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ON DEVIATIONS FROM NEWTON'S LAW AND THE PROPOSAL FOR A "FIFTH FORCE"*

by

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ABSTRACT

The results of geophysical and laboratory measurements of the Newton's constant of gravitation, seem to disagree by one percent. Attempts to explain this has led to the revival of the proposal for a fifth interaction in Nature. The experimental results on measurements of G and tests of Newton's inverse square law are reviewed. The recent reanalysis of the Eötvös experiment and proposals for new experiments are discussed.

Key-words: Gravitation; Geophysical; Laboratory; Measurements; Fifth force.

1 INTRODUCTION

In the last few months there has been quite a lot of discussion in the Physics literature about the possibility of the existence of a new interaction in Nature. The renewal of interest in the subject is due to the publication of a paper by Fischbach et al. [1]. In this paper they claim that the data of the classical Eötvös experiment [2] published in 1922 is compatible with the existence of an interaction which couples to baryon number or hypercharge. They proposed that this new interaction is mediated by a spin 1 particle, called hyperphoton, with a mass of about 10^{-9}eV, a slightly modified version of a model which dates from the fifties and the sixties (see section 4). They also claim that this new interaction could also explain the high values of the Newtonian constant of gravitation G mesured by geophysicists [3] in mines as well as the anomalies in the K_0-$\bar{K}_0$ system [4].

This new interaction would superimpose to the gravitational force and the potential energy for two point-like masses separated by a distance r would be,

$$V(r) = - G_\infty \frac{m_1 m_2}{r} \{1+\alpha_{12}\exp[-(r/\lambda)]\} \quad , \tag{1.1}$$

where G_∞ is the Newtonian gravitational constant for $r \to \infty$, α_{12} is a material dependent constant which for bulk matter is of the order 10^{-3} and λ is approximately equal to 200m (we will see later that this choice is rather arbitrary; for instance for $\alpha \approx 10^{-3}$, λ can in fact take values in the interval (0.1-10km). From (1.1) we see that in experiments involving the *force* between material bodies, under the assumption of an inverse square law, the Newton's universal constant G would have to be replaced by a quantity depending on the distance,

$$G(r) = G_\infty\{1+\alpha_{12}\exp[-(r/\lambda)](1+r/\lambda)\} \quad (1.1a)$$

which would be the gravitational constant effectivelly measured in those experiments.

At first sight this proposal seems to be very unrealistic and probably one would not bother about it because they will find it is wrong soon or later. However, this sort of proposals can be done nowadays because we know very little about the validity of Newton's law at intermediary distances (0.1-10km). Since the pioneering experiments of Michell-Cavendish [5] in 1797 several others have been done at laboratory scale [6] (0.1-1m) and the result is that no deviation from Newton's inverse square law greater than 10^{-4} is permitted [7]. As far as we are concerned the most precise determination of Newton's constant at laboratory scale, denoted G_0 has been done by Luther and Towler [8] in 1982 and it is,

$$G_0 = 6.6726(5) \times 10^{-8}\ cm^3 g^{-1} s^{-2} \quad , \quad (1.2)$$

and is precise to 75 ppm. At astronomical scale Newton's law has been tested with an even higher precision and it seems to be right apart of course from relativistic corrections. However the Newtonian constant has not been measured directly at this scale yet. The reason is that when observing the orbit of a satellite around the Earth or the orbits of the planets around the sun what is determined is the product GM and unless we can determine the masses in an independent way we can not determine G_∞. In fact the masses of the planets are calculated using the laboratory value of Newton's constant and if the existence of a fifth force would be confirmed the values of these masses would have to change a little. In fact the mass would change by a factor $1|(1+\alpha)$. The verification of Newton's law at intermediary distances (0.1-10km) is more difficult to be done. At this scale the only available information comes from geophysical determinations of the Newtonian constant of gravitation. These methods are generally used to search for anomalies in the gravity acceleration that could indicate the existence of ore. However if the density inhomogeneity around the mine is reasonably known these methods can be used to determine Newton's constant. The precision of these determinations is not as good as the laboratory measurements of Newton's constant because it is quite difficult to determine the density inhomogeneities in a mine with a high degree of confidence.

However these methods have been improved [20] and several determinations [18,19] of Newton's constant have been done in the last years. The amazing thing about these measurements is that they all give values for Newton's constant which are about 1% higher [10] than the laboratory value [8]. We will discuss these results in more detail later, but one of the most precise determinations of G done by Holding Stacey and Tuck [19] is:

$$G(\text{geophysical}) = (6.720 \pm 0.002 \pm 0.024) \times 10^{-8} cm^3 g^{-1} s^{-2}, \quad (1.3)$$

where the first error is the standard deviation from the statistical analysis of the data and the second is due to the possible systematic errors which arise from the lack of precision in density determinations. Notice that this value differs from the best laboratory value (1.2) by 0.7% which means 23 standard deviations. If the esti mated systematic errors is considered instead, they differ by 2 error bars. Obviously these results are not conclusive at all but they are sufficiently intriguing to motivate the experimentalists to do more precise experiments and the theorists to speculate around.

2 LABORATORY TESTS OF NEWTON'S LAW OF GRAVITATION

Several experiments [11,12,13,14,15] have been performed to test the validity of Newton's inverse square law of gravitation at laboratory scale. The results of all these experiments except one [11] have confirmed the validity of Newton's law with an increasingly precision. Under the assumption of a supplementary Yukawa-type potential (1.1) these results impose limits on the allowed values of the parameters α and λ. For $\alpha<0$ (repulsive potential) Chen et al. [15] gives the best result, leaving the possibility of a deviation from Newton's law corresponding to $\alpha<10^{-4}$ in the λ-range of 3-10cm (see fig. 3). A similar result exists for the possibility of an extra attractive force ($\alpha>0$). In this case Hoskins et al. [16] limits the allowed deviation to $\alpha \lesssim 3\times10^{-4}$ within the λ-range 1-10cm. In a earlier experiment Long [11] compared the measured gravitational constants at separations between the test bodies of 20.90cm and 4.48cm. Long's apparatus is composed of two fixed rings and a Cavendish balance from which hangs a ball. The system is in vacuum and the vacuum chamber wall temperature is controled (the interested reader will find details on the composition and dimensions of the pieces of the apparatus in Long's paper). The quantity measured in the experiment is,

$$\Delta = (1/\tau)(\tau'-\tau) \quad , \qquad (2.1)$$

where τ and τ' are respectively the torques produced by the near and the far rings. The result of the measurements gives $\Delta_{exp}=0.04174 \pm 0.0004$, while the Newtonian value is found to be $\Delta_N=0.03807$, giving the discrepancy

$$\delta = \Delta_{exp} - \Delta_N = 0.0037 \pm 0.0007 \quad , \tag{2.2}$$

(the greater error 0.0007 instead of 0.0004 is due to errors in the distance measurements). Long claimed that there was no error present in the measurements large enough as to account for (2.2), which would thus indicate a deviation from Newton's law, or since the experiment was carried out in the presence of the Earth gravitational field, a failure of the supperposition principle.

However, subsequent measurements by Spero et al. [17] yielded results which are inconsistent with Long's both for a null and a non-null experiment. The later case seems to rule out also Long's explanation for the gravitation anomaly he founds, as being a vacuum polarization effect analogous to that which produces a logarithmic deviation from Coulomb's law in Electrodynamics at very short distances.

Chen et al. [15] performed another laboratory experiment using the apparatus reproduced in (fig. 1). The idea of the experiment is to compare the gravitational attractions of two cylinders of different masses and dimensions (masses B,C in fig. 1), by putting each in turn into equilibrium with a third cylinder (mass A in fig. 1). The attraction between the removible cylinder (B,C), the third one (A) and a test mass is indicated by the deflection of a torsion balance placed between the cylinder B(C) and A. With this geometry are performed a null experiment (a null field at the test mass position) and a non-null experiment (a net field at the torsion balance). The quantity measured in the experiment is the relative difference between the attractions of cylinders B and C $\Delta F/F$, respective to A, which must be compared to the expected theoretical (Newtonian) result. The result of 43 measurements compared to the Newtonian (N) value for a non-null experiment, repported by Chen et al. [15] is,

$$(\Delta F/F)_{exp} - (\Delta F/F)_N = (1.1 \pm 1.35) \times 10^{-4} \qquad (2.3)$$

while for a null experiment is,

$$(\Delta F/F)_{exp} - (\Delta F/F)_N = (0.6 \pm 2.0) \times 10^{-4} \quad , \qquad (2.4)$$

the uncertainty being in both cases the standard deviation.

These results mean that at distances of the order of 10cm any deviation from the inverse square law must be smaller than $\alpha=10^{-4}$ (see fig. 3) which considerably narrows the window opportunity for a supra-Newtonian force at laboratory scale.

Now, under the assumption of a potential of the type (1.1), a measure of the ratio $G(r_1)|G(r_2) = \beta$ (see 1.1a) at two distances r_1 and r_2 imposes a relationship between the relative intensity α_{12} and the range λ given by,

$$\alpha_{12} = \frac{\beta-1}{[1+(r_2/\lambda)\exp(-r_2/\lambda)-\beta[1+(r_1/\lambda)]\exp(-r_1/\lambda)} \qquad (2.5)$$

Varying β within the experimental limits constrains α and λ to lie in a region of the $(\alpha-\lambda)$-plane. In (fig. 2) is shown the result of this procedure for the laboratory experiments of [11], [12] and [13]. In (fig. 3) we reproduce the allowed region for $\alpha>0$ in the $(\alpha-\lambda)$-plane as given by the experiment of Chen et al. [15]. We see that the allowed region at a laboratory scale for a non-Newtonian force is still narrowed respective to the preceeding experiment by Spero et al. [12]. We note that the laboratory experiments impose severe restrictions on the existence of a non-Newtonian interaction of the type (1.1) for small values of λ. However it leaves a wide window of opportunities for λ greater than 100 meters.

