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to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

on

NASA Grant NSG 7268

GRAVITATIONAL TIME DELAY IN ORTHOGONALLY POLARIZED RADIATION PASSING BY THE SUN

September 1, 1976 through August 31, 1978

Principal Investigator: Martin Harwit

Summary

Prior to the commencement of the work covered by the present contract, our group had conducted two parallel investigations into the degree, if any, to which orthogonally polarized rays are deflected differently on passing through the gravitational field of the sun. The first of these involved very long and intermediate length baseline radio interferometry. The second investigation initially was based on observations made by Stelzried and co-workers at the Jet Propulsion Laboratory, on radiation transmitted by the spacecraft Pioneer 6, on passing behind the sun in 1968. As part of the present study we extended this work using the spacecraft Helios-A and Helios-B. If the deflection of radio waves had been dependent on the state of polarization this would have expressed itself as a time delay during passage of radiation past the sun. Since the radiation transmitted by the spacecraft was plane polarized, any time delay in the radially and tangentially oriented plane polarized components would have appeared as a tendency toward elliptical polarization. The upper limits on this ellipticity obtained by us in the present study amount to a delay less than about one part in 1.5×10^7 of the total delay suffered by the radiation. (See attached reprint.) Expressed in more conventional language this means that the differential deflection between

orthogonally polarized components is less than one part in 10^7 of the total gravitational deflection, or less than about 10^{-7} arc sec, in total.

A continuation of these observations, in collaboration with Dr. Stelzried's group, was also undertaken in the hope that these observations might be increased in accuracy through a variety of improvements. With care, a factor of 3 to 5 improvement on the upper limit on the differential deflection was to be expected. Because the resulting incremental uncertainty is such a small fraction of the total deflection such an upper limit would have been of interest.

These follow-on studies involved data that would be taken by a number of the deep space network (DSN) stations. However, limitations in available funding, as well as complexities arising from the need to recover data from stations across the globe that could not be personally visited by the scientific investigators, made this particular effort less worth while than had been originally anticipated.

The end-product of this investigation, nevertheless, provides the scientific community with a measurement of unprecedented precision of the identity of deflection of orthogonally polarized components of radiation beams passing close to the limb of the sun.

Ph.D. Thesis Work connected with the present contract.

Brian K. Dennison, a graduate student at Cornell University, made use of some of the results of the project in a thesis submitted to the graduate school at Cornell University. Dr. Dennison now is an assistant professor at the Virginia State Polytechnic Institute and State University.

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Status of Funding

At the termination of the contract period $0.00 were left in the grant budget.

Appendix

"Deflection of polarized radiation: relative phase technique." B. Dennison, G. Melnick, M. Harwit, T. Sato, C. Stelzried and D. Jauncey, reprinted from Nature 273 (1978).

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Deflection of polarised radiation: relative phase delay technique

THE weak equivalence principle states that the world line of a freely falling test particle is independent of its structure and composition. Until recently[1,2], experiments designed to detect variations in the geodesic motion of test particles of differing internal properties have been confined to particles of non-zero rest mass[3–5]. The experiment discussed here applies the same question to photons by asking whether oppositely polarised photons fall at the same rate.

It is expected that orthogonally polarised photons would be deflected equally by the gravitational field of a non-rotating mass. When rotation is introduced, the angular momentum of the deflecting source couples to the photon spin through the action of the gravitational field. This results in separate trajectories for orthogonal polarisations. In the low frequency limit, that is $M/\lambda << 1$, the angular splitting between polarisations, δ, is proportional[6] to a/λ where M and a are the mass and angular momentum respectively of the deflecting source and λ is the wavelength of the incident radiation. In the high frequency limit, $M/\lambda >> 1$ and $\delta \propto a\lambda$ (ref. 7). For a solar experiment with, $\lambda = 13$ cm and an impact parameter $= 5.5R_\odot$, $\delta \lesssim 10^{-14}$m arc s, a deflection too small to be detected. In our experiment, however, we can set upper limits to the magnitude of this effect. Any other effects that would produce differential deflection of orthogonally polarised radiation components are subject to similar upper limits.

