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Abstract: During the solar eclipse of 9 March 1997 a Chinese group carried out an experiment specifically designed to detect possible gravity variations. They identified two significant anomalous lateral valleys, interpreted by them as a possible shielding effect of the Moon on the gravitational force of the Sun. This interpretation was criticized because only one central valley centered at maximum eclipse is conventionally expected. In April of 1918 Quirino Majorana started his work on gravity absorption at the Polytechnic Institute of Turin (Italy); experimentally he found that the value of his universal gravity quenching coefficient was $h \approx 10^{-12}$ cm^2/g. In 1922 Majorana moved to the University of Bologna where he repeated the experiments obtaining h-values of the same order of magnitude. Estimates for h from the shielding of solar gravity by the Moon during solar eclipses typically are 2 to 3 orders of magnitude smaller, down to $h \approx 10^{-21}$ cm^2/g from fluctuations of Moon’s orbit. Then, some theoreticians discount the higher empirical laboratory values as being wrong. By analogy with photon attenuation in matter, an extension of Majorana’s hypothesis is proposed here, where h represents both absorption and scattering, and becomes a variable parameter, dependent on the baryonic mix (Z, N) of the substance interacting with gravity. When attenuation is dominated by scattering, the residual gravity curve may exhibit two lateral valleys, as effectively observed in at least six solar eclipses from 1954 to 1999, described in the text. Therefore, gravity attenuation during solar eclipses is dominated by scattering, instead of absorption as conventionally believed.

Résumé: Au cours de l'éclipse solaire du 9 mars, 1997, un groupe chinois a réalisé une expérience spécifiquement conçu pour détecter de possibles variations de la gravité. Ils ont identifié deux importantes anomalies en forme de vallées latérales, interprétées par eux comme possiblement reliées à un effet d’écran de la Lune sur la force gravitationnelle du Soleil. Cette interprétation a été critiquée car une seule vallée centrée au maximum de l'éclipse est normalement prévue. La possibilité d'une absorption de la gravité, suggérée en 1920 par Quirino Majorana en Italie, est définie par le coefficient universel $h \approx 10^{-12}$ cm^2/g qu’il a déterminé à partir de mesures en laboratoire. Les évaluations de h pour l’effet d’écran de la Lune sur l’attraction solaire pendant les éclipses solaires sont généralement inférieures de 2 à 3 ordres de grandeur, et même jusqu'à $h \approx 10^{-21}$ cm^2/g en se basant sur les fluctuations de l'orbite de la Lune. Certains théoriciens considèrent alors que ces valeurs empiriques élevées sont fausses. Par analogie avec l’atténuation des photons par la matière, une extension de l'hypothèse de Majorana est proposé ici, où h représente à la fois l'absorption et la dispersion, et devient un paramètre variable qui dépend du mélange baryonique (Z, N) de la substance interagissant avec gravité. Lorsque l'atténuation est dominée par la dispersion et la réflexion, la courbe de gravité résiduelle peut présenter deux vallées latérales, ce qui a été effectivement observées dans au moins six éclipses de Soleil, de 1954 à 1999, tel que décrit dans le texte. Par conséquent, l'atténuation de la gravité pendant les éclipses solaires est dominée par la dispersion au lieu de l’absorption comme on le croit conventionnellement.

Keywords: Gravity anomalies, gravity shielding, gravity attenuation, Majorana shielding, solar eclipse anomalies, Majorana constant, gravity scattering, gravity absorption, gravity reflection, gamma ray analogy for gravity.

I. INTRODUCTION

At an isolated geophysical station in northern China, during the solar eclipse of 9 March 1997 a group led by Wang and Yang[1] carried out an experiment specifically designed to detect possible gravity variations, and identified in the recordings the presence of two significant anomalous valleys (about 6 and 7 μGal[a] deep), thirty minutes before first contact C1, and just after last contact C4. Wang *et al*. suggested a “*possible shielding effect of the Moon on the gravitational force of the Sun*” (Ref. 1, page 041101-3), interpretation criticized in the same journal[2] on the grounds “*that the expected shape of the signal in any reasonable model of shielding would be a bell shaped curve*” (emphasis in the original, Ref. 2, page 062002-2). The Chinese group reconsidered their initial interpretation[3], and later[4] invoked a “*rapid air mass movement for the bulk of the atmosphere ... as a sufficient explanation ... of the anomaly*” (Ref. 4, page 022002-1). However, the validity of the latter explanation is also controversial,[5,6] because it “*presumes that air streams from the surrounding with speeds of the order of several 100 m/s*”,[b] leading Duif to suggest that “*balloon measurements of pressure and temperature during solar eclipses at altitudes of the order of 10 km would therefore be very useful*” (Ref. 5, page 5, and Ref. 6, page 276).

Duif also reviewed several possible explanations of gravity anomalies based on conventional changes during an eclipse: geomagnetism, seismicity, surface tilting, and atmospheric parameters (pressure, temperature and humidity).[5,6] He found that they do not suffice. Duif also discussed periodic gravity anomalies under non-eclipse conditions, and found that conventional explanations are not sufficient, with the possible exception of a differential heating of the laboratory roof due to asymmetric cloud cover.[6] Other possible explanations of the observed anomalies during eclipses are based on thermo-elastic deformations of earth’s surface,[7] and in the scattering of solar wind or some other particles coming from the sun.[8] Such explanations, however, are not applicable to Majorana’s laboratory experiments, to which we turn our attention now.

