MEASUREMENT OF THE DEFLECTION OF 9.602-GHz RADIATION FROM 3C279 IN THE SOLAR GRAVITATIONAL FIELD

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During its occultation by the sun in October 1969, the position of the radio source 3C279 was interferometrically monitored to determine the deviation of its 9.602-GHz radiation in the solar gravitational field. Rapid instrumental calibration and negligible coronal diffraction enabled the measurement of a general relativity deflection of $1.77'' \pm 0.20''$ at the limb of the sun. This is in close agreement with Einstein's prediction.

We have used an interferometer at the Owens Valley Radio Observatory consisting of one 27-m antenna and the new 40-m antenna to measure the deflection of electromagnetic radiation in the solar gravitational field predicted by the general theory of relativity.[1] The test was performed by measuring the phase of the interference fringes from 3C279 [assumed $\alpha(1950.0) = 12^{\mathrm{h}}53^{\mathrm{m}}35.92^{\mathrm{s}}$, $\delta(1950.0) = -05°31'08.9''$] relative to that of nearby 3C273 [assumed $\alpha(1950.0) = 12^{\mathrm{h}}26^{\mathrm{m}}33.20^{\mathrm{s}}$, $\delta(1950.0) = +02°19'41.2''$] many times each day from 30 September through 15 October 1969. The daily vector separations between the sun's center and the two sources are presented in Table I for local sidereal times (LST) between 9.0^{h} and 16.5^{h}. The distances ρ are in units of solar radii (using 1 radius $\equiv 16'02.0''$), and the position angles Θ are in degrees measured from north through east to the vector from sun to source.

The interferometer was conventional, differing only slightly from the system described by Read.[2] Both the common local-oscillator signal delivered to the two elements and the returning i.f. signals were carried on buried low-loss coaxial cables. The so-called "high-frequency reference" within the phase-lock system was the highly amplified output of a crystal-controlled frequency synthesizer at 30.188 679 2 MHz. At each antenna, harmonics of this signal were generated, the 159th then beating in the "special mixers" with klystron oscillators operating at 4.801 GHz. The resultant 1-MHz difference signals were then treated as in Ref. 2.

The only other significant change is that the phase-locked 4.801-GHz klystron outputs passed through frequency doublers just before entering

Table I. Sun-3C273 and sun-3C279 separations.

	3C273		3C279	
Date (1969)	Distance, ρ_3 (Solar Radii)	Position Angle, Θ_3 (Degrees E of N)	Distance, ρ_9 (Solar Radii)	Position Angle, Θ_9 (Degrees E of N)
Sept. 30	19.2-19.6	1.8-0.0; 0.0-358.7	27.8-26.6	111.7-111.6
Oct. 1	20.8-21.4	352.4-349.7	24.1-23.0	111.4-111.3
2	22.9-23.7	344.4-342.3	20.4-19.3	111.1-110.9
3	25.4-26.2	337.9-336.1	16.8-15.6	110.5-110.3
4	28.1-29.0	332.6-331.1	13.1-12.0	109.7-109.4
5	31.0-32.0	328.2-327.0	9.4- 8.3	108.4-107.7
6	34.1-35.1	324.6-323.6	5.8- 4.6	105.4-103.5
7	37.3-38.3	321.6-320.7	2.2- 1.2	92.4- 72.2
8	40.6-41.6	319.0-318.3	1.8- 2.9	317.3-307.8
9	43.9-45.0	316.8-316.2	5.4- 6.5	300.7-299.2
10	47.3-48.4	314.9-314.3	9.1-10.2	297.3-296.7
11	50.7-51.8	313.2-312.7	12.7-13.9	295.8-295.5
12	54.2-55.3	311.7-311.3	16.4-17.6	294.9-294.7
13	57.7-58.8	310.4-310.0	20.1-21.3	294.3-294.2
14	61.2-62.3	309.2-308.9	23.8-25.0	293.9-293.7
15	64.8-65.9	308.1-307.8	27.5-28.7	293.5-293.4

the mixers preceding the i.f. preamplifiers. Lobe rotation was thus performed at twice the usual rate. Otherwise, the 3-cm wavelength interferometer functioned as described in other Owens Valley Radio Observatory publications.[3] In particular, both sidebands were accepted, so that the phase was insensitive to slight misadjustments of the delay line or to changes in the amplifiers and transmission lines.[2]