The most sensitive technique to emerge from earlier studies[1] involves searching for a change in polarisation in a deflected beam. If one polarisation mode is deflected more than its orthogonal state, then it will suffer a greater phase delay than the orthogonal mode. The phase delay is a result of the gravitational bending and is approximately 10^5 wavelengths (for 13-cm microwaves) at the solar limb. If any two orthogonal polarisation states suffer differential bending to within 1 p.p.m. of the total deflection, then significant phase differences between the two will be introduced.

Deflection of orthogonal circular polarisations by differing amounts would manifest itself as a rotation of the plane of polarisation. In a single frequency experiment this effect cannot be separated from Faraday rotation in the solar corona, and upper limits can only be set at those solar elongations at which no Faraday rotation is observed. An upper limit of 2.1×10^{-3} arc s was set[1] using the Pioneer 6 occultation data[8].

If the beam is split into orthogonal linear polarisations, then the final polarisation would, in general, be elliptical. We utilised this technique by searching for a development of ellipticity in the linearly polarised carrier waves from the spacecraft, Helios 1 and Helios 2. The Helios carrier waves are transmitted with the plane of polarisation perpendicular to the ecliptic. Helios 1 was occulted by the Sun in April 1975 and August 1975, and Helios 2 in May 1976. The Helios experiments have the advantages of higher gain in the transmitted signals and lower noise from contamination of the antenna sidelobes due to the Sun (which was near minimum activity in 1975).

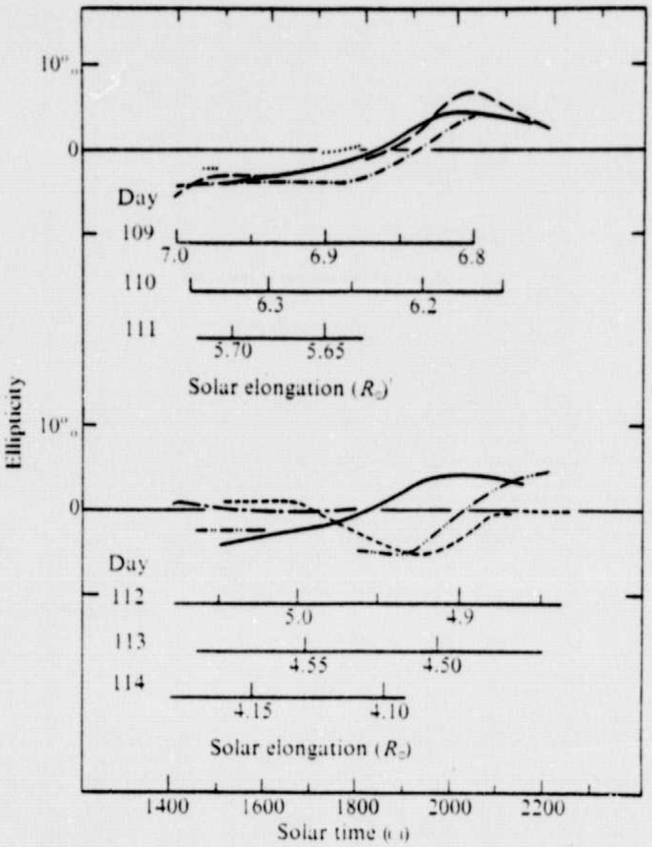

Fig. 1 Ellipticity scans obtained during the April 1975 Helios 1 occultation. The system ellipticity measured on day 96, and reproduced on days 97 and 100 appears as a solid line. The scans for the observing days appear as follows: 109 (—·—·), 110 (— — —), 111 (. . . . .), 112 (- - - -), 113 (-··-··), and 114 (— - — -).

Symmetry considerations indicate that any splitting in which orthogonal linear polarisations are deflected by different amounts must involve modes aligned parallel and perpendicular to the radial direction. (In the field of a rapidly rotating object, however, this symmetry is broken, and various splittings into differing modes, in different directions are calculable.) In searching for this splitting, Faraday rotation plays an important role because the polarisation of the transmitted signal is aligned perpendicular to the radial direction. After ±45° of Faraday rotation the signal becomes an even mixture of these modes at which point the maximum gravitational phase shift could occur. Stelzried, *et al.*[8] have calculated typical values of the Faraday rotation in the corona of the 'quiet' Sun, and from this we can see that the signal should reach ±45° of Faraday rotation at closest approach, within the impact parameter of $4R_\odot$ to $7R_\odot$. The observed Faraday rotation is usually the result of the net accumulation through several partially cancelling sectors in the magnetic field emanating from the Sun. During the April 1975 occultation Volland *et al.*[9] observed that the Faraday rotation varied from about 20° to −45° between $7R_\odot$ and $4R_\odot$. For elongations $\leqslant 4R_\odot$ the magnitude of the Faraday rotation grows rapidly as the elongation decreases.

