Possible Resolution of the Brookhaven and Washington Eötvös Experiments

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Seemingly contradictory results from Eötvös-type experiments have been reported by Thieberger and by Adelberger and collaborators. Attempts to reconcile the discrepancy have mainly focused on a single moderate-ranged (of order hundreds of meters) force, coupled to various charges. However, because the local geologies are significantly different in these two experiments, they may be compatible with an alternative scenario: new spin-1 graviphoton and spin-0 graviscalar partners of the gravition, both with longer ranges (tens to hundreds of kilometers). We discuss this and other new data in terms of these two concepts.

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An understanding has yet to develop of the difference between the results of the experiments by Thieberger[1] and by Adelberger and collaborators[2] regarding the so-called[3] "fifth force" of range 100 to 1000 m. Explanations have so far focused on systematic effects and on various subtle choices of couplings for the new force.

We suggest here that there need not be unrecognized errors in either experiment. This possibility arises from our proposal[4] that the most likely origin for new gravitational-strength forces may be found in quantum theories of gravity. These theories predict two kinds of symmetry partners of the graviton: spin-1 graviphotons and spin-0 graviscalars. The small Eötvös and Thieberger effects, as well as deviations from the inverse-square law reported by Stacey and co-workers,[5,6] could then have a common origin, in the imperfect cancellation between repulsive graviphoton exchange and attractive graviscalar exchange.[6] Both fields could then have much longer ranges than the fifth force, and through coupling to fundamental fermions, lead to composition- (baryon number-) dependent forces. The difference between the Thieberger[1] and Adelberger[2] results could then be due to differences in the local topography and geology over distance scales larger than 1 km.

Phenomenologically, the gravitational potential between point objects becomes[4]

$$V=-\frac{Gm_1m_2}{r}\left[1\mp a e^{-r/v}+b e^{-r/s}\right], \qquad (1)$$

where $a^{1/2}$ and $b^{1/2}$ are the graviphoton and graviscalar coupling constants normalized to Newtonian gravity, and v and s are their respective ranges. (In general, there are more than one new spin-0 and spin-1 particles, yielding more new Yukawa terms.) The minus (plus) sign in the second (vector) term of Eq. (1) applies to the matter-(anti)matter interaction.

In contrast to Eq. (1), for a single Yukawa modification of gravity,[3,4] the point potential is

$$V=-\frac{Gm_1m_2}{r}\left[1+\alpha e^{-r/\lambda}\right]. \qquad (2)$$

The latest analysis[5] of the Australian mine data yields a fit of

$$\alpha\cong-(0.008 \text{ to } 0.01),\quad \lambda\cong 200 \text{ to } 1000 \text{ m}. \qquad (3)$$

Such a force is repulsive, and hence is due to a vector interaction.

However, an analysis of the Australian mine experiments in terms of the potential (1) leads to the conclusion[6] that ranges of up to 450 km are allowed,[7] with the restrictions (for these large ranges)

$$a-b=d,\quad s/v-1=\delta/a,\quad (d,\delta)\approx 0.01. \qquad (4)$$

The gravitational acceleration of antimatter could then be as much as 14% greater than that of matter,[8] for $a=1$, and scales with a. An experiment to perform such a measurement on antiprotons is scheduled at CERN,[9] and a positron experiment is under consideration at Stanford.[10]

To see that the two fits of Eqs. (3) and (4) are consistent, we note that the force per unit mass f, produced by a Yukawa potential of range much less than the radius of an earth of uniform density ρ, is, for Eq. (2),

$$f_\lambda=2\pi G\rho(-\alpha\lambda), \qquad (5)$$

and for Eq. (1),

$$f_{v,s}=2\pi G\rho(av-bs)$$
$$=2\pi G\rho[v(d-\delta+\delta d/a)]. \qquad (6)$$

Equations (5) and (6) give approximately the same result after substitution from (3) and (4), respectively.

We now review the experiments[1,2] before applying these ideas.

