# Anomalous gravity data during the 1997 total solar eclipse do not support the hypothesis of gravitational shielding

C. S. Unnikrishnan*
*Gravitation Group, Tata Institute of Fundamental Research, Mumbai 400 005, India and NAPP Group, Indian Institute of Astrophysics, Bangalore 560 034, India*

A. K. Mohapatra†
*Gravitation Group, Tata Institute of Fundamental Research, Mumbai 400 005, India*

G. T. Gillies‡
*School of Engineering and Applied Science, University of Virginia, Charlottesville, Virginia 22904-4746*

(Received 19 September 2000; published 12 February 2001)

We present arguments that rule out the recent suggestion by Wang *et al.* that their observations of anomalous gravity data during the 1997 total solar eclipse in China could be evidence for shielding of gravity of the Sun by the Moon, or could be pointing to some new property of gravitation. In fact, we are able to use their stretch of data obtained before and after the eclipse to constrain the characteristic shielding parameter to the lowest bound ever from a terrestrial experiment.

DOI: 10.1103/PhysRevD.63.062002 PACS number(s): 04.80.Cc, 04.80.Nn

In a recent paper Wang *et al.* have made the suggestion that the anomalous gravity data obtained in their gravimetric experiments during the total solar eclipse of 1997 in China could be evidence for the shielding of the Sun's gravity by the eclipsing Moon [1]. They also suggest that the anomaly might be pointing to some new property of gravitation. The purpose of this brief paper is to point out the several circumstances that rule out, with certainty, these suggestions by Wang *et al.* Strong constraints from previous laboratory experiments as well as from astronomical and planetary observations, including well known gravimetric observations during total solar eclipses, convincingly reject the hypothesis of gravitational shielding as the cause of anomalous gravimetric data in their experiments. Also, the details and structure of the data obtained by Wang *et al.* are not consistent with the hypothesis of gravitational shielding in any reasonable empirical model for gravitational shielding.

Interestingly, and perhaps ironically, we are able to obtain a new lower limit—the lowest ever from a terrestrial experiment—on the Majorana shielding parameter [2] using the data obtained by Wang *et al.* over a week's duration bracketing the solar eclipse. For this we use an argument due to Harrison [3] regarding an additional tidal force on a gravimeter on Earth, with a diurnal period, observable during night if there is gravitational shielding.

The hypothesis of gravitational shielding or absorption of gravity by intervening matter has been of empirical and fundamental interest for over a century [4]. There have been many laboratory experiments to test the hypothesis of gravitational shielding [4,5], inspired by the experiments and positive claims by Majorana in the 1920s [2]. In a weak shielding model, the change in gravity due to shielding by matter can be modeled as

$$\frac{\delta g}{g} = -h\int \rho(r)dr, \tag{1}$$

where $h$ is a phenomenological parameter introduced by Majorana. $\int\rho(r)dr$ is the column density of the intervening matter and $g$ is the gravitational acceleration without shielding. The constraints on parameters of gravitational shielding from the modern experiments are very reliable since the experiments are done in well controlled and repeatable conditions. The best limit from these experiments is the recent one by Unnikrishnan and Gillies [6], obtained from an analysis of the experiment at the Universität Zürich to measure the gravitational constant [7], and it constrains the shielding coefficient to less than about $4\times10^{-14}$ cm$^2$/g. Using this number, we can estimate the upper limit on the signal observable in a gravimetric experiment during a total solar eclipse. As discussed in the later sections, the anomalous data in Wang *et al.*'s experiments imply two orders of magnitude more shielding than allowed by this constraint, clearly ruling out the possibility that their observations could be due to gravitational shielding. There are also constraints on gravitational shielding from previous gravimetric observations during total solar eclipses. These constraints, more stringent than the laboratory limits, are in contradiction with the claim by Wang *et al.*, and were not discussed in their report.

The following table (Table I) lists information on two of the gravimetric observations during solar eclipses in the past that yielded constraints on gravitational shielding. The corresponding limits on the Majorana parameter are in the last column. In the same table we also include a limit obtained by Harrison [3] by considering the shielding of the Sun's field on the gravimeter by the Earth, when the Sun goes below the horizon (see details in the later sections). All three used gravimetric observations with noise level of about 1 $\mu$gal. The numbers listed in the third column are the limits on

*Email address: unni@tifr.res.in
†Email address: ashok@tifr.res.in
‡Email address: gillies@virginia.edu

 

TABLE I. Limits on the Majorana parameter (last column) from gravimetric observations during solar eclipses in the past. The limit obtained by Harrison by considering the shielding of the Sun's field on the gravimeter by the Earth itself is also listed.