The Helios 1 carrier wave was monitored for a development of ellipticity on days (of the year) 109–114 inclusive during the April 1975 occultation, and days 244–246 during the August

1975 occultation. The observations were conducted with the NASA/JPL 64-metre antenna of the Deep Space Network at Goldstone, California (DSS-14). A closed loop polarimeter discussed by Stelzried[10] automatically tracked the polarisation of the signal, and monitored the signal for ellipticity. The resulting integrated ellipticity scans are shown in Figs 1 and 2. As the solar elongation decreased the system noise increased due to the interference of the Sun through antenna sidelobes. The ellipticity scans have been averaged with an effective integration constant of about several hundred seconds of observed time and the random errors are comparable to the widths of the curves in the figures. The main limitation seems to be due to the system polarisation which has ellipticity components. Several per cent of systematic ellipticity errors may stem from errors in zeroing of the ellipticity. The system ellipticity was measured by carrying out observations on days 96, 97, 100 and 251 when the angle between Helios 1 and the Sun was large ($\sim 20R_\odot$). The instrumental ellipticity was found to depend on hour angle, and to be reproducible from day to day. The resulting curves are shown in Figs 1 and 2. However, when the main beam is near the Sun the curves vary by up to 8% (maximum), and we attribute this to interference from the Sun through sidelobes having different instrumental ellipticity, and possibly to heating of the various parts of the telescope structure. The instrumental effects seem to be the main limitation of this technique.

The data obtained during the April 1975 occultation cover the elongation range 7–4$R_\odot$. In this range (Fig. 1) Faraday rotation produced optimal conditions for the gravitational phase shift. The observing periods were spaced at frequent intervals with respect to the rate of variation of the observed Faraday rotation, thus any gravitational phase shift should have been detectable during at least one of the periods. The observed ellipticity does not deviate from the system ellipticity by more than 10% (in power), indicating an upper limit to the phase shift between orthogonal components of ~ 0.2 cm. As the time delay for a wave passing within 4–7$R_\odot$ is $\sim 2\times10^6$ cm, then the time delay and therefore the bending should be identical for both linear polarisations to one part in 10^7 of the total bending (at that elongation).

Data taken during the August 1975 occultation extended our results to a smaller elongation than previously studied. Because of the excellent signal-to-noise ratio it was possible to observe Helios 1 to as close as 2$R_\odot$ (ref. 9). The circumstances of our observations permitted us to obtain the scan of day 244 covering the range 3.3–3.95$R_\odot$. During this scan Volland *et al.*[9] recorded a variation in Faraday rotation from about −220° to −40°. At some time during this period optimal conditions for the gravitational phase shift must have occurred, yet no signal ellipticity exceeding 0.1 was observed, indicating a phase shift between orthogonal components < 0.2 cm. At this elongation, the time delay is $\sim 3\times10^6$ cm, and thus the bending of both linear polarisations are identical to a part in 1.5×10^7 of the total bending.