Thieberger[1] has found that a neutrally buoyant copper sphere on top of a cliff moves in the direction of the outward normal to the cliff. The strength of repulsion is found to be consistent with the proposed single new Yukawa-potential[5] violation of the inverse-square law with a coupling strength about 0.01 that of gravity and a range on the order of 100 m. His experiment is about

500 times more sensitive to a horizontal non-Newtonian force than to one parallel to the local (Newtonian) gravitational acceleration.[11] His signal is about a factor of 3 greater than the experimental sensitivity, and a factor of 4 larger than the sensitivity of the Eötvös experiment[12] to a horizontal non-Newtonian force.

The *local* cliff in question is part of the Palisades,[13] on the western shore of the Hudson River near the New Jersey–New York border [see Fig. 1(a)]. The cliff, which is the crucial geological feature there, is the eastern terminus of a diabase sill, with density $\simeq 2.9$ g/cm^3, that extrudes to form the 80-km-long Palisades outcrop [Fig. 1(a)]. In comparison,[13] the rocks to the east consist of Precambrian granites and gneisses having a density of about 2.7 g/cm^3. The Hudson River itself and the deposition under it have densities of about 1.0 and 2.0 g/cm^3, respectively. The sill is about 275 m thick and extends to the west, with about a 10° dip, all the way into Pennsylvania.[13] It concordantly intrudes sandstones with densities approaching 2.7 g/cm^3.

Adelberger's group[2] compared the differential force exerted by a hill on two materials. The sensitivity of the Washington experiment is also a factor of 500 greater for a horizontal non-Newtionian force than for one parallel to the Newtonian gravitational acceleration.[11] However, they quote a limit on the strength of a single non-Newtonian force which is about a factor of 10 smaller than that reported by Thieberger.[1]

The *local* scale of the Washington experiment is dominated by a hill of size 100 m [see Fig. 1(d)] on the northeast corner of the University of Washington campus.[2,15] The geology in the vicinity of the Seattle site consists of glacial till with a bulk density taken to be[2] 2.1 g/cm^3 [see Fig. 1(c)].

