a distance of 3.4 solar radii from the center of the sun.

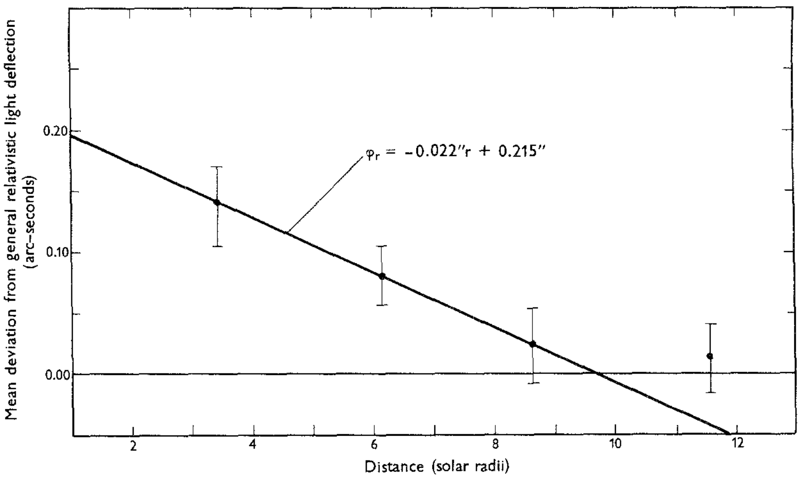

Figure 2 - Mean deviations of observed optical light deflection from the general relativistic prediction. Four samples grouped near four integer distances from the center of the sun ranging from 2 to 12 solar radii. The horizontal line represents the Einstein prediction. The slanted line represents a least squares fit for the three first mean deviations.

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