| Experiment | Reference | Detection limit | $h$ cm$^2$/g $(2\sigma)$ |
|---|---|---|---|
| Total eclipse 1954 Unst, Shetlands | Tomaschek [8] | 1.4 $\mu$gal | $<10^{-14}$ |
| Total eclipse 1965 Florence, Italy | Slichter [9] | 0.47 $\mu$gal | $<2\times10^{-15}$ |
| Gravimeter at equator Bunia, Congo, 1963 | Harrison [3] | 2 $\mu$gal | $<10^{-15}$ |

detectable signal during the eclipse and not the statistical error on a long stretch of data, which is smaller. The important summary of the table is that the observed residual accelerations during total solar eclipses were smaller than that corresponding to a value of the Majorana parameter of $10^{-14}$–$10^{-15}$ cm$^2$/g at the 95% confidence level.

Since only a small part of the Earth is geometrically shielded from the Sun by the Moon during the eclipse, the effective acceleration of the Earth does not change significantly due to shielding during the eclipse. But the gravimeter is partially or completely shielded from the Sun and this gives rise to the possibility of a differential acceleration that could be measured by the gravimeter.

In the crudest estimate, without considering the variation of density of the Sun and the Moon, the maximum change of gravity of the Sun that can be expected at the location of the gravimeter is given by $\delta g/g_\odot = h\rho_m d_m \cos(\theta)$, where $\rho_m$ is the average density and $d_m$ is the diameter of the Moon. $\theta$ is the (slowly varying) angular position of the Sun and the Moon from the zenith during eclipse. The Sun's gravity at Earth, $g_\odot$, is approximately 0.6 cm/s$^2$. Using $\theta = 69°$ for the 1997 eclipse at the location of the gravimeter, we get

$$\delta g \leqslant h\cdot 0.6 \ \ \mathrm{cm/s^2}\cdot 3.3 \ \ \mathrm{g/cm^3}\cdot 3.5\times10^3 \ \ \mathrm{km}\cdot\cos(69°)$$
$$\simeq h\times 2.5\times10^8 \mathrm{cm/s^2}. \tag{2}$$

Using the limits on $h$ from the past experiments [6] we get the value of the *maximum* allowed differential acceleration due to gravitational shielding as

$$\delta g \ \ 10 \ \ \mu\mathrm{gal\ using} \ \ h\leqslant 4.3\times10^{-14} \ \ \mathrm{cm^2g}$$

from laboratory experiments,

$$\delta g < 0.5 \ \ \mu\mathrm{gal\ using} \ \ h\leqslant 2\times10^{-15}\mathrm{cm^2/g},$$

from earlier gravimetric observations during eclipse.

Clearly, the results from earlier gravimetric observations already rule out with good confidence the hypothesis of gravitational shielding as the cause of anomalous data in the observations by Wang *et al.* Note that the *sign of $\delta g$ is positive*, indicating an apparent increase of local gravity. Since the acceleration (towards the Sun) of the gravimeter mass element (suspended as a nearly free mass from a weak spring) decreases if part of Sun's gravity is shielded, whereas the average acceleration of the Earth towards the Sun is more or less unaffected, one should see a gravimeter signal corresponding to an *increase in the local gravity* towards the Earth (this fact is noted earlier in Ref. [7]). But the anomaly observed by Wang *et al.* has its sign opposite to what is expected from shielding.

The following detailed analysis shows that the magnitude of the anomaly seen by Wang *et al.* is actually two orders larger than what is allowed by the laboratory limits, and more than three orders larger than what is allowed by constraints from past eclipse observations. This leaves no room for the hypothesis of gravitational shielding.

A detailed numerical calculation of the expected signal under the hypothesis of shielding can be done, along the lines of the treatment by Slichter *et al.* [9] (their calculation in 1965 had used overestimated values for the densities of the Sun in the central part, and this needs correction). But in the present case this detail is not required since the observed anomaly is confined to the early and late fractions of the eclipse where simple approximate estimates of the expected signal can be made. (The only detail we want to note here is that the expected shape of the signal in *any reasonable model of shielding* would be a bell shaped curve, with its maximum absolute value close to the totality of eclipse. This expectation is grossly violated in the anomalous signal observed by Wang *et al.* [1].) The density of the Sun varies sharply from center outwards, with its maximum value of about 155 g/cm$^3$ at the center, and dropping to 10% of the maximum for $r/r_\odot$ less than 0.28. For $r/r_\odot \simeq 0.5$, the density has already dropped to 1% of the central density [10]. This means that the eclipsing Moon can have significant effects on shielding only after the eclipse has progressed well. Even at about 25% (in terms of elapsed time) of the total eclipse from first contact, the gravitational mass that is shielded from the gravimeter is less than 1% of the total mass of the Sun. Also the shielding matter of the Moon at that stage is effectively only about 1/3 in length along the line from the gravimeter to the Sun. Using the relatively less constraining, but most reliable laboratory limit of $h\leqslant 4.3\times10^{-14}$ cm$^2$/g the allowed gravimeter signal then is only about $4\times10^{-2}\mu$gal when the eclipse has progressed to 25% of totality. Such a signal is far less than the noise of the best gravimeters.