In April of 1918 Quirino Majorana started his work on gravity absorption at the Polytechnic Institute of Turin (Italy), which is described in detail in a series of nine notes written in Italian during 1919 and 1920, a summary translated into English appeared in 1920.[9]

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[a] The usual unit in geophysics is the microGal: 1 μGal = 10^{-8} m/s^2.
[b] Such high speeds would be noticeable by commercial aircraft in flight during solar eclipses.

Majorana hypothesized that the intensity of the Newtonian gravitational force decreases after traversing a substance of density ρ and thickness r, according to

$$\mathbf{F}_{Majorana} = \mathbf{F}_{Newton} \exp\left(-h\int \rho(r)dr\right) \qquad (1)$$

where h is a "*quenching factor*" with dimensions of (length)^2/mass that "*represents a* <u>*universal constant*</u>" (emphasis in the English paper, Ref. 9, page 495). Preliminary experiments started in October 1918; Majorana took advantage of the general strike of July 20-21, 1919 – when the city of Turin was very quiet – and used a cylinder filled with 104 kg of mercury to screen gravity. It was found that the weight of a lead ball decreased when terrestrial gravity was screened by the mercury leading to $h = 6.7\times10^{-12}$ cm^2/g (Ref. 9, p. 504). The experiment was repeated in Turin using a sphere of 9,603 kg of lead to screen gravity, leading to $h = 2.5\times10^{-12}$ cm^2/g; Majorana also mentions other measurements with the lead sphere in various geometries, whose results cast some doubts on the rigorous validity of Newton's gravity law.[10] Majorana also says that his results exclude Le Sage's hypothesis (Ref. 10, page 479). In 1922 Majorana was appointed Physics Professor at the University of Bologna; repetition of the experiments yielded *h*-values of the same order of magnitude.[11] Majorana noted that if his experiments were correct, the active gravitational mass would not be the same as the inertial mass, and pleaded for a repetition by third parties of his experiments. However, Majorana's experiment has never been repeated.[12]

Instead, Majorana's model was attacked on theoretical grounds by Russell[13] because Majorana's high value of h would imply a solar mass inconsistent with planetary stability. Another criticism by Crowley, Woodward, and Yourgrau[14] noted that the energy associated with the absorption of gravity would heat the interacting bodies; the geothermal evidence leads to $h = 1.9\times10^{-30}$ cm^2/g. Thermal data for Jupiter and Saturn produce values of h about ten times larger, while data for the Moon leads to $h = 2.4\times10^{-28}$ cm^2/g, which still is 16 orders of magnitude lower than Majorana's laboratory value. Caputo recently reviewed[15] the values of h obtained by three different methods: (i) Screening by the Moon during solar eclipses, as in Caputo's analysis of the 15 February 1961 eclipse leading to $h < 6\times10^{-16}$ cm^2/g.[16,17] (ii) Screening by the Earth, as in Harrison's analysis of the data gathered with gravimeters during the International Geophysical Year[18] leading to $h < 1\times10^{-15}$ cm^2/g.[19] (iii) Fluctuations of the orbit of the Moon, as done by Eckhard[20] using data from the lunar laser ranging experiment to obtain $h < 1\times10^{-21}$ cm^2/g, which is 6 orders of magnitude smaller than the geophysical constraints. Then, it is obvious that the value of h depends on the method used for its evaluation.

In a recent historical survey of non-Newtonian gravity models[21] the high values for h obtained by Majorana in his laboratory are discounted as being wrong. Since Majorana was a careful experimenter, in the present paper we take the opposite view, and accept that the high values obtained by Majorana are not experimental artefacts. Rather, we note that the equivalence between gravitational and inertial mass does not hold in Majorana's model, which implies that h need not be a universal constant. In this spirit, it is assumed here that h depends upon the chemical and nuclear composition of matter represented by atomic and neutron number (*Z*, *N*). In such context, the low values of h arising from self-shielding in the Sun,[13] or from gravity screening by the Moon,[15,16,17] or by the Earth[19] may not be used to disprove Majorana's empirical values for h obtained with lead and mercury, materials that are not significantly present in our Sun, Moon, and even in the terrestrial crust. Regarding the heating problem in Le Sagian-type models,[14] if gravity screening is dominated by elastic scattering processes, the problem disappears as discussed in some detail by the present author elsewhere.[22]