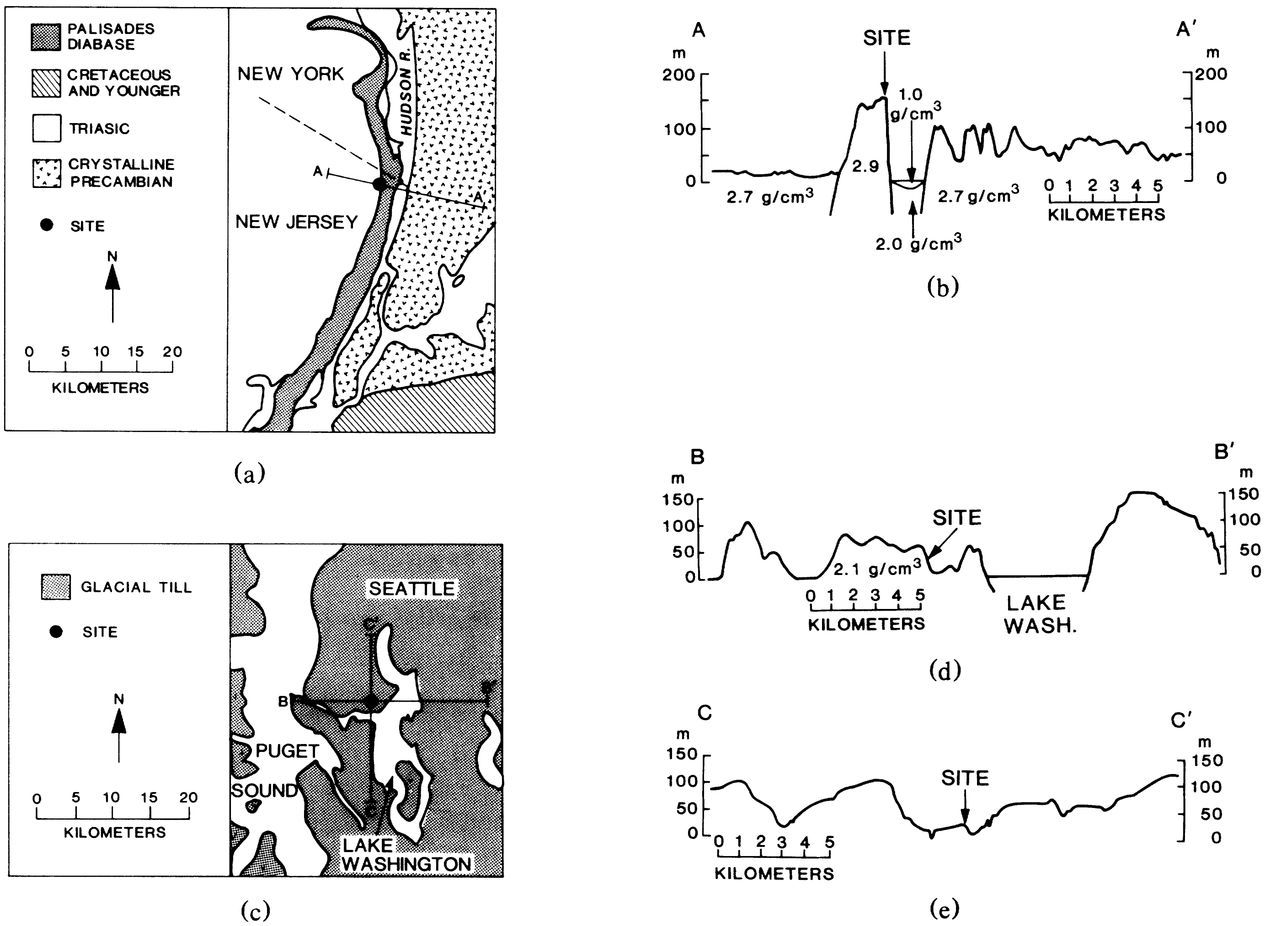

FIG. 1. Geologic (Ref. 13) and cross-sectional maps of (a), (b) the Palisades site and (c)–(e) the Seattle site. The lines AA', and BB' and CC', label the traces of the cross sections in the geologic maps for the Palisades and Seattle sites, respectively. Note that the vertical scales of the cross sections relative to the horizontal scales are *exaggerated by a factor of 25.* At the Palisades site, for a circle of about 10 km radius, there could be more mass to the east due to terrain elevations. However, for the radii of interest to us, about 40 to 400 km, the opposite is true. In (d), the trace direction $B'B$ is slightly to the south of the resultant of the Washington experiment, 285° (Ref. 14). The cross section of this trace reaches a depth of approximately 200 ft in the lake (Ref. 15).

From Fig. 1, the topography and geology for the Palisades site can be considered, for our purposes, to be approximately two-dimensional in the east-west directions. A similar assumption is not as valid for the Seattle site. Actually, the Seattle site can be thought of as sitting on the northeast side of a bowl. (See the profiles BB' and CC' in Fig. 1.) In terms of possible short-range (≤ 1 km) forces, both experiments sit against roughly 300000 m^2 of east-west cross-sectional topography, although the rock densities are higher for the Palisades.

The strength of possible long-range (>10 km) new forces at the Seattle site is not truly known because of the lack of detailed knowledge of the local geology far below the surface. Even so, we can infer that at that site the experiment is most probably insensitive to such forces because the air-rock interface is the only source of large density contrast. We already know that there is insufficient large-scale mass, due to topography, to affect the horizontal component to which the experiment is sensitive. It is also general geophysical knowledge that although large-scale density contrasts do exist in the crust and upper mantle, they decrease with depth. In the upper crust of tectonically active regions they seldom exceed 0.2 g/cm^3. However, even if such large-scale contrasts existed in the crust or upper mantle beneath the site, they would produce dominantly vertical components of new forces. The Washington experiment was insensitive to these components. This was understood by the Adelberger group.[2]

Conversely, at the Palisades site there may be strong horizontal components of new long-range forces because it sits at the eastern terminus of the diabase sill. This sill can be represented as a 275-m-thick semi-infinite horizontal slab, extending far to the west, of density 0.2 g/cm^3 (the density contrast).