For the total solar eclipse of 1997, the duration from first contact to total eclipse is about 68 min. Curiously, the anomalous data of the Chinese observations peak almost half an hour before the first contact. The signal drops to zero at about 20 min from the first contact and remains close to zero till about 20 min before the last contact. Then the signal increases, and peaks again at about 30 min after the last contact. This structure in the data is already suggesting that the anomaly cannot be due to gravitational shielding. The constraints we have described do not allow the slightest margin to accommodate even the possibility that a component in the data might be due to shielding. Our constraints limit the observable signal at about 15 min into eclipse to less than

$10^{-2}\,\mu$gal, and the observed anomaly is reported to be about $1\,\mu$gal, with the wrong sign. Thus the observed signal is at least two orders of magnitude too large to be arising from gravitational shielding. The constraints from previous eclipse observations are another 50 times more stringent. This means that the hypothesis of shielding as the cause of the anomaly can be ruled out with certainty. The argument can be inverted, and the fact that Wang *et al.* do not see any anomalous signal during the totality can be used to constrain the shielding parameter to be less than $10^{-15}\text{cm}^2/\text{g}$, similar to the constraints from previous gravimetric observations during eclipses.

We note further that we can do much better than this for obtaining new constraints on the Majorana shielding parameter using the data obtained by Wang *et al.* This is ironical to some extent, but the good quality of the data for a stretch of about one week bracketing the eclipse turns out to be useful in obtaining this new limit. The idea is originally due to Harrison [3] who obtained a constraint on the Majorana parameter by observing that gravitational shielding of the Sun's field at the gravimeter by the Earth itself would give rise to a differential force to which the gravimeter responds (in fact, any hypothetical effect that is attributed to the eclipse of the Sun, and not specific to the properties of the Moon, can be tested by monitoring the effect of this pseudoeclipse by the Earth itself on the detector).

Without shielding, the gravimeter responds to the tidal forces (the difference between the force on the Earth's center of mass and the force on the gravimeter mass element) and this has a magnitude (for the Sun's field) of

$$|a_{2\omega}|=\frac{2GM_\odot}{D_\odot^2}\frac{R_E}{D_\odot}\simeq 50\ \ \mu\text{gal}.$$

$M_\odot$ and $D_\odot$ are the mass of the Sun and the average distance from the Earth to the Sun. $R_E$ is the radius of the Earth. $GM_\odot/D_\odot^2=g_\odot$. At equator the tide is at the second harmonic of the diurnal cycle. Nowadays, this component as well as the diurnal component arising from observations away from equator can be subtracted out accurately to a level of about $1\,\mu$gal. Indeed the long stretch of data from the Chinese observations after subtractions show that these subtractions were effected good to an rms level of about 0.2–0.3 $\mu$gal [1]. If the gravitational field is shielded to first order as

$$g_{eff}=g_\odot\{1-h\rho_E(r)l(\theta_z)\},\tag{3}$$

then the field at the gravimeter mass element changes due to the additional effect of shielding by the Earth, and this should show up as anomalous acceleration in the gravimetric signal. $\rho_E(r)$ is the density of the Earth and $\theta_z$ is the zenith position of the Sun. Clearly, the effect begins when the Sun goes below the horizon, and peaks when the Sun is at the ''midnight'' position, and drops to zero when the Sun comes up at the other horizon. So, this signal is diurnal, but it is a periodic wave that is truncated to zero for about half the period. (Note that the Moon's gravity is insignificant for this calculation since the effect is proportional to the field and not to its gradient.) The length through the Earth on the line connecting the Sun and the gravimeter is $l(\theta)\simeq 2R_E\cos(\theta_z)$. We use the average density for the calculation. The signal along the local vertical from shielding is then

$$a_\omega\simeq 2g_\odot h\rho_E R_E\cos^2(\theta_z)\simeq 2h\times 3\times 10^9\cos^2(\theta_z)\ \ \text{cm/s}^2.\tag{4}$$

For estimates on $h$ we will drop the factor 2 since the signal is active only for half the time during a period. An approximate limit is obtained by noting visually that the amplitude of any periodic signal in the Chinese data is less than about 0.3 $\mu$gal, corresponding to $h\leqslant 10^{-16}\ \text{cm}^2/\text{g}$.