The observing frequency of 9.602 GHz was chosen both to achieve high angular resolution and to lessen refraction effects in the solar corona. Assuming the electron distribution of the Allen-Baumbach model,[4] $N=1.55\times10^{14}\rho^{-6}$ m^{-3}, the angular deviation ω of a ray of frequency 9.6 GHz is given by[5] $\omega=82\rho^{-6}$ sec, where ρ is the distance in solar radii of the ray's point of closest approach to the sun's center. If, instead, we use Erickson's coronal model[6] for $\rho=4\text{-}20$, $N=5\times10^{11}\rho^{-2}$ m^{-3}, the angular deviation is[5] $\omega=0.14\rho^{-2}$ sec. For either model refraction effects are only significant on 7 and 8 October, when $\rho<3$. These days are then useful for studying the corona itself. Two independent analyses of a closely related radar experiment likewise both conclude that the solar corona can be virtually ignored at frequencies of 8-10 GHz.[7]

The baseline of the interferometer[8] was calibrated initially at frequencies of 958.0 and 2881.6 MHz to eliminate any possible lobe ambiguities. Then, the 9.602-GHz baseline was determined repeatedly and in several ways, always during the hours about local midnight to minimize thermal effects. The antenna separation was found to be 3498.0512 ± 0.001 ft (1.066 206 0 km or 34 149.27 wavelengths), and the extended baseline intersected the celestial sphere at hour angle $=06^{\mathrm{h}}01^{\mathrm{m}}38.84^{\mathrm{s}}\pm0.01^{\mathrm{s}}$, declination $=-00^\circ18'20.2''\pm0.1''$. No temporal changes were detected throughout the observing period.

The entire system was tested in several ways. By observing with intentional pointing offsets in October 1968, we demonstrated that the measured phase of small-diameter sources is not noticeably affected by pointing errors. This conclusion is also verified experimentally with the National Radio Astronomy Observatory interferometer.[9] To maintain parallel feeds throughout each day, we rotated both feed and receiver together on the 40-m antenna, which has an altitude-azimuth mounting. Tests in June 1969 demonstrated that the phase was insensitive to this rotation. The phase was likewise insensitive to voltage changes in the phase-lock correction signals. Refocusing either feed, however, produced arbitrarily large phase changes. Therefore, the entire relativity test was peformed with fixed foci. Also in June, we determined the LST dependence of the phase difference between 3C279 and 3C273 at intervals of about 7^{m} when the sun was absent. The standard deviation of a single difference from the curve best fitting all differences was 0.042 lobes. The observed phase scatter could all be attributed to instabilities of the local-oscillator system and fluctuations in the atmospheric water-vapor content, with no attempt made to separate the two. Ionospheric effects at this frequency are negligible.

Most of these tests were repeated in October 1969 with essentially the same results. On 7 October the sun's influence was tested by observing, with nearly identical effective baselines, blank sky at several of the same positions relative to the sun's center as 3C279 had occupied on other days. In no case was a signal significantly exceeding noise detected. At a point less than 3 radii from the center, the measured amplitude was only 0.2% of the flux density of 3C279.

Unpredictable phase changes can arise from instrumental and environmental effects. Examples are differential changes in the structures of the antennas, differential phase shifts in the exposed local oscillator cables to the foci, atmospheric water-vapor fluctuations, instabilities in the local oscillator system, and phase scatter due to receiver noise. By cycling rapidly between 3C273 and 3C279 and considering only phase differences, these and similar effects were minimized. Our actual cycling time was such that over 900 reliable phase differences were obtained in about 100 h of observing.

The phase differences between the two sources did not remain constant throughout the day. Changes having the same LST dependence every day were caused by incorrect source positions, source structure, and incorrect baseline parameters. Dependences which changed daily because of the sun's apparent motion were produced by solar refraction and gravitational deflection. The two dependences were separated by day-to-day comparisons of the data obtained at similar sidereal times.