The similarity of Majorana's hypothesis with optical models, and the similitude between Newton's and Coulomb's force laws are well-known. The formal analogy between electromagnetism (EM) and the gravitational equations for weak-field and slow moving sources has been known for at least fifty years;[23-26] there is current revival of interest in those representations.[27,28] According to Weber[23] "*the general theory of relativity enables us to calculate gravitational shielding and absorption. These effects are analogous to the shielding of electromagnetic fields with the exception that in the lowest order quadrupoles rather than dipoles are involved*." In this context, by analogy with gamma-ray attenuation,[29,30] it is proposed here, that gravitational attenuation is formed by three mechanisms: absorption h_A, (elastic and inelastic) scattering h_S, and, possibly, deflection h_D. Then, Majorana's h becomes a gravitational mass attenuation coefficient $h = h_A + h_S + h_D$ dependent upon (*Z*, *N*) of the interacting matter.[c] When absorption is dominant $(h_A >> h_S)$ the expected shape of gravity attenuation is a "bell shaped curve",[2] as explicitly or implicitly assumed in the (negative) interpretation of solar eclipse gravity anomalies up to the present date.[2,15,16,17,31,32] But when scattering is dominant $(h_A << h_S)$, then the shape of the gravity curve is quite different, and exhibits two lateral valleys. Attention is restricted here to data gathered by mechanical gravimeters − which only react to the local vertical component of gravity; a qualitative discussion of the difficult task of extracting quantitative information from the data obtained with extended pending devices appears elsewhere.[33] It is argued that the novel scattering-dominated two-valley curve has been already observed during at least six solar eclipses in the period 1954-1999.[1,16, 31,32,34,35] The data reduction process to extract a positive signal from the observations is a non-trivial task because the size of the eclipse anomaly may be at the level of instrumental resolution, so that it is quite possible that positive signals may be present in other data sets.[d]

II. GRAVITY ATTENUATION BY THE MOON

A detailed calculation of gravity scattering requires a full-blown three-dimensional model for the gravitational interaction with matter. For the purposes of the present note, let us consider a simple two-dimensional phenomenological model similar to the shielding of gamma radiation.[29,30] Consider a flux I_0 of gravitons per unit area and unit time, parallel to the x-axis, impinging upon the Moon, represented by a homogeneous disk of radius R, unit

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[c] The deflection term will be ignored in the remainder of this paper.

[d] For instance, one of the anonymous referees that reviewed this paper mentions the recent gravimetric observations at Prague during the latest solar eclipse of 04 January 2011, where there appeared two shallow valleys at the beginning and end of the eclipse, but just at the level of instrumental resolution.

thickness, and density ρ, located at the origin of coordinates. The unperturbed flux $I_U(y)$ of gravitons exiting the Moon at position y is (see Fig. 1)

$$I_U(y) = I_0 \exp\left(-\int (h_A + h_S)\rho dr\right) \cong I_0\left(1 - \rho(h_A + h_S)\int xdx\right)$$

$$I_U(y) \cong I_0\left(1 - \rho(h_A + h_S)w(y)\right) \qquad (2)$$

where $w(y) = 2R\sqrt{1-(y/R)^2}$

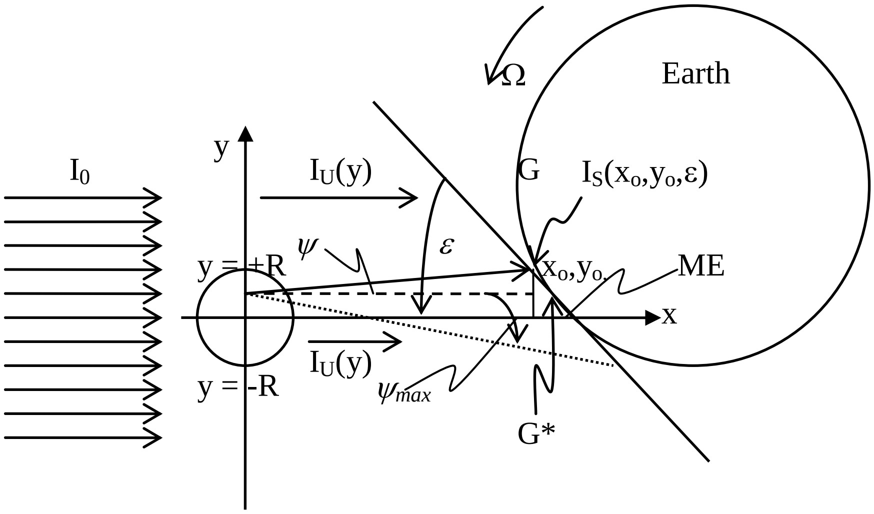


FIG. 1. Gravity absorption and scattering by the Moon at the instant of maximum eclipse (ME); instruments G and G* receive different position-dependent signals $I_T = I_U + I_S$. In a first approximation, the figure may also represent the time-dependent signal received by an apparatus G on the surface of the Earth, rotating with angular speed Ω.

Attention is focussed in Eq. (2) upon absorption and scattering only, and the approximation is valid for the expected small values of $\rho Rh << 1$. The right-most term in Eq. (2) means that the Moon may be considered as a thin slab of variable thickness $w(y)$ as shown in Fig. 2; a similar approximation was used long ago[17] to estimate a limit for Majorana's h .*N*ote that absorbed gravity may produce heating of matter,[14] but elastically scattered radiation does not. The scattered flux $S(y)$ at position y on the surface of the Moon is

$$S(y) = I_0 - I_U(y) = I_0(1 - \exp\left(-\int h_S \rho dr\right)) \cong I_0 \rho h_S w(y) \qquad (3)$$