3 GEOPHYSICAL DETERMINATIONS OF NEWTON'S CONSTANT

A class of experiments leading to an apparent deviation from Newton's law are the geophysical measurements of gravity gradients in mines. These gives values of Newton's constant of gravitation systematically higher than the values measured in laboratory experiments. Compare the data given in table 1 for measured values of G from geophysical experiments reproduced from Stacey and Tuck [18], with the standard laboratory value $G_0=(6.672\pm0.004)\times10^{-11}m^3kg^{-1}s^{-2}$. If this effect is a real one and not a consequence of systematic errors, one could try to explain it by introducing a non-Newtonian potential of the form given in (1.1). In this case the force derived from the extra Yukawa-like potential has to be a repulsive one, since from (1.1a) we get that for $r\sim\lambda$, $G(r)=G_0+\eta(\alpha)$, and in order to have $\eta(\alpha)>0$ we need $\alpha<0$. Let us discuss the claimed evidences the geophysical data provides for such a force.

The method geophysicists use to determine Newton's constant is the following: by using gravity meters they measure the gravity acceleration in mines and then by assuming that Newton's square inverse law of gravitation is correct they calculate the gravity acceleration at a point in the mine as a function of Newton's constant G which is left as an arbitrary parameter. Then by comparing the measured value to the theoretical one they determine G as a function of depht. In order to calculate the gravity acceleration at an internal point in the Earth using Newton's law they assume that this is formed of co-centric ellipsoidal layers of constant density and that all ellipsoidal surfaces have the same ellypcity. This calculation is simplified by the fact that gravity at any internal point is due only to the mass within the ellipsoidal surface through the point in question. We now refer to (fig. 4). Let B be an internal point in the Earth and let A be a point at the surface vertically above B. The distance between them is z. The difference is gravity acceleration for these two points, calculated using the model above is,

$$g(z) - g(0) = U(z) - 4\pi G\, X(z) \quad , \tag{3.1}$$

where,

$$U(z) = \frac{2g(0)z}{R}\{1+\frac{3}{2}\frac{z}{R}-3J_2(\frac{3}{2}\sin^2\phi_0-\frac{1}{2})\} + 3\omega^2 z(1-\sin^2\phi_0) \tag{3.2}$$

$$X(z) = \frac{c}{a}\{1+\frac{2z}{R}+\frac{1}{2}(1-\frac{c^2}{a^2})\}\int_0^z \rho(z)dz - \frac{2}{R}\int_0^z z\rho(z)dz. \tag{3.3}$$

R is the radius of the Earth at the site of measurements (see fig. 4), ϕ_0 is the geocentric latitude, $J_2=1.08264\times10^{-3}$ is the inertial ellipticity coefficient, $\omega=7.292\times10^{-5}$ rad s^{-1} is the angular rotation rate, a and c are the equatorial and polar radii, where $a=6.37814\times10^6$ m and $(1-\frac{c^2}{a^2}) = 0.006944$ and $\rho(z)$ is the density. In this determination of G it is assumed an average density throughout the mine. Then corrections must be done to account for the localized departures from average density. This is in fact the most important source of errors in the determination of G by geophysical methods.

Values of G found by several geophysical experiments are shown in table (1). They include measurements in mines, boreholes and marine surveys. The data measurements in the sea were made by Exxon Exploration Department in Gulf of Mexico and their data were used by Stacey and Tuck [18] to determine G. There are two more recent determinations of G by the Australian group using the data obtained in two mines in Queensland, Australia. These mines, according to them, are reasonably surveyed and this minimises the systematic errors due to density inhomogeneities. The first determination [48] is from Hilton's mine in 1984 and the value found is

$$G = (6.734 \pm 0.002) \times 10^{-8} cm^3 g^{-1} s^{-2} \qquad (3.4)$$

The error shown is one standard deviation and the systematic error due to density inhomogeneities is certainly higher. The other determination of G[19] was done in 1985 in Hilton and Mount Isa mines which are 20km apart. The results are:

$$\text{Hilton mine: } G = (6.720 \pm 0.002 \pm 0.024) \times 10^{-8} cm^3 g^{-1} s^{-2} \qquad (3.5)$$

$$\text{Mount Isa mine: } G = \left\{ \begin{bmatrix} 6.691 \pm 0.007 \\ 6.693 \pm 0.010 \\ 6.729 \pm 0.009 \\ 6.702 \pm 0.007 \end{bmatrix} \begin{matrix} + 0.089 \\ - 0.022 \end{matrix} \right\} \times 10^{-8} cm^3 g^{-1} s^{-2} \qquad (3.6)$$

The first error is one standard deviation and the second is the systematic error due to uncertainties in the density measurements.

One can see that these values of G as well as those shown on table (1) are about 1% higher than the laboratory scale value of G given by (1.2). This discrepancy could be produced by density inhomogeneities in the vicinity of mines and boreholes or also "by extensive local bias in gravity gradient by deep-seated mass irregularities" [19]. In the case of Hilton and Mount Isa mines the first cause seems to be ruled out. On the other hand the second cause seems to be improbable since measurements have been done in several parts of the world and they all have given higher values for G. The results obtained up to now are still unconclusive and more precise measurements have to be done. Experiments in the sea seems to be the most suitable ones to check these determinations of G since the uncertainities in density are much lower.

If a "normal" explanation for this anomaly is not found we have a verification that Newton's law of gravitation is not valid at intermediary distances (0.1-10km). One explanation for this is that there exist a new medium range interaction in Nature, probably of the type (1.1). If we assume this, the geophysical data can be used to set limits on the values of α (relative intensity) and λ (range) for this interaction. In order to do that we calculate the gravity gradient $g(z)-g(0)$ due to the potential (1.1) assuming that the range of the interaction is much smaller than the Earth radius (since the satellite measurements gives no anomalies), then subtract from this the value of $g(z)-g(0)$ that is expected if the Newton's inverse square law is correct (in this calculation we use the value of G determined by laboratory experiments). This difference is called the gravity residual, and is given by,

$$\Delta g(z) = \frac{4\pi G_0 \bar{\rho} \alpha}{1+\alpha} \{z - \frac{\lambda}{2} [1-\exp(-(z/\lambda))]\} \qquad (3.7)$$

Now, taking for $\Delta g(z)$ the observed value at a given depth z we obtain a relationship between α and λ. From the results of measurements at several depths and taking $\Delta g(z)$ between the experimental limits, gives an allowed region in the ($\alpha-\lambda$)-plane. For the experiment described by Stacey et al. [20] the allowed region is displayed in (fig. 5). In the more recent experiment by Holding et al. [19], λ is fixed at a series of values and the corresponding values of α are obtained by best fits to the data, giving the curve in (fig. 6) (Of course, taking into account the error bars in the determination of α, the curve is replaced by a band in the ($\alpha-\lambda$)-plane). We see from (fig. 6) that a relative intensity α of the order -7.5×10^{-3}, as taken by Fischbach et al. is compatible with a range λ of $2-10^4$m. Ranges smaller than 2m or greater than $\sim 10^4$m are disallowed by results from other experiments. We also show in (fig. 7) the window opportunity for an extra-Newtonian force, mentioned bv Glashow [34], taking together laboratory and geophysical results as given by Gibbons and Whiting [35].

4 THE IDEA OF A FIFTH FORCE IS NOT A NEW ONE-HISTORICAL AND THEORETICAL BACKGROUND

The idea of a fifth kind of interaction in Nature is not a new one. Also, other theoretical proposals have been done which implied deviations from Newton's law of gravitation (see the end of this section). A fifth force has been suggested by Wigner [21] and by Lee and Yang [22] in the fifties, in connection with the experimentally observed conservation of baryon number. Lee and Yang guided by the yet recent ideas on gauge theories proposed the existence of a massless gauge vector boson coupled to the baryonic charge f (+f for baryons, -f for antibaryons) in close analogy with Electrodynamics. On a static macroscopic level this new interaction would manifest itself as a repulsive force between two composite point-like bodies of baryon numbers B_1 and B_2 respectively, which modifies the Newtonian gravitational force between then,

$$\text{Force} = -G \frac{m_1 m_2}{R^2} + f^2 \frac{B_1 B_2}{R^2} = -G(1+\alpha_{12}) \frac{m_1 m_2}{R^2} \quad , \qquad (4.1)$$

where $\alpha_{12} = -\frac{B_1 B_2}{m_1 m_2}\frac{f^2}{G}$, m_1, m_2 are the gravitational masses and R the distance. As already remarked by Lee and Yang this supplementary infinite range force would have to be several orders weaker than gravitation, in order not to be in contradiction with the result of Eötvös experiment [2] on the equivalence of inertial and gravitational masses.