In determining the phase differences, $\varphi_9-\varphi_3\equiv\Delta$, we linearly interpolated between adjacent measurements of one source to the time of measurement of the other. The subsequent data analysis was performed in three different ways.

All assumed that the gravitational bending was radially directed and varied as $1/\rho$, and all neglected the data from 7 and 8 October.

In two of the methods (carried out independently by G.A.S.), all data from 12-15 October were averaged to obtain an initial calibration curve of phase difference Δ_0 vs LST when both sources were far from the sun. Reasonable agreement with the June results was achieved. This calibration curve was then subtracted from the phase differences for all days. Daily averages of these differences of differences, $\Delta - \Delta_0 \equiv \Box^2$, were formed over four LST intervals.

In one method these means, $\langle\Box^2\rangle$, were compared with values computed for an assumed gravitational deflection of 1.75″ at the solar limb. Differences between the measured and predicted values were used to improve the calibration curve, Δ_0 vs LST. Ratios of the modified measured means to those predicted were then averaged, finally giving measured/predicted $= 1.02 \pm 0.12$, or a deflection at the limb of $1.79'' \pm 0.21''$.

In a second method both the projected baselines (length s in $\sec^{-1}$ and position angle of fringe normal p) and the relative coordinates ρ and Θ at the times appropriate for each mean were calculated for both sources. The quantities $s_9 \cos(p_9 - \Theta_9)/\rho_9 \equiv 1/R_9$ and $s_3 \cos(p_3 - \Theta_3)/\rho_3 \equiv 1/R_3$ represent the inverse angular distances of 3C279 and 3C273, respectively, as measured in the coordinate system of the interferometer. We expect $\langle\Box^2\rangle = K(1/R_9 - 1/R_3)$, where K is the gravitational deflection at the solar limb in seconds of arc.

Separately for each of the four LST intervals, a least-squares straight line was fitted to the data. The values of $\langle\Box^2\rangle$ at $1/R_9 = 1/R_3$ were used to improve the initial calibration curve. The corrected data were then combined and a final least-squares fit, illustrated in Fig. 1, gave $K = 1.77'' \pm 0.19''$.

The third and most general method of data analysis (performed independently by K.W.W. and R.A.S.) fits, by the method of least squares, a curve of the form

$$-\Delta = A + B\sin(\mathrm{LST}) + C\cos(\mathrm{LST}) + K(1/R_3 - 1/R_9)$$
$$-D(1/\rho_3 R_3 - 1/\rho_9 R_9) - E(1/\rho_3{}^5 R_3 - 1/\rho_9{}^5 R_9)$$

to <u>all</u> 914 individual values of the measured phase differences. The first three terms represent empirically those variations with LST which are the same every day. We find $A = -0.030 \pm 0.018$, $B = -0.108 \pm 0.007$, and $C = -0.350 \pm 0.021$ lobes. The fourth term represents the general relativistic effect. We find $K = 1.74'' \pm 0.21''$ for the deflection at the solar limb. The last two terms represent coronal refraction. As asserted previously, this has an insignificant effect in the data considered, for all of which $\rho \gtrsim 5$. For example, holding D fixed at 0.14″ while varying E between 0″ and 100″ changes K by only 0.015″. Likewise, fixing E at 82″ and varying D between 0.0″ and 0.5″ changes K only between 1.72″ and 1.79″. In neither case does A, B, or C change. Figure 2 illustrates the curve fit using $D = 0.14''$ and $E = 82''$ with the A, B, C, and K given above. The general relativity deflection can be clearly seen in the displacement of the curve down for 6 October and up for 9 October as compared with the relatively undisplaced level for the days farther from the sun on 1 October and 14 October.