An alternative reading of Eq. (3) is that the Moon is a line source emitting scattered gravitons with variable intensity $S(y)$. The average intensity of the source (over Moon's diameter) is $S_{av} = \pi I_0 \rho h_S R/2$. Another important physical parameter is the direction of emission of the scattered radiation, described by $f(\psi)$ the probability density function (pdf) for emission of rays from position y along angle ψ. The scattered gravity flux I_S

reaching a small detector parallel to the surface of the Earth and located at coordinates (x_0, y_0) is

$$I_S(x_0, y_0, \varepsilon) = (y_0 \cos\varepsilon + x_0 \sin\varepsilon)\int_{-R}^{+R} \frac{S(y)\, f(\psi)dy}{x_0^2 + (y_0 - y)^2} - (\cos\varepsilon)\int_{-R}^{+R} \frac{yS(y)\, f(\psi)dy}{x_0^2 + (y_0 - y)^2} \qquad (4)$$

where the local elevation (or altitude) of the Moon is ε (see Fig. 1). The auxiliary variables $z = y_0 - y$ and $\psi = z/x_0$ represent the linear and angular positions of the observer relative to the point of emission. Let all lengths be reduced variables in terms of Moon's radius R represented by capital letters, $Z = z/R$, $X_0 = x_0/R$, $Y_0 = y_0/R$, and substitute in Eq. (4) to get

$$I_S(X_0, Y_0, \varepsilon) = (\sin\varepsilon)\int_{\psi-}^{\psi+} \frac{S(\psi)\, f(\psi)d\psi}{1+\psi^2} + (\cos\varepsilon)\int_{\psi-}^{\psi+} \frac{\psi S(\psi)\, f(\psi)d\psi}{1+\psi^2}, \qquad (5)$$

$$\psi^- = (Y_0 - 1)/X_0, \psi^+ = (Y_0 + 1)/X_0$$

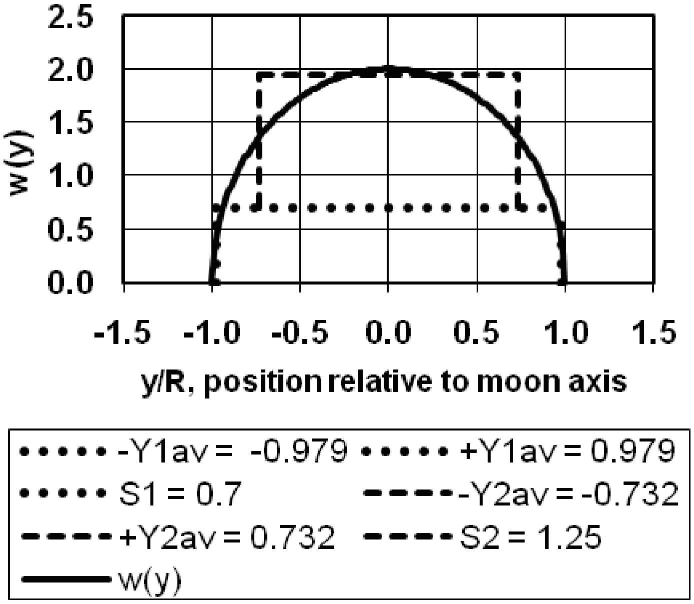


FIG. 2. The Moon acts as a slab of variable thickness $w(y)$ for attenuation of gravity. The scattered component appears as a source $S(y)$ of variable intensity. The sum of the two rectangular areas equals the total area under $w(y)$.

The total flux of gravitons I_T transmitted through the Moon is then

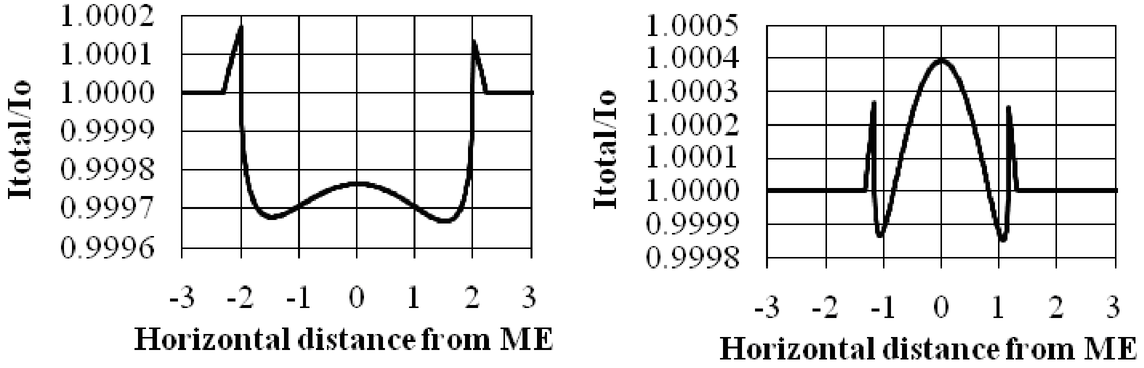
$$I_T = I_U + I_S \qquad (6)$$

To simplify the evaluation of the integrals in Eqs. (5), the variable scattering source $S(y)$ of Fig. 2 was substituted by two superimposed uniform sources of intensities S_1 and S_2 and equivalent lengths $2Y_{1,av}$ and $2Y_{2,av}$ respectively, as represented by the dashed rectangles in Fig. 2. For the low intensity gravitational field in our planetary system, it is assumed that elastic gravity scattering − similar to reflection and refraction of light − is the dominant mechanism, so that $f(\psi)$ is strongly peaked forward, as described by a parabolic pdf:

$$\begin{aligned}
&f(\psi) = f_0\left(1 - f_1\psi^2/(1+\psi^2)\right) \text{for} -\psi_{\max} \le \psi \le \psi_{\max} \\
&f(\psi) = 0 \text{ elsewhere, where} \qquad\qquad (7) \\
&f_1 = (1+\psi_{\max}^2)/\psi_{\max}^2,\ f_0 = 0.5\left((1-f_1)\psi_{\max} + f_1 \tan^{-1}\psi_{\max}\right)^{-1}
\end{aligned}$$