About ten years later, Bernstein, Cabbibo and Lee [23] and independently Bell and Perring [24] proposed in the context of the K_0-$\bar{K}_0$ oscillation, the long range fifth interaction as an alternative for CP-violation in the long-lived neutral kaon decay. The only modification respective to the preceeding model of Lee and Yang was the coupling of the vector boson to hypercharge instead of baryonic charge. They assumed that an almost massless vector boson coupled to hypercharge provide a "cosmic background" from all the galaxy inducing a potential energy difference V between the K_0 and the $\bar{K}_0$. A meson state in the laboratory frame, considered as a linear mixing of the K_0 and the $\bar{K}_0$,

$$K(t) = \alpha(t) K_0 + \beta(t) \bar{K}_0 \quad ,$$

then evolves in time following an equation of the type [23]

$$i \frac{dK(t)}{dt} = H(m_1, m_2, \Gamma_1, \Gamma_2; V) K(t) \quad , \qquad (4.2)$$

where m_1, m_2, Γ_1, Γ_2 are respectively the masses and widths of the K_o, $\bar{K}_o$ components K_1^0 and K_2^0, $K^0 = (1|\sqrt{2})(K_1^0+K_2^0)$, $\bar{K}_o = (1|\sqrt{2}(K_1^0-K_2^0)$. Eq. (4.2), has two eigensolutions,

$$\begin{cases} K_S^0 = \dfrac{1}{\sqrt{1+|\varepsilon|^2}} (K_1^0 - \varepsilon K_2^0) \\ \\ K_L^0 = \dfrac{1}{\sqrt{1+|\varepsilon|^2}} (K_2^0 + \varepsilon K_1^0) \end{cases} \tag{4.3}$$

where for a locally isolated meson,

$$\varepsilon \approx (1/2)\sqrt{1-(v^2/c^2)}.V[(m_1-m_2)-(i/2)(\Gamma_1-\Gamma_2)]^{-1} . \tag{4.4}$$

The solutions K_o^s and K_L^0 are to be identified respectively with the short-lived and the long-lived neutral kaon components. From (4.3) we see that *under the assumption of CP-conservation* ($K_1^0 \to \pi^+\pi^-$ is allowed, while $K_2^0 \to \pi^+\pi^-$ is not), the long-lived neutral kaon component has a decay probability $K_L \to \pi^+\pi^-$ relative to $K_s^0 \to \pi^+\pi^-$, of order $|\varepsilon|^2$. Experimentally, from the observed decay rates one has $|\varepsilon| \approx 2.0 \times 10^{-3}$ [25], which in the context of this model gives from (4.4) $V \approx 5.0 \times 10^{-4}\ cm^{-1}$. On the other side, the potential energy difference between the K_o and the $\bar{K}_o$ due to the "fifth interaction" with the galaxy is given by,

$$V = (1/2)f^2(M_g/m_H)R_g^{-1} \approx 5.0 \times 10^{-4} cm^{-1} \quad , \tag{4.5}$$

where M_g and R_g are respectively the mass and the "effective radius" of the galaxy. From (4.5), taking the numerical values for M_g ($\approx 10^{11}$ solar masses) R_g($\approx$10kpc) and m_H, one obtains $f^2 \approx 2.5 \times 10^{-49}$. Then the ratio between the intensities of the long-range "fifth force" and gravitation is found to be $(f^2/Gm_H^2) \approx 10^{-10}$, which is too small to be detected in any classical experiment on the equivalence of inertial and gravitational masses. Therefore, with a very small coupling an interaction mediated by "hyperphotons" could be responsible for the CP-conserving long-lived kaon decay into pions.

However, Weinberg [26] studying the decay of a K_0 into $\pi^+\pi^-$ and a hyperphoton, noted that as hypercharge is not exactly conserved, the hyperphoton would have to be slightly massive. In this case he founds the branching ratio for the emission of a hyperphoton γ' of mass μ and energy $\leq E$ in the decay $K^0 \to \pi^+\pi^- + \gamma'$,

$$B(K^0 \to \pi^+\pi^- + \gamma') \approx (f^2/\mu^2)E^2/8\pi^2 \quad , \qquad (4.6)$$

for $E \approx 100MeV$ and $\mu << E$. For an interaction range μ^{-1} of the order of the effective galactic radius $R_g \approx 10Kpc$, the branching ratio (4.6) take the enormous value $4x10^{19}$. For it to have a reasonable value, the range of the interaction must fall to the order of kilometers [26], so being unsuitable to explain the K_L^0 decay into pions in the way thought by the authors of refs. [23,24]. Weinberg [26] still refers to a number of contemporary essays on the possibility of vector bosons of very small masses coupled to hypercharge or strangeness, but with no apparent connection with K_0 decays.

We note also that in another context, namely the breaking of SU(3) symmetry, Ne'eman [27] proposed the existence of a heavy vector boson, the χ, with a coupling intermediary between strong and electromagnetic interactions, $0.1 \leq g^2/4\pi \lesssim 0.3$, corresponding to a mass $3GeV \lesssim M_\chi \lesssim 5\,GeV$.

Besides the above mentioned proposals of a "fifth force" some theoretical models have been constructed, for instance by Fujii [28], O'Hanlon [29], Wagoner [30], which implied a deviation from Newton's Universal law of gravitation appearing as a finite range additional force. The common feature between these models and the proposals for a "fifth force" is that they modify the Newtonian potential energy between two point-like bodies in the way indicated by equ. (1.1). Fujii's dilaton (the non-zero Goldstone boson associated to scale invariance) theory [28] and the O'Hanlon model for intermediate range gravity [29] both give $\alpha=+1/3$ which hints for an extra attractive force with an intensity comparable to gravity. As far as we know, no evidence for such a force has ever been repported.

5 THE REANALYSIS OF THE EÖTVÖS EXPERIMENT

Motivated by the geophysical results, which we discussed in section 3, Fischbach et al. [1] decided to have a closer look at the data from the Eötvös experiment [2], done more than 60 years ago (although published in 1922, the experiment was really done in the beginning of the century). According to their reanalysis, these data are compatible with the existence of a medium-range force coupled to hypercharge or baryon number (the coupling to hypercharge is now discarded [31,32,33]; see next section). This force would be mediated by a spin 1 particle of mass of about 10^{-9}eV, and it would superimpose to ordinary gravity to produce at a static macroscopic level the potential given by (1.1). This model is a slightly modified version (massive hyperphoton) of the fifth interaction described in the preceeding section. If this force couples to baryon number for example, the constant α_{12} in (1.1) takes the form

$$\alpha_{12} = -(f^2/G_\infty m_H^2)(B_1/\mu_1)(B_2/\mu_2) \quad , \tag{5.1}$$

where f is the coupling constant of this new particle to baryon number, B_1 and B_2 are the baryon numbers of the particles in question and μ_1 and μ_2 their masses in units of atomic hydrogen, $m_H = 1.00782519(8)u$ and G_∞ is Newton's constant for astronomical distances.

Since the ratio of baryon number to mass varies from element to element, the acceleration of a body under the action of the potential (1.1) will depend upon its composition. One can check that the difference in acceleration for two free falling bodies on Earth under the action of the potential (1.1) is given by [1],

$$\frac{\Delta a}{g} = \frac{a_1 - a_2}{g} = -\frac{f^2}{G_0 m_H^2}\,\varepsilon(R/\lambda)\left(\frac{B_\oplus}{\mu_\oplus}\right)\left(\frac{B_1}{\mu_1} - \frac{B_2}{\mu_2}\right) \qquad (5.2)$$

(This expression in Fischbach et al. paper has a minus sign wrong - see discussion below), where $B_\oplus/\mu_\oplus$ is the ratio of baryon number to mass to the Earth, and is assumed to be close to 1. $\varepsilon(R/\lambda)$ comes from the integration of the contribution of the medium-range baryonic force over the Earth, assummed to be a uniform sphere of radius R. For $R \gg \lambda$, which is the case we are interested, $\varepsilon(R/\lambda) \approx \frac{3}{2}\frac{\lambda}{R}$. So, if the fifth force exists bodies will not fall with the same acceleration to Earth as Newton's law demands. The difference in acceleration for two bodies depends linearly upon the difference of their ratio of baryon number to mass, according to (5.2). Eötvös-type experiments are a good way of checking the existence of such a force. Fischbach at al. [1], used the 1922 Eötvös data and their result is shown in (fig. 8) where it is plotted $\frac{\Delta a}{g}$ measured by Eötvös against $(B_1/\mu_1) - (B_2/\mu_2) \equiv \Delta(B/\mu)$ evaluated by Fischbach et al. [1]. The equation of the line shown on the graph given by least squares fit is,

$$\frac{\Delta a}{g} \equiv \Delta K = a\Delta(B/\mu) + b \quad ,$$

$$a = (5.65 \pm 0.71) \times 10^{-6}$$

$$b = (4.83 \pm 6.44) \times 10^{-10} \qquad (5.3)$$

$$\chi^2 = 2.1 \text{ (5 degrees of freedom)}$$

According to their reanalysis there is a good agreement between Eötvös data and the theory of the hyperphoton. However several authors have some objections to this - see discussion below. Using these results and (5.2) we can evaluate f^2:

$$[f^2 \varepsilon(R/\lambda)]_{\text{Eötvös}} = G_0 m_H^2 a = (4.6 \pm 0.6) \times 10^{-42} e^2 \quad , \qquad (5.4)$$

where e is the electric charge in Gaussian units. The geophysical data can also be used to determine f^2, although in this case there are some uncertainities. The geophysical data indicate that this new force must be repulsive but it leaves a reasonably wide window of possibilities for the values of α and λ appearing in (1.1) (see section 3). Fischbach et al. [1] fitted the geophysical data with the following values for α and λ,

$$\alpha = -(7.2 \pm 3.6) \times 10^{-3} \qquad \lambda = (200 \pm 50)\text{m} . \qquad (5.5)$$

From (5.1) we see that in the approximation $B \approx \mu$ (for bulk matter) α_{12} reduces to a constant $\alpha \approx -f^2 | G_\infty m_H^2$, and from (1.1a) we have for $r >> \lambda$, $G_\infty = G_0 | 1+\alpha$. Then,

$$\frac{\alpha}{1+\alpha} \approx - \frac{f^2}{G_0 m_H^2} \quad , \qquad (5.1a)$$

which is the formula given by Fischbach et al. [1] to relate the unit of hypercharge f and the parameter α. Using $\varepsilon(R/\lambda) \approx \frac{3}{2}\frac{\lambda}{R}$, for $R >> \lambda$, (5.5) and (5.1a), one gets,

$$f^2 \varepsilon(R/\lambda)\Big|_{\text{Geoph.}} = (2.8 \pm 1.5) \times 10^{-43} e^2 \quad . \qquad (5.6)$$

So the geophysical an Eötvös determinantions of f^2 differs by a factor 16. This factor could be lower or higher depending on the values of α and λ one extracts from the geophysical data. In addition, we will see in the next section that the topograpical features close to the site where the Eötvös experiment was done can modify (5.4) substantially.