To apply our model to the Thieberger experiment, consider the experiment to be at the midpoint of the flat edge of a half-disk with radius R, thickness t, and density ρ_+, which represents the material excess (0.2 g/cm^3) over the average (2.7 g/cm^3) contained in the diabase sill. As we let R become large with respect to v, the horizontal force per unit mass due to graviphoton exchange is[8]

$$f_v = aG\rho_+ 4v\int_0^{t/2v} dk\, K_0(k), \tag{7}$$

where K_0 is the modified Bessel function. As t goes to infinity, the integral become $\pi/2$, as it should. However, for small $t/2v$ the integral I is, to a good approximation, given by

$$I(Y) = [1+\ln(2)-\gamma-\ln(Y)]Y, \quad Y=t/2v, \tag{8}$$

where γ is Euler's constant.

Now using both graviphoton and graviscalar exchange, and the parametrization of the fit to the mine data, we find for small Y that, to a good approximation, the differential force per unit mass in this model of the Thieberger experiment is

$$\Delta f_{v,s} = G\rho_+\Delta[2t][d(1-\ln Y+\ln 2-\gamma)-\delta]. \tag{9}$$

In Eq. (9) $\Delta = 0.00171$ is the difference of baryon number per unit atomic mass between copper and water.

For definiteness, take $t=250$ m and the conservative value $v=50$ km. Then Eq. (9) gives a value of 7×10^{-8} cm/sec^2 for $\Delta f_{v,s}$, compared to Thieberger's experimental value of $(8.5\pm1.3)\times10^{-8}$ cm/sec^2. For $v\approx 200$ km, exact agreement is obtained.

The model ignores the sill dip of 10° and has the experiment at the center of the flat edge instead of on top of it (an overestimation). The model underestimates the force by ignoring the extra nearby westerly mass contribution of 0.7 to 2.7 g/cm^3. This is the amount by which the real density of the western cliff (not accounted for in the half-disk) exceeds the density in the easterly air, water, and sediment of the Hudson River valley. The two-component quantum-gravity–inspired model can therefore be considered a viable explanation of Thieberger's result.

If the non-Newtonian forces at the Seattle site, resulting from integration over a similarly large scale, were sufficiently parallel to the torsion fiber so as not to be measureable, there would be no contradiction with Thieberger's result. This could have been the case, given the approximately uniform topography on a large scale. [Note, for example, the hill to the right in Fig. 1(d).] However, this would not be true for a single–Yukawa-potential model, with range $\lambda\approx 100$ m and relative coupling $\alpha\approx 0.01$. Such a new force should have been seen in the Washington experiment.

Of course, if our explanation is correct, Thieberger should see little or no signal if he were to repeat his experiment near a small, isolated hill. Conversely, Adelberger's group should observe a positive effect upon repeating their experiment on the New Jersey cliff or at some other geologically larger-scaled location, such as at their proposed Grand Canyon site.

Further, there is fascinating, newer experimental evidence.

First, Hsui[16] has reported an analysis of Michigan borehole gravity data which finds a value of G consistent with the Austrialian value. Of interest to us, to depths of 1.2 km, there was "no apparent length-scale dependence in G over this range."

Second, the new Galileo experiment[17] "at 200 m is not competitive with the geophysical limit" (from the Australian mine data). It also does not conflict with our model because the usual figure of merit ($\alpha\lambda$) becomes $-av+bs$, which is small [Eqs. (4)–(6) above].

Third, in the new Eötvös experiment of Boynton *et al.*[18] no signal was found on the Seattle campus, while a smaller result than expected from a short-range force coupled to baryon number was found near Index, Washington. They have speculated that an isospin coupling might make all the new experiments[1,2,18] compatible. But an extension of the argument against hypercharge coupling,[19] based on the lack of observed $K^+ \to \pi^+ +$ (unobserved neutral) decays, severely constrains this notion. Further, the horizontal components of non-Newtonian forces, to which their instrument responds, could be much smaller if the ranges were as large as in our scenario.

Fourth, measurements of gravity up a 2000-ft television tower by the Air Force Geophysical Laboratory have been interpreted to indicate a new *attractive* force.[20] Thus, if their results are correct, there is now direct evidence for both types of force predicted by quantum gravity. Of course, the $\simeq$500-m range reported by the Air Force Geophysical Laboratory is less than that required for the attractive component in our present resolution of the Eötvös experiments.