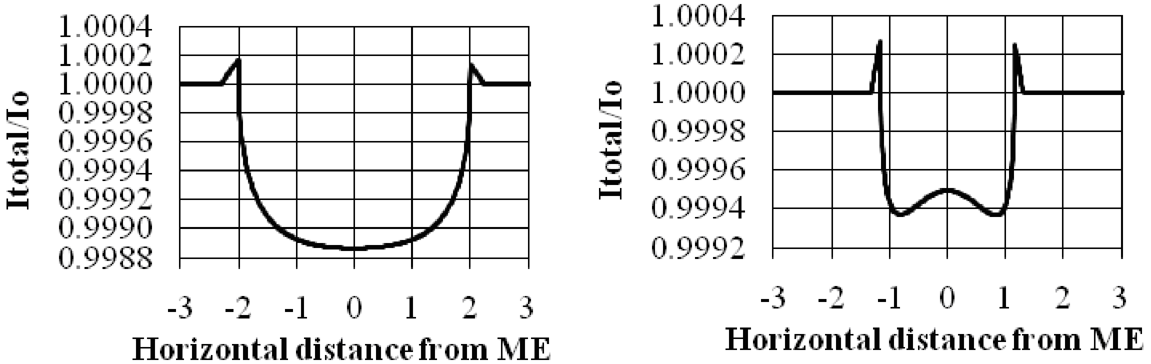
The amount of scattered radiation reaching an observer depends on the relative geometry radiation-scattering body-observer, on the fraction of the incoming radiation that is scattered, and on the size of the scattering body. In particular, the two-valley signal is a result of the finite size of the scattering body, leading to an edge-effect. Such phenomena are familiar to the radiation protection community; for instance, in the case of gamma radiation interacting with a lead screen used to protect human beings, less radiation is scattered in the outside air than in the lead shield.[30] Two effects result: (i) A decrease of scattered radiation near the border of the lead material – the gravity valleys in our case. And, (ii) An increase in the amount of scattered radiation (coming from the lead) near the border of the air region – these are the humps appearing in Figs. 3a to 3c. In a solar eclipse, the relative geometry of the centres of mass of the Sun, Moon and Earth is given by the Saros cycle, but for this paper the relative position of the observing apparatus with respect of the line of totality is more important; this is captured by the azimuth and elevation of the Sun during the optical eclipse. The orientation of the apparatus itself relative to the plane containing the solar azimuth is also relevant. This implies that the question of repeatability of eclipse observations is non-trivial. For a given apparatus-eclipse azimuthal orientation, the sun may be low at the horizon when elevation is near 0º, or it may be high near the zenith when elevation is 90º. Figure 3 shows the total signal I_T given by Eq. (6) in units of I_0 for two representative moon elevations $\varepsilon = 30°, 60°$ – which approximately are equal to solar elevation during a solar eclipse. The third parameter of importance in radiation transmission through an attenuating material is the ratio between the scattering and absorption probabilities, given here by $h_S / h_A = 10, 1, 0.1$. Up to now, in the discussion of Majorana's model it has been implicitly assumed that $h_S / h_A = 0$, so that the fact that some experiments report that Majorana's effect was not observed at the centre of the eclipse cannot be exhibited as evidence against the far more comprehensive model propounded here. During the solar eclipse of 19 August 1999, superconducting gravimeters were used at some stations with negative results, for instance Ref. 32; however, these devices measure gravitational acceleration indirectly, and require an auxiliary calibration, so that the so far unknown detailed understanding of the interaction between super-conductivity and scattered gravity is a pre-requisite. For such reason, we only mention here data obtained with mechanical devices.

Cases (a) and (b) in the upper row of Fig. 3 show the curves for scattered-dominated attenuation $h_S / h_A > 1$, while cases (e) and (f) in the lower row depict absorption-dominated attenuation $h_S / h_A < 1$, exhibiting the conventionally expected inverted bell-curve. The value $\rho Rh = 10^{-3}$ was used in the first two rows, while $\rho Rh = 10^{-4}$ was used in the third row. The two uniform scattering sources are modeled with the values shown in Fig. 2, and the strong forward scattering is captured by $\psi_{\max} = 0.3°$. The horizontal axis is a line on the osculating plane at ME (see Fig. 1) in the direction of the local Moon's azimuth, which is given by the intersection of the osculating plane with the plane defined by three points: the observation site at ME, and the centers of mass of earth (E) and Moon (M).