Several criticisms were made to Fischbach et al. reanalysis of Eötvös experiment. The first one [36] is that there is a minus sign wrong in equations (4) and (9) of reference [1]. If one looks on page 42 of Eötvös original paper one will see that his results imply that water falls more slowly than copper. The nuclear binding energy for water is smaller than for copper and so the ratio of baryon number to mass is greater for copper than for water. Therefore if one assumes the existence of a fifth force coupled to baryon number it has to be an attractive force according to the Eötvös results. Obviously this is in contradiction with Fischbach et al. reanalysis. We have seen that the geophysical data instead support the existence of a repulsive medium range force and therefore one could think that these data and the correlation of $\Delta(B/\mu)$ and $\Delta a/g$ found by Fischbach et al. in the Eötvös data could not be explained by the same fenomena. However in the next section we will see that an Eötvös-type experiment can not be used to determine the sign and strenght of a would be medium-range force unless the topographical features around the apparatus are taken into account. Since the topography of the site where the

Eötvös experiment was done is not known with the accuracy needed we have to wait for new experiments to be done in order to solve this question.

In the original Eötvös experiment the test bodies (of different compositions) were placed in a brass container. Of course this container has some influence on the outcome of the experiment and Eötvös has corrected his data to account for the use of this brass container. Fischbach et al. [1] in their reanalysis of the Eötvös experiment have used the corrected data. Keiser et al. [40] claim that one should consider the $\Delta a/g$ data of Eötvös and calculate B/μ including the brass container. In doing that they have found that those points (in (fig. 8) where copper is one of the materials of the pair have moved towards the origin more or less along the line fitted by Fischbach. The fitted line for these new points does not differ considerably from the Fischbach et al. line and therefore the value of $f^2\,\varepsilon(R/\lambda)$ obtained from these new points will not differ considerably from the value found by Fischbach et al. and given by (5.4). Keiser et al. have also pointed out that the results of the experiment done by Renner [41] should also be taken into account in Fischbach et al. reanalysis. Roll, Krotkov and Dicke [42] have criticized Renner's experiment on the basis that his standard deviations should be 3 times as large. However in spite of these criticisms the Renner's data can not be plotted together with the Eötvös data on the same graph because the two experiments were done in different sites and the influence of topography was not necessarily the same for both (see next section).

Elizalde [37] has also made several criticisms to Fischbach et al. reanalysis. He rose as Keiser et al. [40] did the question of the container and estimated the errors that it could be responsible for. However he seems to ignore the fact that the material of the container was brass since he refers to it as a "cylindrical measuring device of completely unknown composition" (perhaps we should say that in german *messing* means brass and *messen* is the verb to measure). We believe that Elizalde's estimated errors would be smaller if he considered that the composition of the container is known. Elizalde also points out that the table [43] used by Fischbach et al. [1] to average the atomic masses over all isotopes of the elements did not show any errors. Other tables [44] give the errors and the uncertainities in the values of the atomic masses according to him "are in no way small". He claims that the Eötvös data for which copper was used as the reference element should be analyzed separately from the data for which platinum was the reference element. After considering the sources of errors described above and some others we did not mention he founds that the errors obtained from the least-square fit of the data (in the graph $\Delta a/g$ against $\Delta(B/\mu)$ are much bigger than those obtained by Fischbach et al. (in the case of copper data the error in the slope of the line is 7 times bigger). According to Elizalde it is hard to see a correlation between $\Delta a/g$ and $\Delta(B/\mu)$ with such high errors.

But perhaps the most serious criticism to Fischbach et al. reanalysis of the Eötvös experiment was done by Chu and Dicke [47]. They say that if there were horizontal thermal gradients in the Eötvös apparatus they could produce a gentle breeze in it. Since the physical dimensions of the samples attached at the ends of the torsion balance are not necessarily the same, this breeze would act differently on them and therefore would produce a net torque. If that is true we would have a correlation between $\Delta a/g$ and $\Delta(1/\rho)$ or ΔS, where ρ is the density and S is the cross sectional surface area of the sample or its container. Some of the Eötvös data does suggest a correlation between $\Delta a/g$ and $\Delta(1/\rho)$ although the Pt data is not well explained by this model. One of the difficulties of the Chu and Dicke [47] thermal gradient model is that the heat source responsible for the effect would have to produce gradients which are steady and constant over a period of months or years when the experiment was performed.

At the present stage there are a lot of uncertainities about the Fischbach et al. reanalysis of the Eötvös experiment that can not be resolved without new experiments. There are several Eötvös-type experiments [45] under way now and there are also some groups doing other types of experiments [46]. Let's wait and see if they come out with new and more precise results that can help claryfing the situation.

6 THE INFLUENCE OF TOPOGRAPHY ON THE RESULTS OF EÖTVÖS-TYPE EXPERIMENTS

As we have seen, if a fifth force does really exist, its range is probably much smaller than the Earth's radius. In this case the intensity and direction of the force experienced by a body on the Earth's surface due to this new interaction can change drastically according to the topography of the region where it is. A large and massive mountain can, in some cases exert a force on it as big as the one exerted by the rest of the Earth altogether. Therefore attention must be paid to the topography when performing experiments to study medium-range interactions. Some authors [39] have studied the effects of topography features on the results of Eötvös-type experiments and some others [46] have used these fenomena to propose new experiments to check the existence of medium-range interactions. Our discussion below is mainly based on Milgrom's paper [39].

Consider a torsion balance, as shown in (fig. 9) where two bodies A and B of different compositions are attached. The force experienced by them can be written in the form,

$$\vec{F}_i = m_i(\vec{g}+\vec{a}) + \vec{f}_i \qquad i = A,B \tag{6.1}$$

where m_i is the gravitational mass of body i, $\vec{g}$ is the gravitational acceleration, $\vec{a}$ is the inertial acceleration due to Earth's rotation and $\vec{f}_i$ is an extra anomalous force due for example to the existence of this fifth interaction or even due to a non-equivalence between inertial and gravitational mass. It is reasonable to suppose that the anomalous force acting on bodies A and B are parallel to each other, and we will write them as $\vec{f}_i = \varepsilon_i m_i \vec{u}$ where $\vec{u}$ is a unit vector in the direction of the anomalous force. The torsion balance supports a torque only along the direction of the wire (see fig. 9) and Milgrom found that the torque is given by,

$$T = \delta\varepsilon\, m_A \vec{r}_A \cdot [\vec{u} \times [\vec{g}+\vec{a}]\vec{k} \quad ,$$

where $\vec{k}$ is the unit vector along the wire (see (fig. 9)), $\delta\varepsilon = \varepsilon_A - \varepsilon_B$, $\vec{r}_A$ is the position vector of the body A with the origin taken at the point 0 (fig. 9). This result is obtained in the approximation that $\vec{g}$ is almost parallel to $\vec{k}$.

If the anomalous force is a medium range one, as the fifth force might be, the direction of the unit vector $\vec{u}$ varies considerably from place to place. Advantage must be taken of this. If $\vec{u}$ is parallel to $(\vec{g}+\vec{a})$ (the downward direction) the torque is null. If $\vec{u}$ is parallel to $\vec{g}$ the torque is $T_{//} \approx (\delta\varepsilon) m_A r_A \sin\theta$, where θ is the latitude of the site where the experiment is being performed. Notice that if the hyperphoton couples to some charge closely proportional to mass, that is the situation where the experiment is performed in an approximately flat region with a homogeneous "strata". However the torque reaches its maximum value when $\vec{u}$ is perpendicular to $(\vec{g}+\vec{a})$. In this case we have $T_{\perp} \approx (\delta\varepsilon) m_A r_A g$ (since $|\vec{g}| \approx |\vec{g}+\vec{a}|$). If we consider that the inertial acceleration is given by $a/g \approx (\cos\theta)\,|290$, we have

$$T_{\perp}/T_{//} = 290/\sin\theta\cos\theta \approx 600/\sin 2\theta \quad .$$

Then the sensitivity of the experiment can increase some orders of magnitude when $\vec{u}$ is perpendicular to $\vec{g}$. For an interaction of range $\lambda \approx 10^2$m this situation can be obtained by performing the experiment at a height λ on the face of a cliff at least 2λ high. If the experiment is performed for example at Rio de Janeiro (latitude $\approx$ 22') at the face of the Corcovado mountain (700m high) the torque will be approximately 860 times higher than the torque observed in the same experiment done in a flat region in Rio.

Another point to note is that if one wants to determine if the medium-range force in question is attractive or repulsive using an Eötvös-type experiment much attention must be paid to the mass distribution surrounding the apparatus. The sign of the torque measured by an experiment performed on the north side of a massive building will be opposite to the sign of the torque measured by an identical experiment performed on the south side of the same building. In fact if the precision of the experiment is high, smaller masses can have the same effect.

As it was pointed out in sections 3 and 5 the geophysical data can be explained by introducing a repulsive medium-range force, while the Eötvös data reanalyzed by Fischbach et al. [1] would need the introduction of an attractive force. This does not necessarily means that the two effects don't have the same cause, since we do not know the mass distribution surroundinσ the Eötvös apparatus in Budapest. It is urgently necessary to repeat this kind of experiments taking into account the topographic features in order to solve this question.

