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Measurements of the Solar Gravitational Deflection of Radio Waves in Agreement with General Relativity

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In two experiments in 1974 and 1975, utilizing a radio interferometer of 35-km baseline, the relative positions of three radio sources were monitored over a period of a month when the sun was within 10 deg of the sources. The mean gravitational deflection is 1.007 ± 0.009 (standard error) times the value predicted by general relativity. These results exclude the Brans-Dicke theory of gravitation with a scalar coupling constant $\omega < 23$ at the 99% confidence level.

This paper reports on the second measurement of the solar gravitational deflection of radio sources using the 35-km baseline interferometer at the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia. The first experiment[1] (paper I) was performed in 1974 and resulted in a measured deflection of 1.015 ± 0.011 (standard error) times the value predicted by general relativity. The estimated error was based on an analysis of the post-fit residual data and a significant systematic error was unlikely because of the nature of the experimental technique. However, to corroborate the 1974 experiment, a second experiment, similar to the first, was performed between 26 March and 27 April 1975. A summary of this experiment is given here. A more complete description of the observations, the data reduction, and references to previous results are given in paper I.

The NRAO interferometer consists of four parabolic, fully steerable antennas: three 26-m-aperture antennas near Green Bank, West Virginia, separated by 1.8 and 2.7 km and a fourth antenna with a 14-m aperture located about 35 km southwest of Green Bank. The four antennas are connected by cable or radio link and each antenna pair is correlated to form a Michelson-type interferometer. Each antenna can receive simultaneously both right- and left-circularly polarized radiation centered at 2695 and 8085 MHz. The maximum baseline is 950 000 wavelengths at 8085 MHz and corresponds to an interference fringe spacing of 0.22 arc sec.

The fringe phase of three radio sources was monitored on thirteen days between 26 March and 27 April 1975 simultaneously at both frequencies. The sources 0116+08 (which was occulted by the sun on April 11), 0119+11, and 0111+02 are located nearly on a straight line in the sky, within a distance of 10°, are smaller than 0.1 arc sec in angular size, and have a flux density of ~ 1.0 Jy [1 Jy (jansky) $\equiv 10^{-26}$ W m^{-2} Hz^{-1}]. Each day's observations lasted 10 h and consisted of 77 scans, each of length 7 min, in the sequence 0119, 0116, 0111, 0116, 0119, ..., 0116, 0119. For each scan a phase at each frequency, polarization, and baseline was measured. On the first two and last two days of the experiment the sun was sufficiently distant from the radio sources that their relative deflection was negligible. On the other nine days when the sun varied between 1.5 and 6.0 deg from 0116+08 there was a significant amount of differential gravitational bending. Within 1.5 deg of the sun, the signal from 0116+08 became too weak at 2695 MHz because of coronal scintillation.

In the first stage of reduction the phases of each scan at 2695 and 8085 MHz were suitably combined in order to eliminate the frequency-dependent refraction of the thin plasma of the solar corona and of Earth's ionosphere. The resultant phases on three days are shown in Fig. 1. Next, by interpolating between the phases of the two outer reference sources, 0119+11 and 0111+02, a "pseudo-reference" source can be created at a position nearly coincident with the occulted source 0116+08. For this reason the three sources were carefully chosen to be collinear. Finally, the phase difference between the pseudo-reference source and 0116+08 was calculated. All phase variations with time scales longer than 30 min and angular scales greater than about 10 deg are largely suppressed by this differencing technique. In particular, long-term differential changes in phase due to atmospheric-refraction, instrumental, and geodetic effects are eliminated to first order in time and angle.

The phase drift remaining between the pseudo-reference source and 0116+08 has two terms: a secular phase variation caused by the gravitational deflection and a diurnal phase function with a sidereal period. Parameters describing these terms were determined by a least-squares fit. From the 1975 experiment alone we find γ' (the observed deflection divided by that predicted by general relativity) equal to 0.999 ± 0.008 (standard error, internal). In Fig. 2 the differential phase is given for the same three days displayed in Fig. 1.

The post-fit residual data were analyzed in order to determine an estimated error which incorporated the nonrandom characteristics of the data and the coupling between the γ' and the sidereal-period term. The method has been fully described in paper I. The derived error distribution of the 1975 experiment is shown in Fig. 3. The standard deviation is 0.011. The results of the same analysis for the 1974 experiment and the error curve for the two experiments combined are also shown in Fig. 3.