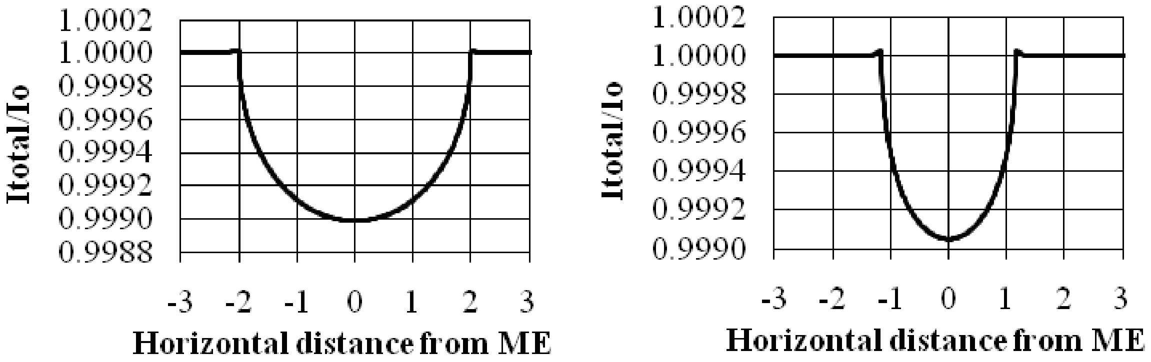
(a) Elevation = 30 °, hs/ha = 10.0

(b) Elevation = 60 °, hs/ha = 10.0



(c) Elevation = 30 °, hs/ha = 1.0

(d) Elevation = 60 °, hs/ha = 1.0



(e) Elevation = 30 °, hs/ha = 0.1

(f) Elevation = 60 °, hs/ha = 0.1

FIG. 3. Total gravity flux I_T due to the Sun after attenuation by Moon, for two moon elevations $\varepsilon = 30°, 60°$, and three ratios $h_S / h_A = 10, 1, 0.1$. One-valley curves appear for absorption-dominated attenuation, cases (e) and (f). Two-valley curves, flanked by edge-scattering peaks, appear in scattered-dominated conditions, cases (a), and (b), and are more marked at high solar positions, cases (b) and (d).

Since the earth rotates with angular speed Ω, an observer at G* at the time of ME actually was at G several hours before ME (see Fig. 1). Taking into account the projection from the osculating plane onto Earth's surface and the value of Ω, the curves in Fig. 3 *approximately* depict the time-varying field observed by a stationary observer on the surface of Earth. The real curves are more complex because the Moon also moves at almost 0.1Ω angular speed towards her position at ME, and due to asymmetries arising from the projection from the tangent plane onto Earth's surface. For instance, for the geometry shown in Fig. 1, the curve is not symmetrical after ME, simply because the gravity rays do not intercept Earth's surface. Despite the simplified character, the present model exhibits the main features detected by mechanical gravimeters during solar eclipses, namely two lateral valleys flanked by positive peaks of edge scattering, as described next. It is also remarkable that the valleys recorded at a low elevation ε station, as in Fig. 3(a), are more separated − and, in some cases, even outside the shadow of the visual eclipse − than the valleys obtained at a high elevation ε station, as in Fig. 3(b).

III. SOLAR ECLIPSES AND TWO-VALLEY CURVES

According to the simple model of section II, the most relevant parameter to describe gravity attenuation at any observation station during a solar eclipse is the local moon elevation ε. Five gravimeter experiments measuring the vertical component of tidal field during solar eclipses are listed; in all those eclipses the empirical data exhibited two-valley curves as in scattering-dominated gravity attenuation, see Figs. 3(a) and 3(b). In several cases the original experimenters[16,31,32] concluded that gravity attenuation was not present, because the expected bell-curves, as Figs. 3(e) and 3(f), were not found.

A. Solar eclipse of 9 March 1997

The values of solar ε at first contact C1, maximum eclipse ME, and fourth contact C4 respectively were $\varepsilon = 13.8°$ at 08:03 local time, $\varepsilon = 21.9°$ at 09:09, and $\varepsilon = 28.3°$ at 10:20.[e] The Chinese team[1] used a high-accuracy LaCoste-Romberg gravimeter, with overall precision of 2-3 μGal. Observations were automatically recorded every minute during seven days (5 to 12 March) thus providing a reliable background for the identification of perturbations of local gravity.

After applying the standard corrections for Earth's rotation and for the tidal effects of Sun and Moon, gravimeter data becomes a vertical gravity residual, which was plotted against time in minutes measured from the beginning of the experiment (see Fig. 2 in Ref. 1): there is a clear anomaly, well beyond the sensitivity of the apparatus, exhibiting edge-scattering

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[e] All solar elevations in this section were read from the Google maps at the NASA eclipse page maintained by Fred Espenak at http://eclipse.gsfc.nasa.gov.

peaks flanking the two lateral valleys, as in our Fig. 3(a). A close-up of the anomaly (see Fig. 1 in Ref. 1) shows two valleys outside the visual eclipse, similar to those in Fig. 3(a) above, corresponding to scattered-dominated gravity attenuation. Our finding is opposite to the conventional view 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 the eclipse. This expectation is grossly violated in the anomalous signal observed by Wang et al.*" (emphasis in the original, Ref. 2, page 062002-2).

B. Solar eclipse of 24 October 1995

Using a LaCoste-Romberg gravimeter of 0.01 μGal accuracy, Mishra and Rao[34] observed in India one deep valley before C1 (9.2 μGal, 40 min wide). However, in Fig. 2 of Ref. 34 there is also a shallow valley close to C4 (2.7 μGal deep, 100 min wide) that was missed by the authors. Solar elevations were $\varepsilon = 7.2°$ at C1 and $\varepsilon = 36.2°$ at C4. Once again, the two observed valleys are qualitatively similar to our Fig. 3(b). It may be noted that the vertical component of the solar tidal field vanishes for $\varepsilon = 35.2644°$, possibly explaining the shallowness of the second valley.