7 THE HYPERPHOTON CAN NOT COUPLE TO HYPERCHARGE. - WHAT ARE THE OTHER CANDIDATES FOR A FIFTH FORCE CHARGE?

The hyperphoton model as it was proposed by Fischbach et al. [1] does not really works. In recent papers, Bouchiat and Iliopoulos [31], Suzuki [32] and Lusignoli and Pugliese [33] have independently shown that the hyperphoton can not couple to hypercharge. They have considered the decay

$$K^+ \to \pi^+ + \gamma' \tag{7.1}$$

where γ' is the hyperphoton. Since weak interactions does not conserve hypercharge, which implies the hyperphoton is massive, Bouchiat and Iliopoulos [31], from whom we reproduce here the essentials of the arguments, considered the above mentioned decay in the presence of weak interaction. The leading contribution to the decay probability for (7.1) summed over the γ' polarizations is given by

$$\sum_{\text{Pol.}} |A|^2 \approx f^2 (q^\mu q^\nu/\mu^2) M_\mu M_\nu \quad , \tag{7.2}$$

where

$$M_\mu = \int d^4x < \pi^+ | T(j'_\mu(x)\ \mathcal{L}_w(0)) | K^+ > e^{iq\cdot x} \quad , \tag{7.3}$$

$j'_\mu(x)$ is the hypercharge current, $\mathcal{L}_w$ the weak interaction Lagrangian. Using current algebra methods, the quantity $q^\mu M_\mu$ is evaluated; the result can be written in the form,

$$q^\mu M_\mu = -i < \pi^+ | \mathcal{L}_w(0) | K^+ > \quad . \tag{7.4}$$

To estimate the matrix element in (7.4) Bouchiat and Iliopoulos appeal to PCAC and the soft-pion limit, to relate it to the amplitude for short-lived neutral kaon decay into pions. Neglecting small CP-violating corrections, the result is,

$$<\pi^+(p)|\mathcal{L}_w(0)|K^+(k)> = 2f_\pi\, A^{os}_{+-}(k,p,o) \quad , \qquad (7.5)$$

where $A^{os}_{+-}(k,p,o)$ is an extrapolation to zero-pion momentum of the K^o_s decay,

$$A^{os}_{+-}(k,p,o) = \lim_{p'\to 0} <\pi^+(p)\pi^-(p')|K^{os}(k)> \quad , \qquad (7.6)$$

which introduces a correction factor, call it, x. A numerical value is $|x|\approx 0.3$. Then one has,

$$\frac{\Gamma(K^+\to\pi^++\gamma')}{\Gamma(K^o_s\to\pi^+\pi^-)} \approx (f^2/\mu^2)4|x|^2 f_\pi^2 \quad . \qquad (7.7)$$

Using the numerical values for f^2, f_π^2 and the kaon decay rates, we obtain the branding ratio,

$$B = \frac{\Gamma(K^+\to\pi^++\gamma')}{\Gamma(K^+\to X)} \approx 2|x|^2 \times 10^{-3} \quad . \qquad (7.8)$$

But the experimental limit for the branching ratio for the decay of the K^+ into π^+ and a slightly massive vector particle is know to be $B_{exp} < 3.8\times 10^{-8}$ [38], which obviously contradicts the expected value (7.8) obtained from the hyperphoton model.

The fact that the coupling to hypercharge is discarded does not invalidate the hyperphoton theory completely. For bulk matter hypercharge and baryon number are the same and the above argument does not apply to baryon number. However other possibilities could be considered too, as the coupling to a linear combination of proton number, neutron number and electron number. For bulk matter we can consider a linear combination of neutron number and proton (or electron) number, since it is electrically neutral. However a coupling to lepton number only seems to be improbable because of the experimental data coming from the study of stellar evolution [46].

8 CONCLUSION

The experimental evidences we have nowadays for the existence of a new intermediary-range force are not very strong and it certainly does not justify the excess of optimism that several people feel about the subject. The fact that geophysical measurements have found values for Newton's constant of gravitation which are about 1% higher than those values measured in laboratory experimants, is perhaps the most relevant contribution to the discussion about a would-be fifth force. It is really intriguing that the geophysical results are confirmed by measurements made in different parts of the world like Gulf of Mexico and Australia, since it is unprobable one can explains these facts on the grounds of possible density inhomogeneities. However one can not take these results as conclusive before the doubts about mass distributions around the mines and also about possible deep departure from the simple layered density structure which the geophysicists assume for the Earth, can be clarified. Geophysical experiments in the sea are perhaps the most promising ones due to the sea homogeneity. By measuring gravity gradients below and above sea level one could make a good test of the hyperphoton theory, since for a Yukawa poten tial the gravity gradient above sea level is very sensitive to variations of the parameters α and λ (see (1.1)). Obviously the main difficulties of such an experiment is the stability of the apparatus one could obtain inside a submarine or on a oil exploration sea platform.

The reanalysis of the Eötvös experiment by Fischbach et al. is vulnerable to several criticisms and it is really hard to draw a confident conclusion from it. We have to wait for the results of new Eötvös-type experiments to be sure of a correlation between the difference in acceleration of two falling bodies and the difference of their ratios of baryon number to mass. However, as remarked by Glashow [34] Fischbach et al. paper has the great merit of bringing to the attention of a wide audience the poor knowledge we have about the validity of Newton's inverse square law at intermediary distances (see (fig. 7)).

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Table 1 Values of G from modern geophysical data

Data source	Type of measurement	Gravity data	Depth range (m)	Density data	$(G\pm\sigma)(10^{-11} m^3 kg^{-1} s^{-2})$
Ref. 12	Mine	21	96–587	∿400	6.795±0.021
Ref. 13	Mine	31	57.3–684.8	47	6.7390±0.0025
		11	57.3–208.5		6.724±0.014
		10	223.1–388.9		6.726±0.012
		10	418.2–684.8		6.746±0.013
		31	57.3–684.8		*6.7427±0.0024
		35	0–684.8		6.7334±0.0037
Ref. 7	Mine	8	0–948	565	6.712±0.037
Ref. 14	Borehole	3	3,712–3,962	16	6.81±0.07
Ref. 15	Mine	7	251–590	53	6.705±0.060
Exxon	Marine Surveys	703	113–687		6.797±0.016

* Result obtained with an assumed deep mass anomaly biasing the gravity profile.
From F.D. Stacey, G.J. Tuck; Nature, 292, 230 (1981). The references are those of Stacey and Tuck.

FIGURE CAPTIONS

Fig. 1 - Schematic diagram of the apparatus used in the experiment by Chen et al. to test Newton's law of gravitation. From Chen et al. [15].

Fig. 2 - The unshaded region represents the allowed values for α and λ, from the results of laboratory experiments. The lower curves are from ref. [11] and [12]. The upper ones from ref. [13].

Fig. 3 - The unshaded region represent the allowed values of the parameters α and λ from the experiments of refs. [11], [12], [15] and [13].

Fig. 4 - Geometry used in the study of the variation of gravity with depth in the Earth. From Stacey et al. [20].

Fig. 5 - The unshaded region corresponds to allowed values for α and λ from geophysical observations. The limits imposed by the laboratory experiments of Long [11] and Spero et al. [12] are also shown, giving an allowed region to the right of the corresponding curves. From F.D. Stacey et al. [20].

Fig. 6 - Curve relating α and λ, obtaining taking λ at a series of fixed values and the corresponding α' by best fit to the data. From S.C. Holding et al.; Phys. Rev. D33 nº 12, 3487 (1986).

Fig. 7 - The unshaded region corresponds to allowed values for α and λ from both geophysical observations and laboratory experiments. Curves a, b, c and g are from laboratory experiments, respectively refs. [12], [11], [13] and [15]. Curves d and e results from geophysical and astronomical observations. Curve f results from calculations for a mine (upper curve) and a submarine experiment (lower curve). From Gibbons and Whiting [35].

Fig. 8 - Correlation exhibited by Fischbach et al. between the difference of accelerations between the components of couples of bodies relative to gravity, and the difference of their

raports of baryon number to mass (in atomic hidrogen units). From Fischbach et al.; Phys. Rev. Lett., 56, nº 1,3 (1986).

Fig. 9 - Schematic illustration of a torsion balance used in Eötvös-type experiments.

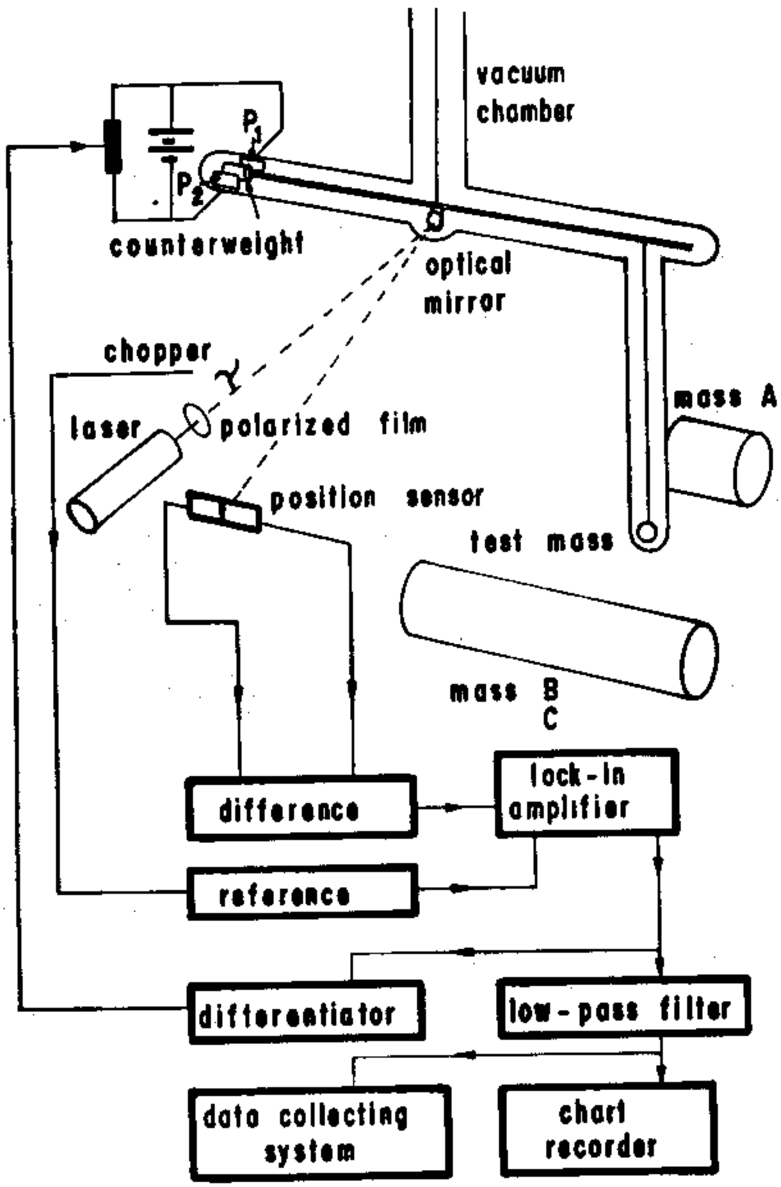
vacuum
chamber
P_1
P_2
counterweight
optical
mirror
chopper
laser
polarized film
mass A
position sensor
test mass
mass B
C
lock-in
amplifier
difference
reference
differentiator
low-pass filter
data collecting
system
chart
recorder