Finally, the Greenland ice-sheet experiment,[21] to measure G to at least 1 part in 1000 over a range from 200 m to 1.6 km down the DYE 3 ice borehole, should soon shed light on the scale of any distance dependence of G. This experiment has taken data which are now being analyzed.

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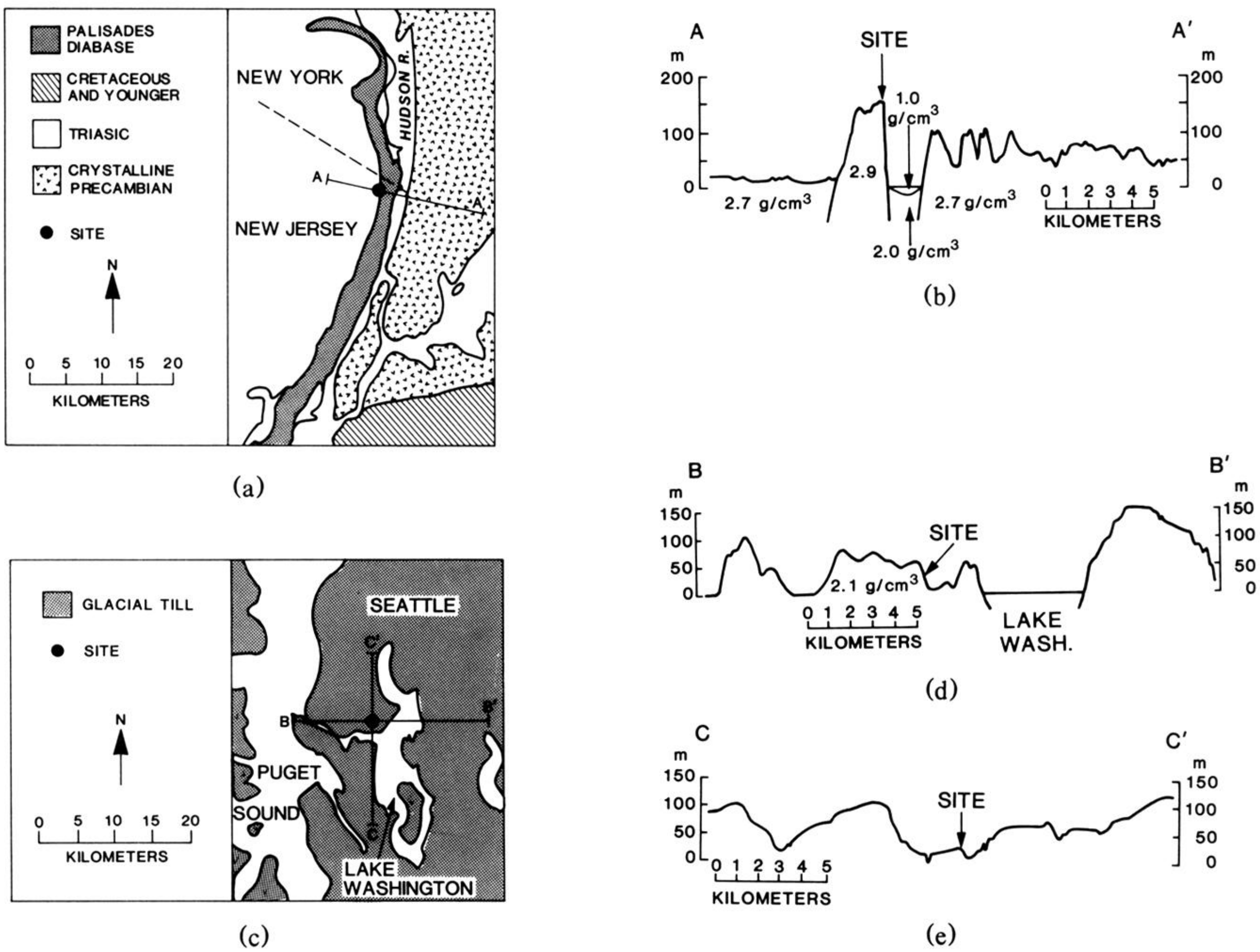

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