C. Solar eclipse of 19 August 1999

A Belgian team headed by Ruymbeke[32] used mechanical gravimeters at four stations: Annelles in France under the ME line (solar elevations $\varepsilon = 42.9°$ at C1, and $\varepsilon = 55.9°$ at C4), and Uccles, Walferdange and Bondy in Belgium. At the beginning of section 2 in their paper, the mentioned authors state that "*spring gravimeters can resolve significant changes in g of 1 μGal*".[32] And at the beginning of section 6 they conclude "*that there is no perceptible change in g, above the ambient noise level during totality, as recorded by spring gravimeters*" (emphasis added).[32] However, they did observe at the Bondy station "*a gravity change about 2 μGal which is beyond the noise level*". For the present paper a more relevant fact is that the two mechanical gravimeters (Geodynamics G-765 and G-084) at the Annelles station exhibit highly correlated patterns, showing a shallow valley after C1, and a deep valley between ME and C4 (see Fig. 3 in Ref. 32), which are qualitatively similar to our Fig. 3(b). The Annelles curves show less short-term variability than the curves from the three Belgian stations; a possible explanation may be the filter applied to the data: a 10 min filter for Annelles versus a 2 min filter for the Belgian stations. It is significant that a 10 min filter was also used for the Chinese data.[1]

D. Solar eclipse of 10 May 1994

Duval[35] reports observations with a LaCoste-Romberg D gravimeter ("*accuracy as low as ±0.5 μGal*") at Boucherville, near Montreal, Canada, where solar elevations were $\varepsilon = 59.9°$ at C1, and $\varepsilon = 48.8°$ at C4. The residual curve is plotted as Fig. 4 in Ref. 35, page 59, and exhibits the shape of our Fig. 3(b), with two almost symmetrical valleys (1 hr wide and 2.5 μGal deep). Duval (page 60 in Ref. 35) noted the intriguing fact that gravity deviations during the visual eclipse were positive, while the Chinese[1] and Indian[34] deviations were negative. This puzzling fact appears here as a natural consequence of the high solar elevation at the observation station in Canada, versus the low elevations at the Chinese and Indian stations (compare our Figs. 3(a) and 3(b) above).

E. Solar eclipse of 30 June 1954

Tomaschek[31] explicitly tested for Majorana's gravitational shielding using 3 gravimeters at two stations in the Shetland Islands, 60 km from ME line; solar elevations at Unst were $\varepsilon = 51.4°$ at C1, and $\varepsilon = 49.2°$ at C4. Since the mythical bell-curve was not found, Tomaschek used the residual gravity variations to estimate an upper limit for Majorana's h. The residuals curve for the Frost 54 gravimeter is shown here as Fig. 4 (adapted from Fig. 1 in Ref. 31). There is a 3.5 μGal valley between C1 and ME, and a 10 μGal valley before C4, the depth of the latter is more than 3 times the statistical standard deviation, which Tomascheck reports to be between 2.7 and 3.7 μGal (Ref. 31, page 939). This curve is similar to our Fig. 3(b), depicting the two lateral valleys flanked by positive edge-scattering.

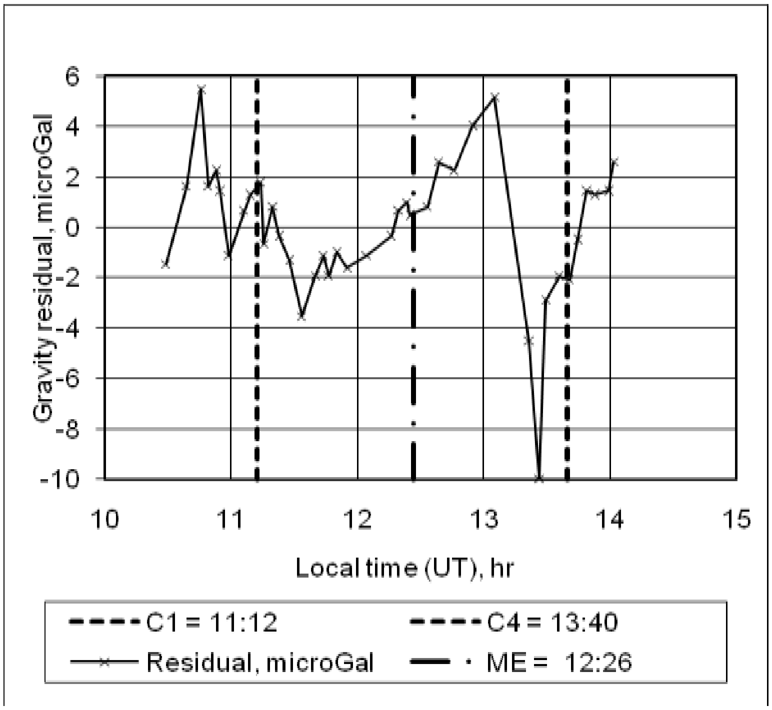

FIG. 4. Gravity anomaly observed during the 30 June 1954 eclipse at Baltasound, near Unst, Shetland Islands, UK by Tomaschek[31] with a Frost 54 gravimeter. Note the two-lateral valleys flanked by positive edge-scattering residuals, as predicted here.