Fig. 1

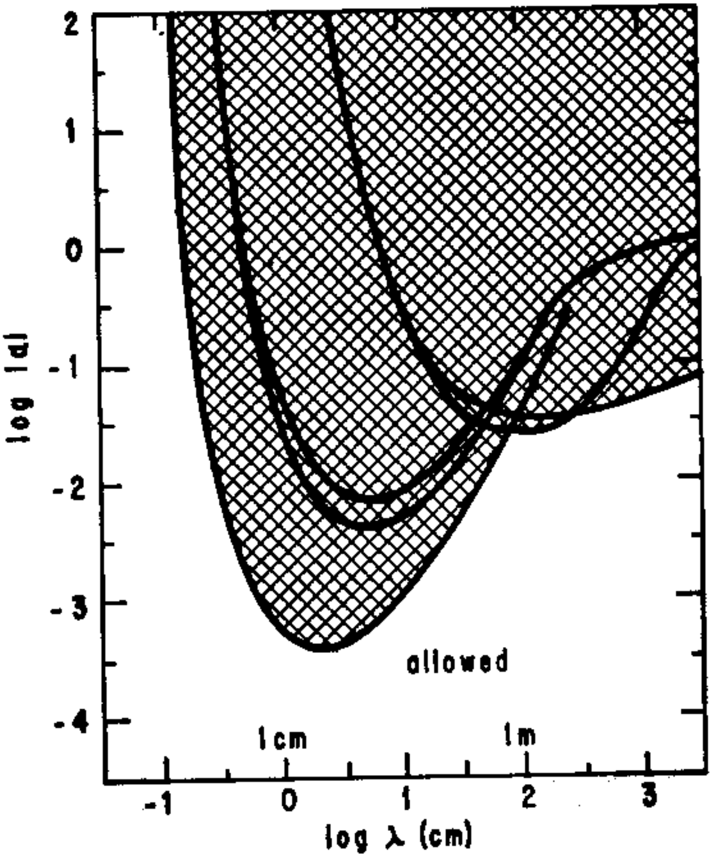

Fig. 2

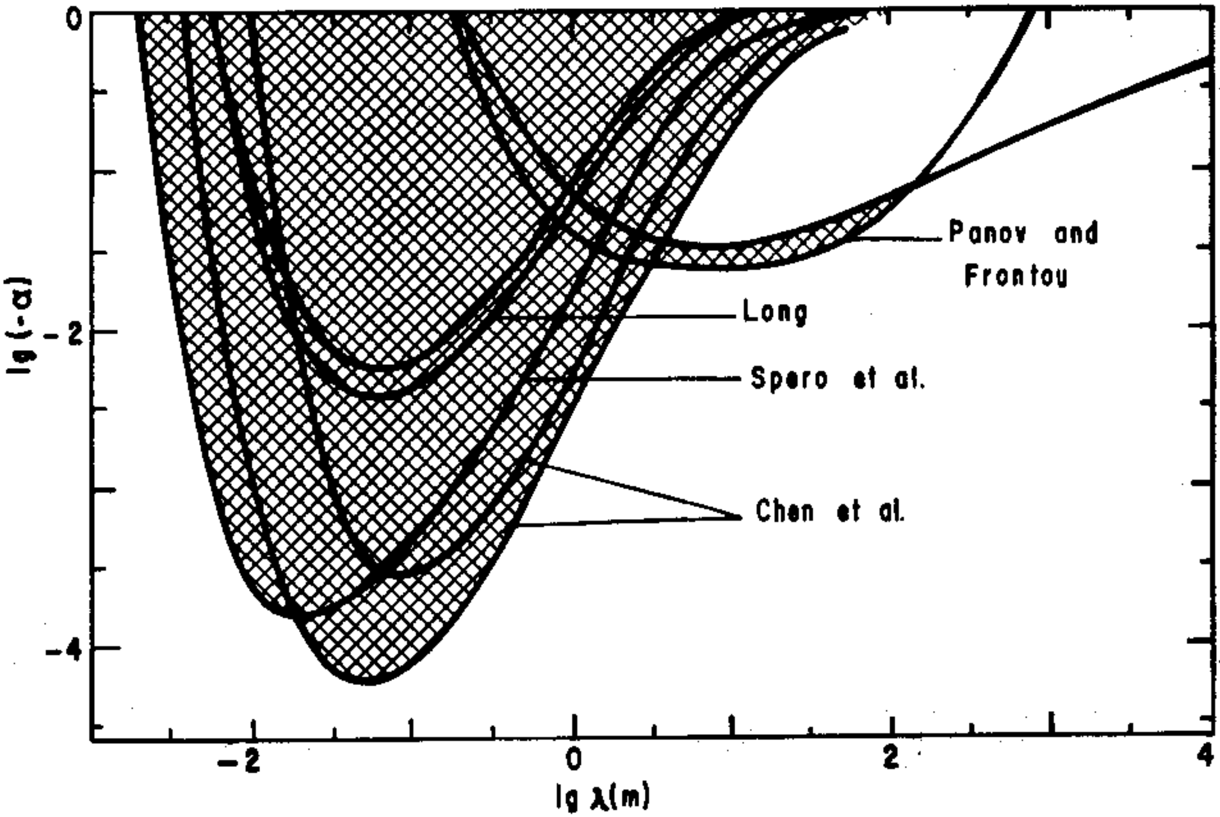
0
-2
-4
lg(-α)
-2
0
2
4
lg λ(m)
Panov and Frontov
Long
Spero et al.
Chen et al.