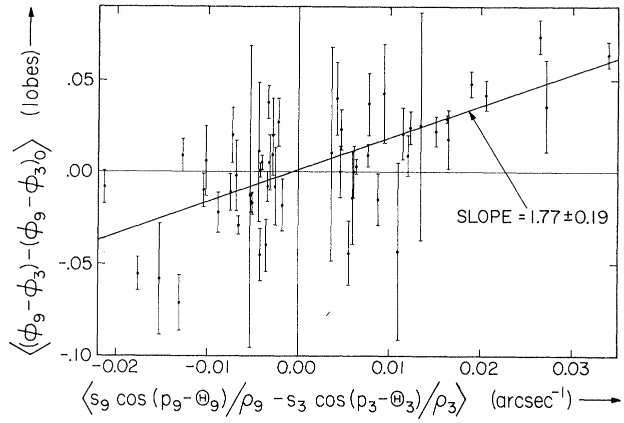

FIG. 1. Mean differences of phase differences, $\langle\Box^2\rangle$, as a function of the difference between inverse angular distances $(1/R_9 - 1/R_3)$ in the interferometer's coordinate system. There are at most four points per day. The line represents a least-squares fit whose slope, $1.77'' \pm 0.19''$, is the gravitational deflection at the solar limb.

The experiment does not yield a good determination of D. However, putting $D = 0.14''$ and including the data from 7 and 8 October, days on which the $1/\rho^6$ term dominates, we find $E = 22''$, corresponding to an electron density of $N = 0.42 \times 10^{14} \rho^{-6}\ \mathrm{m}^{-3}$.

We conclude that the gravitational deflection at the limb of the sun is $1.77'' \pm 0.20''$ (standard deviation) in near exact agreement with Einstein's prediction.[1] This result agrees precisely with that determined in the totally independent experiment at another frequency with a different interferometer by Muhleman, Ekers, and Foma-

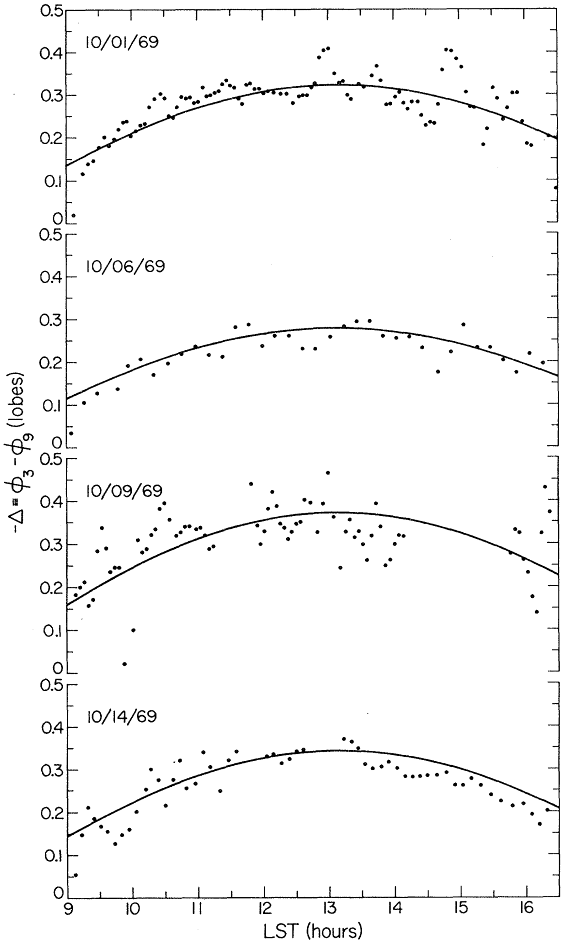

FIG. 2. Examples of four days for the least-squares best-fit curve to the data.

lont, presented in the following Letter.[10]

The scalar-tensor theory of gravitation now predicts a deflection ~0.93 times as large as does Einstein's,[11] and therefore cannot be definitely ruled out by these measurements. However, they seem a significant improvement over most, perhaps all, previous optical determinations (summarized by von Klüber[12]). Not only do these latter have poor internal agreement and even disagreement between different investigators' analyses of the same data, but have indicated that the gravitational deflection appears somewhat larger than the value predicted by the general theory, a result not confirmed by our experiment.

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[8] See Ref. 2 for a definition of the baseline and a fuller explanation of its determination. Note also that the azimuth and elevation axes of the 40-m telescope intersect at a point.

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