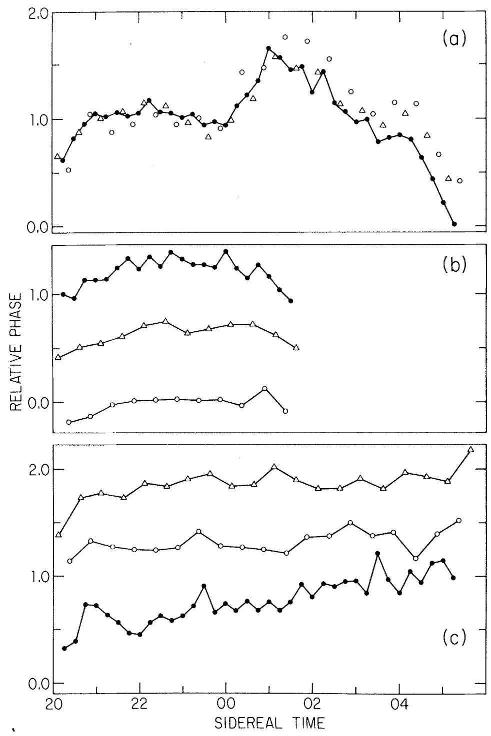

FIG. 1. The measured phase in revolutions for the 35.3-km baseline of the three ratio sources after correction for coronal refraction on (a) 27 March 1975 when the sun was more than 10° away from the sources; (b) 9 April 1975, two days before the occultation of 0116+08; (c) 13 April 1975, two days after the occultation of 0116+08. The phase for each scan is denoted by the symbols ● (0116+08), △ (0119+11), and ○ (0111+02) and the data for each source are connected by straight lines. The fluctuations in the phases over time scales of hours are caused by relatvie changes of the integrated index of refraction along the various ray paths and are well-correlated among the three sources. The displacement of the phase among the sources on April 9 and April 13 are caused by the gravitational deflection.

The gravitational deflection for the separate observation days could be obtained and the result for the 1975 experiment is shown in Table I. A similar table for the 1974 experiment is given in paper I. The best evidence against uncalibrated phase deviations on a time scale of one day to one month is the consistency of the daily solutions given in the table. The scatter about the mean is no larger than that expected from a random distribution of errors and there appears to be no significant trend with time or sun-source separation. The dependence of the gravitational deflection d with the sun-source angular separation r was fitted by a power law using both ex-

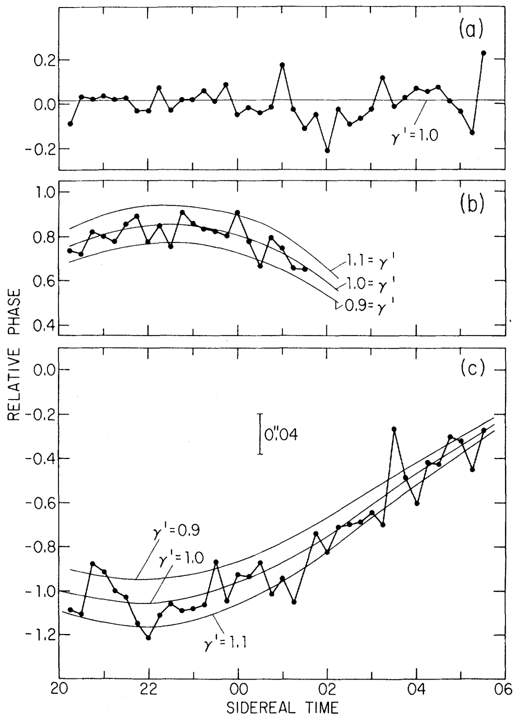

FIG. 2. The differential phase in revolutions for the 35.3-km baseline on (a) March 27, (b) April 9, and (c) April 13. The phase was determined every fifteen minutes by the suitable combination of data from the three sources (see paper I) with the sidereal phase dependence subtracted and the individual points connected by straight lines. These data are compared with the phase corresponding to a relative gravitation deflection among the sources with $\gamma' = 0.9$, 1.0, and 1.1. The long-term fluctuations in the differential phase are smaller than the fluctuations in Fig. 1. The approximate angular resolution of 0.04 arc sec is shown in (c).

periments and we find that $d \propto r^{-1.02+0.03}$. Within 10 deg of the sun, general relativity, the scalar-tensor theory, and most metric theories predict $d \propto r^{-1}$ to sufficient accuracy.

We cannot categorically exclude systematic errors which are significant yet do not manifest themselves in the post-fit residual data. However, the agreement between the 1974 and 1975 experiments is a strong indication of the lack of an undetected systematic error. The removal of the solar-coronal refraction using simultaneous observations at two frequencies is critical. The reduction method assumes (1) that the coronal refraction is caused by a thin plasma (the observed refraction angle was less than 0.1 arc sec) and (2) that the integrated refraction at any moment does not differ among the various rays by more than about 5%. The ray paths, at a distance of 4 solar radii (3×10^6 km), traverse the corona with a maximum separation of 60 km. Furthermore, the dependence of the coronal bending on angular separation r is about $r^{-2.3}$. The measured exponent of 1.02 suggests little or no coronal contamination.