Fig. 3

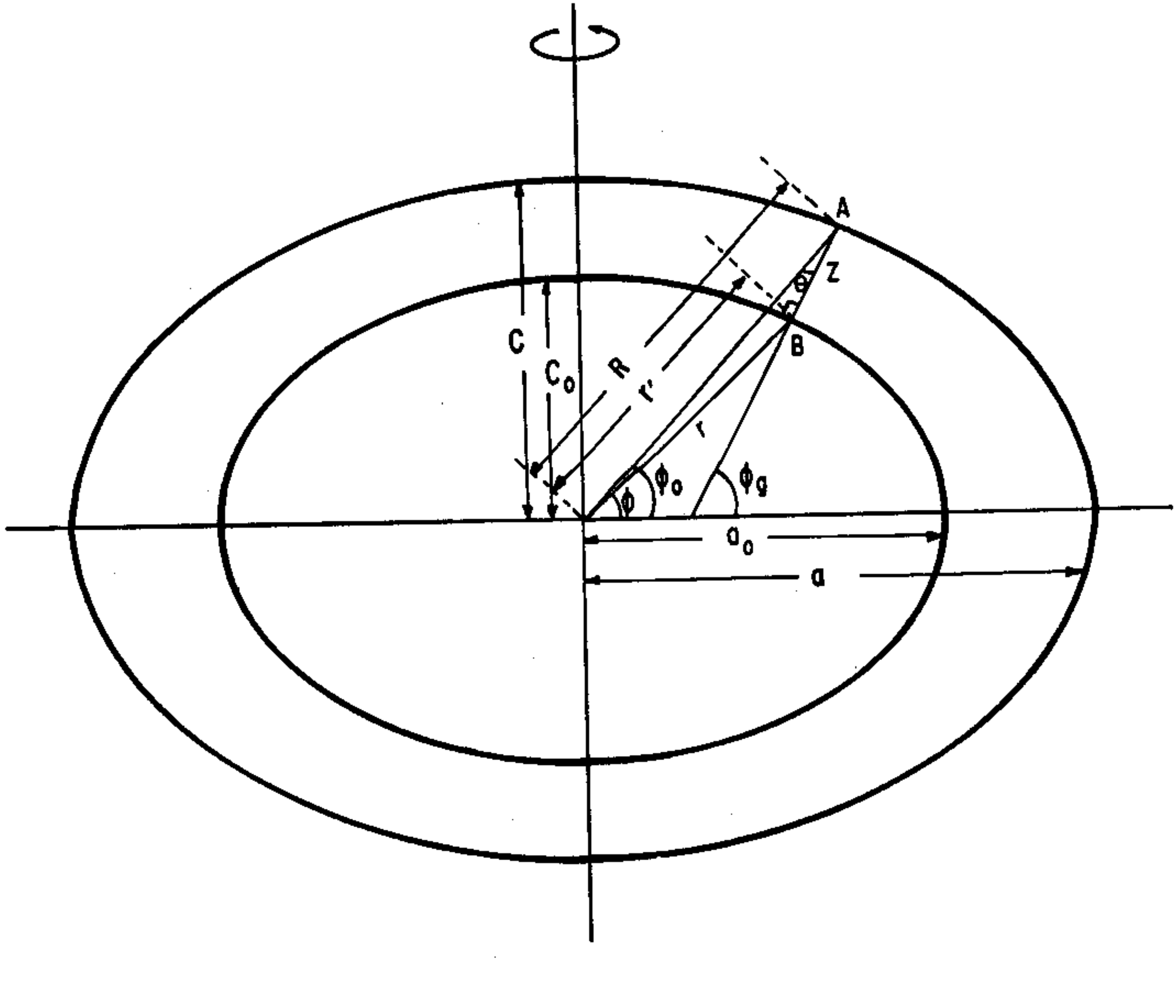

Fig. 4

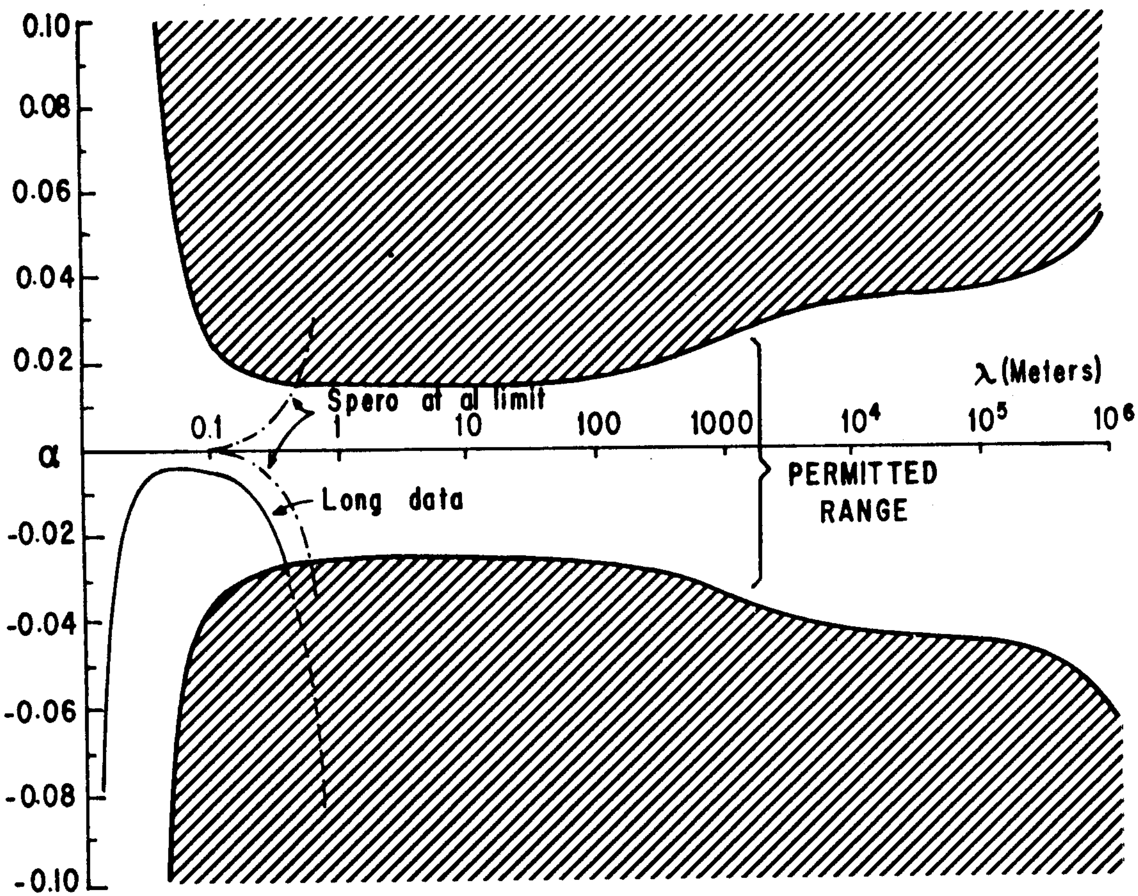
0.10
0.08
0.06
0.04
0.02
α
-0.02
-0.04
-0.06
-0.08
-0.10
λ (Meters)
Spero et al limit
0.1
1
10
100
1000
10^4
10^5
10^6
Long data
PERMITTED
RANGE

Fig. 5

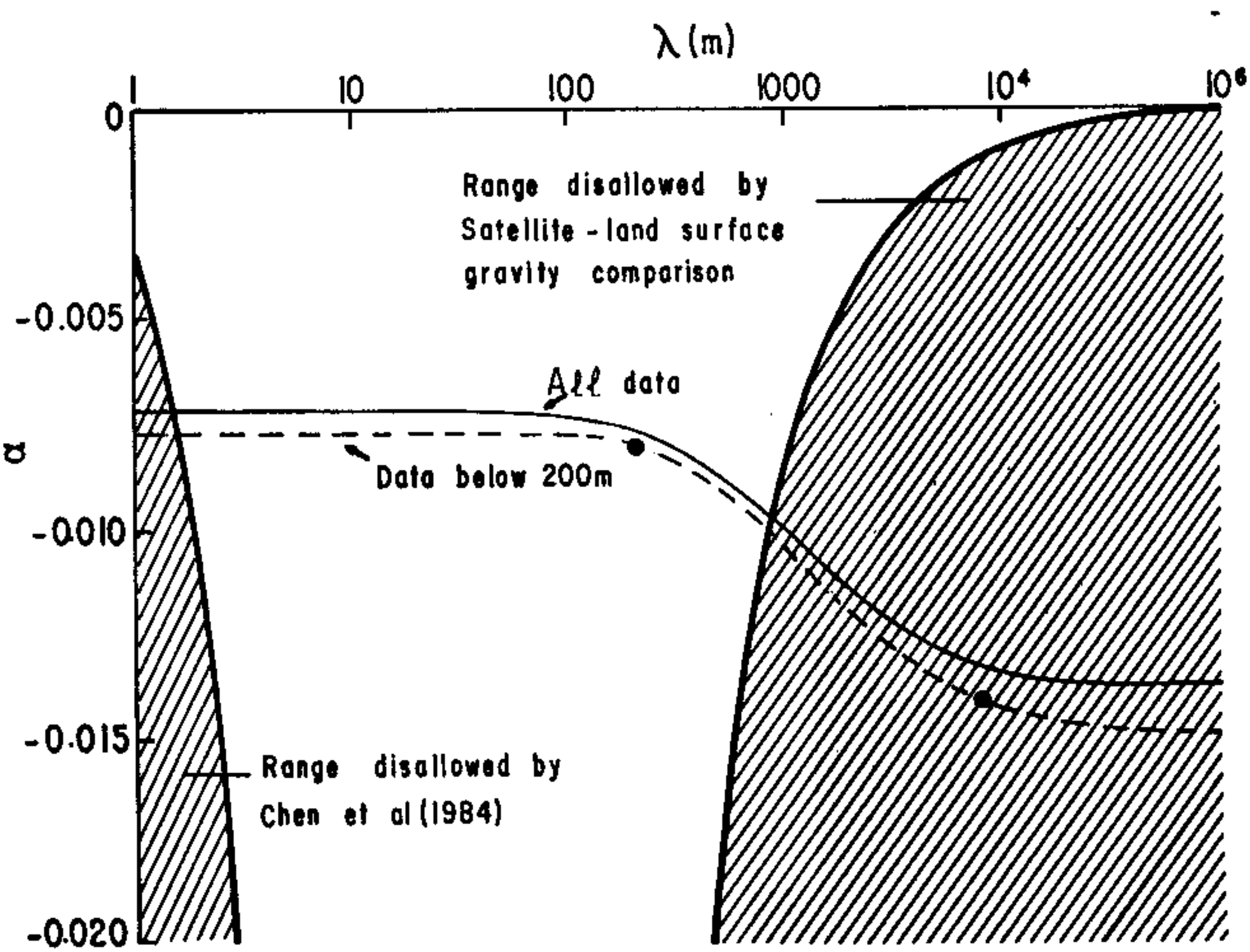
λ(m)
1
10
100
1000
10⁴
10⁶
0
-0.005
-0.010
-0.015
-0.020
α
Range disallowed by
Satellite - land surface
gravity comparison
All data
Data below 200m
Range disallowed by
Chen et al (1984)