F. Solar eclipse of 15 February 1961 and other anomalies

Two huge horizontal pendulums oriented WE (west-east) and SN (south-north) at a geophysical station inside the Grotta Gigante, near Trieste (Italy) are in use to study tides in the earth crust since 1958. Caputo[16] carefully analyzed data captured during the 15 February 1961 solar eclipse with pendulum period adjusted such that the WE sensitivity was 657 sec and the SN sensitivity 580 sec; the solar elevation at ME was $\varepsilon = 13.5°$. Horizontal pendulums, in contrast to gravimeters, are sensitive to the horizontal component of tidal force. Of course, Caputo did not find the bell-curve, but a close inspection of the residuals in the upper panel of his figure for the WE-pendulum[16] allows identification of edge-scattering plus two valleys coinciding with C1 and C4, as in our Fig. 3(a). The same features are present, although less markedly, in the lower panel of the same figure for the SN-pendulum.[16]

Foucault pendulums and ball-borne pendulums[36] have more degrees of freedom than the horizontal pendulum, thus significantly increasing the difficulty for a quantitative analysis of possible gravity anomalies.[33] Several reports of putative gravity anomalies during solar eclipses observed with tilt-meters and similar devices are listed by Duif.[5,6] For instance, Kuusela[37] mentions a possible eclipse related variation of the vertical during the 11 July 1191 eclipse in Mexico City. To confirm the latter observation Kuusela designed magnetic double pendulums to measure variations in the horizontal component of tidal force. Three instruments were deployed during the solar eclipse of 29 March 2006 at three locations in Turkey: Antalya, 60 km away from the ME line, and Manavgat and in Akseki, both under the ME line. It was found that there were no observable "*eclipse related changes*" at Antalya, but in Manavgat "*there is some oscillation especially in the y-direction during the eclipse*", while in Akseki "*there are aperiodic oscillations during and nearby the eclipse but curiously also approximately 24 before and 24 hours after the eclipse*" (p. 122004-6 in Ref. 37). It is submitted here that all those oscillations during and near the eclipse, and in the days before and after eclipse, are manifestations of gravity scattering, when the Sun and Moon are at a close angular distance.

IV. CONCLUDING REMARKS

Ninety years ago, Majorana suggested the existence of gravitational absorption, described by his universal coefficient h, but Majorana's hypothesis leads to a wide range of values for h,[15] from $h \approx 10^{-12}$ cm^2/g for laboratory measurements, down to $h \approx 10^{-21}$ cm^2/g from fluctuations of the Moon orbit as measured with laser ranging.[20] By analogy to electromagnetic theory (in particular, gamma ray interaction with matter), it was suggested here that h is not a constant but an empirical parameter $h(Z,N)$ dependent upon the baryonic numbers Z and N for the matter interacting with gravity. According to De Rújula[38] the standard model only allows new forces within a restricted domain: "*the most general 'unused' anomaly-free diagonal charge of ordinary stable matter is a linear combination,* $N\cos\theta + Z\sin\theta$*, of neutron number and atomic charge*". The present extension of Majorana's hypothesis is thus in the right track towards unification of gravity with the other forces of nature.

The new parameter $h(Z,N)$ represents both absorption and scattering, and possibly deflection, of gravity. A simple phenomenological model similar to gamma-ray attenuation was used to predict solar gravity at the surface of the earth, when attenuated by the Moon during a solar eclipse. For scattering-dominated gravity interaction in the Moon, the residual gravity curve exhibits two lateral valleys flanked by positive edge-scattering peaks. It was submitted that the novel attenuation has been already observed at least during six eclipses that occurred within the second half of the 20th century. Depending upon the elevation of Sun and Moon at the moment of the eclipse, the central part of the residual curve may be positive or negative, prediction also observed for high solar elevations at the observation station. On the contrary, when the gravitational interaction is dominated by absorption, the shape of the residual curve is an inverted bell, that has never been observed in eclipses, thus leading to previous negative interpretations regarding the existence of gravity attenuation.[2,31,32] Therefore, gravity attenuation during solar eclipses is dominated by scattering, instead of absorption as conventionally believed. On the contrary, Majorana's laboratory observations[9,10,11] may be related to absorption-dominated interaction of terrestrial gravity with materials having high Z (as lead and mercury).

In summary, the empirical evidence discussed here is consistent with a hypothesis of gravity attenuation, containing two terms: gravity scattering as in solar eclipses, and gravity absorption as in Majorana's laboratory measurements, both dependent on Z and N . Such hypothesis clearly violates the principle of equivalence for mass. Hence, theoretical models for the evaluation of $h(Z, N)$ will require theories beyond Einstein's general relativity as, for instance, fourth-order gravity theories with a Podolsky potential, or non-metric gravity theories,[21] or even Le Sage-type models.[39] In the latter vein, the present writer has proposed a general Le Sagian gravity model,[22] which corrects for the weak aspects of traditional Le Sagian models, and is consistent with the gamma-ray analogy model presented in the present paper to describe gravitational solar eclipse anomalies.

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