Systematic effects could also arise if the phase distortions in the experiment cannot be described as a smooth function of time or angular coordinate of the incoming radiation. In this case the three-source calibration technique would not be valid. Possible causes of this type of phase variation could be a large proper motion or paral-

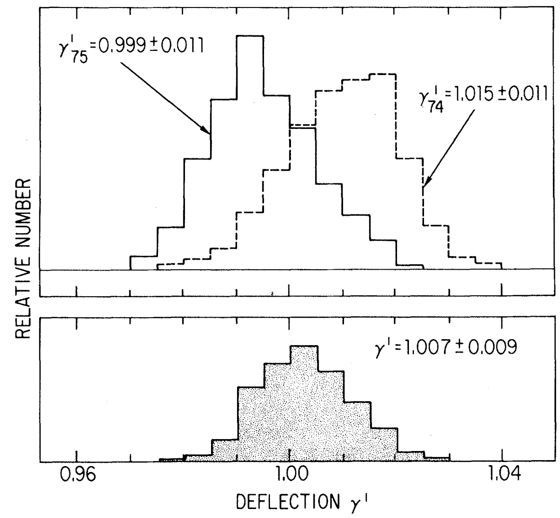

FIG. 3. The error determination of the experiments based on an analysis of the post-fit residual data. Top: the derived distribution of γ' for the 1974 and 1975 experiments. Bottom: the distribution of γ' for both experiments determined by taking the product of the 1974 and 1975 distributions. The mean and standard deviation are given for each distribution.

TABLE I. Daily solutions for gravitational deflection in 1975.

Day	Sep[a]	γ'
April 5	22	1.00 ± 0.08
April 6	18	0.96 ± 0.06
April 7	14	1.02 ± 0.04
April 8	11	1.00 ± 0.03
April 9	7	1.002 ± 0.016
April 13	8	1.022 ± 0.020
April 14	11	0.99 ± 0.04
April 15	15	0.98 ± 0.04
April 16	19	0.93 ± 0.06

[a]Separation of sun and 0116+08 in solar radii.

lax of the sources or phase changes associated with the instrument *selectively* occurring for one source. However, any such variation must also mimic the phase change due to the gravitational deflection which is antisymmetric with respect to the occultation of 0116+08 near the middle of the experiment. Otherwise, these phase distortions would be readily apparent in the post-fit residual data and included in the error estimate anyway.

A systematic effect associated with the orientation in the sky of the three sources is unlikely since the signals from all of the sources were significantly deflected in a variety of directions during the course of the experiment. A significant departure of the gravitational bending from the expected angular dependence would also lead to large, inexplicable post-reduction residuals.

The measured gravitational deflection determined from the 1974 and 1975 NRAO experiments is $\gamma' = 1.007 \pm 0.009$ (standard error). This corresponds to a value of the parametrized post-Newtonian parameter[2] $\gamma = 1.014 \pm 0.018$ and a deflection at the solar limbs of 1.761 ± 0.016 arc sec. The experiment places significant limits on the scalar coupling constant ω of the Brans-Dicke[3] theory as shown in Table II. With these limits the differences between general relativity and the Brans-Dicke theory of gravitation are slight for most astrophysical applications.

TABLE II. Limits to the scalar coupling parameter ω.

Parameter / Probability[a]	γ'	ω
99.9%	>0.97	>15
99 %	>0.98	>23
90 %	>0.99	>35

[a]Based on curves in Fig. 3.

Increased accuracy of the radio deflection experiment can be obtained by using longer baselines. However, even with intercontinental baselines, an improvement by a factor of 5 or 10 may be difficult. Other accurate tests of general relativity, especially those associated with bound orbits, are extremely important since these tests can measure parametrized post-Newtonian parameters other than γ. The deflection experiment can exclude a subset of possible metric gravitational theories.

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Further Data on the High-y Anomaly in Inelastic Antineutrino Scattering*

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The high-y anomaly in inelastic $\bar{\nu}_\mu$-nucleon scattering is shown to exhibit effective violations of scale invariance and charge-symmetry invariance. The anomaly cannot be explained by scattering from antiquarks in the usual three-quark model.

Earlier, we presented data on high-energy inelastic ν_μ- and $\bar{\nu}_\mu$-nucleon collisions leading to a single final-state muon which were not readily understood on the basis of present knowledge of semileptonic weak processes at lower energy.[1,2] The $\bar{\nu}$ data showed a significant departure from the expected inelasticity distribution[1]—since called the high-y anomaly after the Bjorken scaling variable $y = (E_{\bar{\nu}} - E_\mu)/E_{\bar{\nu}}$—and exhibited an energy threshold for this effect. This result strongly suggested new-particle production by $\bar{\nu}$; it provided no evidence for or against new-particle production by ν.

We also reported additional stronger evidence