Fig. 6

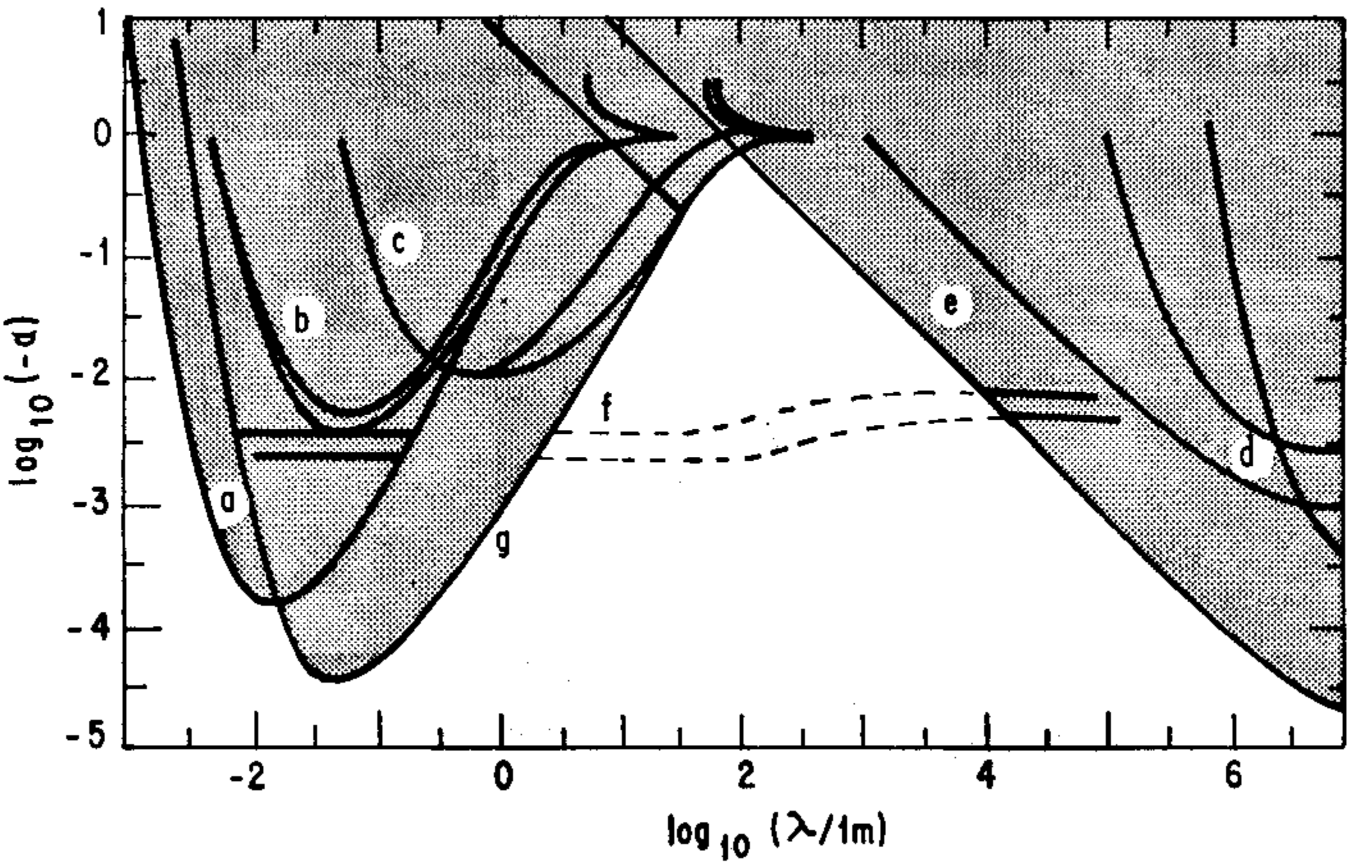

Fig. 7

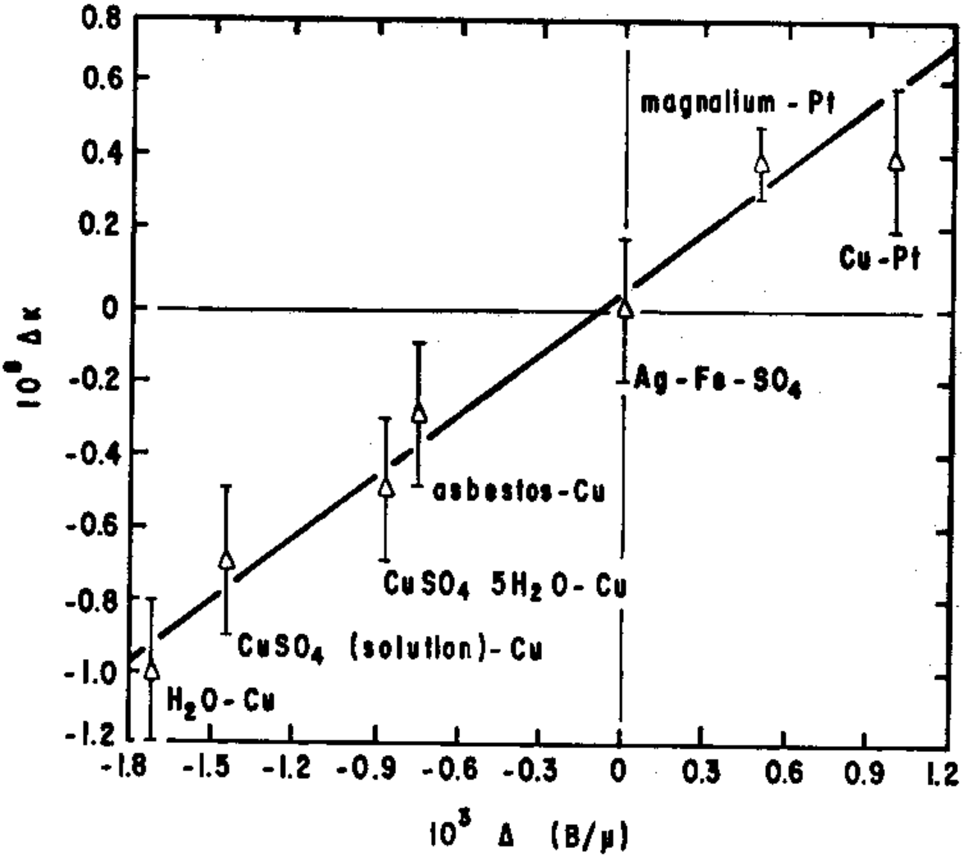
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
$10^8\ \Delta\kappa$
magnalium - Pt
Cu-Pt
Ag-Fe-SO_4
asbestos-Cu
$CuSO_4$ $5H_2O$-Cu
$CuSO_4$ (solution)-Cu
H_2O-Cu
-1.8
-1.5
-1.2
-0.9
-0.6
-0.3
0
0.3
0.6
0.9
1.2
$10^3\ \Delta\ (B/\mu)$

Fig. 8

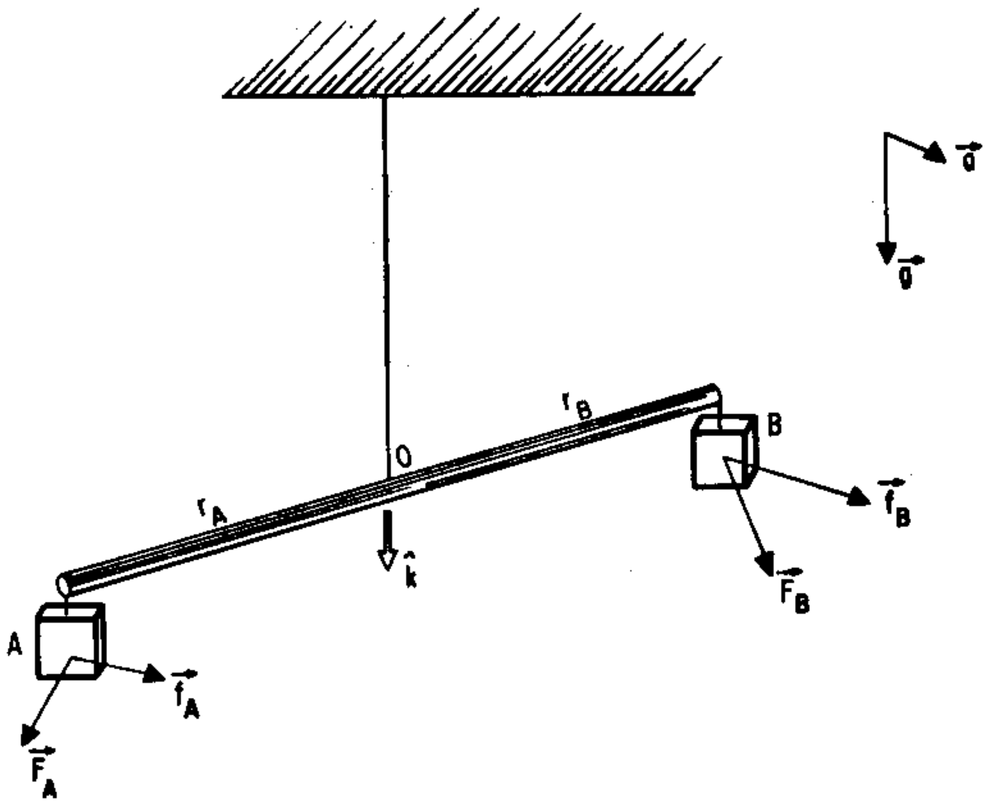

Fig. 9

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Several experiments were proposed and several are under way. Here we list some of them: (from E.Fischback et.al. Univ. of Washington preprint)

Laboratory Eötvös experiments

. D.F.Bartlett [Colorado]

. C.W.F.Everitt and P.Worden [Stanford]

. J.Faller and P.Keyser [JILA, Colorado]

. G.Luther [NBS, Maryland]

. R.Newman and P.Nelson [U. California, Irvine]

Eötvös experiments near a mountain

. E.Adelberger, B.Heckel, F.Raab, and C.Stubbs [U.Washington,Seattle]

. P.Boynton, D.Crosby, P.Ekstrom, and A.Szumilo [U.Washington,Seattle]

. G.Edwards [U.Washington, Seattle]

. R.Newman and P.Nelson [U. California, Irvine]

. P.Thieberger [BNL]

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Other types of experiments proposed to check the existence of the "fifth force" are: (from E.Fischback et. al. Univ. of Washington preprint)

Repetitions of the Galileo experiment

. V.Cavasini, E.Iacopini, E.Polacco, and G.Stefanini [CERN/Pisa]

. J.Faller and T.Niebauer [JILA, Colorado]

. S.Richter [Harris Corp. Florida]

. a.Sakuma [BPIM, Paris]

Other experiments

. E.Amaldi, R.Bizzarri, A.Degasperis, G.Muratori, G.V.Pallotino, G. Pizzella, F.Ricci, and C.Rubbia [Rome and CERN] - An Eötvös experiment using a gravity-wave detector and external rotating masses.

. N.Beverini, et. al. [Pisa, LANL, Rice, Texas A&M, Genoa, Kent State, Case Western Reserve, CERN, NASA/Ames] - Comparison of p and $\bar{p}$ masses at LEAR in a vertical drift tube.

. R.Davisson [U.Washington, Seattle] - Variant of the Kreuzer experiment.

. G.Gabrielse, X.Fei, K.Helmerson, H.Kalinowsky, W.Kells, S.Rolston, R.Tjoelker, and T.A.Trainor [Washington, Mainz, Fermilab] - comparison of p and $\bar{p}$ in a Penning Trap at LEAR.

. H.J.Paik [Maryland] - Measurement of the Laplacian of the gravitational field over various distance scales.

. C.C.Speake and T.J.Quinn [BPIM, Paris] - Beam balance comparison of two masses.

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