A Fourier analysis (without a phase analysis) of the data for a diurnal signal was done to obtain a more reliable limit. For this, we made enlarged photocopies of the published data (Fig. 2 of Ref. [1]) and digitized it with an accuracy better than 0.05 $\mu$gal, at intervals of approximately 50 min, resulting in about 220 data points. The timing error for each data point is about 10 min, and the accumulated timing error is less than 30 min for the data extending for 11000 min (multiple references for timing is available in the published record). The anomaly near the eclipse, was filtered out and the rest of the data was smoothed with a time constant of approximately 200 min. This low pass filtered data was then subjected to a fast Fourier transform (FFT) analysis. There is no detectable feature above noise near the diurnal period. A diurnal signal of

$$|a_{\omega=24hrs}|\geqslant 0.06\ \ \mu\text{gal}\tag{5}$$

would have been detected at the $2\sigma$ level. This corresponds to a limit on $h$ of

$$h\leqslant 0.06\times 10^{-6}/3\times 10^9\leqslant 2\times 10^{-17}\ \ \text{cm}^2/\text{g}.\tag{6}$$

*This represents the best limit on the Majorana parameter from any terrestrial experiment*. (We note that Eckhardt [11] has set a still more stringent limit on the effect, based on a possible violation of the equivalence principle, by analysis of the lunar laser ranging data, as have Crowley *et al.* who assessed the internal heating of the planetary bodies [12]. A direct analysis of the lunar laser ranging data during lunar eclipses also leads to a new limit comparable to the geophysical limits [13].)

Before we end, it may be useful to speculate on what the observed gravity anomaly might be due to. It could easily be a secondary signal generated from unaccounted environmental changes. The Chinese data can be reproduced directly if we model the gravimeter base as being subjected to a large number of small impulses, possibly seismic disturbance due to human activity, during the first and last phase of the eclipse (this need not be very close to the gravimeter). These unidirectional impulses, possibly arising from large number of people and vehicles moving into the eclipse zone just before the start of the eclipse would shift the mean equilibrium separation between the mass element and the reference point on the base of the gravimeter. During the eclipse, there will be comparatively less activity, especially close to the totality, and then after the eclipse again there will be large number of impulses to the ground while people are dispersing. Of course, it is impossible to model this quantitatively without knowing in detail the properties of the ground and the magnitude of the human activity during the eclipse. But such effects are important and easy to miss while analyzing the data. Though Wang *et al.* state that care was taken to avoid man-made *gravitational* disturbances near the gravimeter (within 200 m), this need not ensure that the cumulative effect of small impulses generated farther is small enough to be neglected.

We can also model the Chinese data remarkably well by conjecturing that the observed signal is proportional to the magnitude or to the square of the temporal gradient of some physical quantity that started changing before the eclipse started, then saturated to a nearly constant value during most of the eclipse, and then changed slowly back to the original values towards the end of the eclipse. When the parameters of such a model is chosen to reproduce the two unequal anomalies in the gravity data, the model *predicts* that the gravity values during most of the eclipse should be slightly smaller than the long term average. This is indeed what is observed. Though such a model is not suggested strongly by the known circumstances of the experiment, it has empirical importance in the absence of any definitely identified cause for the observed anomaly.

It is difficult to pinpoint the exact cause of the observed anomaly without knowing many more details of the experiment and the environment during the eclipse. But our speculations will help in taking precautions during future experiments.

In summary we have shown that gravity anomaly observed by Wang *et al.* during the total solar eclipse is not gravitational shielding. It does not point to any new property of gravitation. We have suggested two models that can reproduce the main features in their data. We have analyzed their data collected for about a week and obtained a significant new lower bound of $h<2\times10^{-17}$ cm$^2$/g, two orders better than the existing limits from any terrestrial experiment, on the Majorana shielding parameter.

C.S.U. thanks D. Suresh for useful discussions on possible environmental effects in the Chinese eclipse data. The non-accelerator particle physics activity at the Indian Institute of Astrophysics is supported by the Department of Science and Technology, Government of India.

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