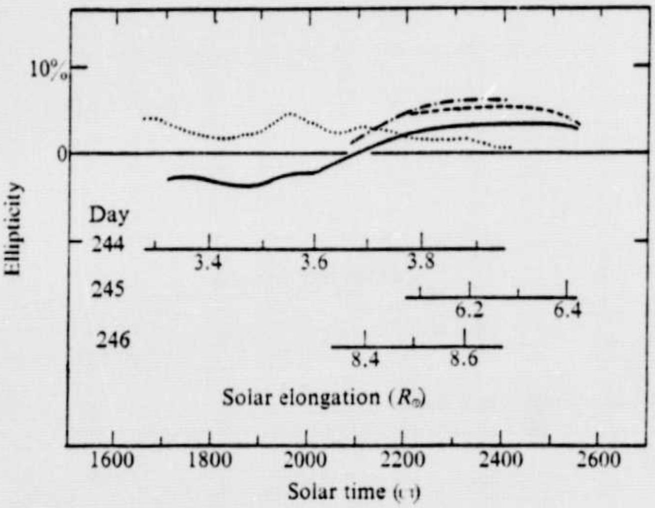

Fig. 2 Ellipticity scans obtained during the August 1975 Helios 1 occultation. The system ellipticity measured on day 251 appears as a solid line. The scans for the observing days appear as follows: 244 (. . . .), 245 (– – – –), and 246 (—·—·).

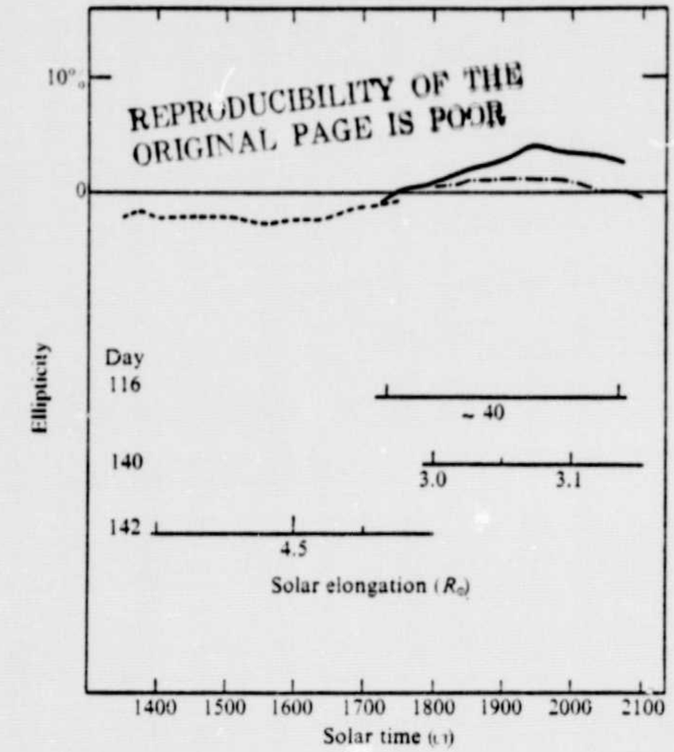

Fig. 3 Ellipticity scans obtained during the May 1976 Helios 2 occultation. The system ellipticity measured on day 116 appears as a solid line. The scans for the observing days appear as follows: 140 (—·—·), 142 (– – – –).

The results from the May 1976 occultation of Helios 2 are shown in Fig. 3. The Faraday rotation on days 140 and 142 was ≃ −40° (M. K. Bird, personal communication) yet ellipticity in excess of instrumental sensitivity was not detected. This agrees with the upper limit set by the Helios 1 data.

Levy[11] carried out a related experiment with the right circularly polarised (RCP) signal of Mariner 4. He looked for a development of left circular polarisation (LCP) when the signal passed within 4.2$R_\odot$ of the sun. LCP was not detected above the 10% level of total signal power. Differential propagation of orthogonal linear polarisations would produce a mixture of LCP and RCP. These results are further confirmation of a lack of radial splitting between linear polarisations at the level of our upper limits. The phenomenon sought by Levy is based upon a postulated relativistic streaming anisotropy in the solar wind[12], and has the same effect as radial splitting between linear polarisations. The Helios 1 data yield no evidence for this streaming effect, and are consistent with the assumption that the electron streaming velocities equal the proton streaming velocities. We know of no other propagation phenomenon which could mimic or obscure the gravitational effect sought. To an excellent approximation the quasi-longitudinal limit is appropriate for the propagation, and the fundamental plasma modes are circular.

The lack of phase shifts implies that the radial difference in bending between orthogonal linear polarisations is less than 5×10^{-5} m arc s in the overall range, 3.3–7$R_\odot$. By careful application of the relative phase shift technique we have reduced the upper limits by nearly an order of magnitude below the previously existing values[1]. We have extended these results to within 3.3$R_\odot$ elongation.

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