TEN YEARS OF THE FIFTH FORCE*

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ABSTRACT

The suggestion in 1986 of a possible gravity-like "fifth" fundamental force renewed interest in the question of whether new macroscopic forces are present in nature. Such forces are predicted in many theories which unify gravity with the other known forces, and their presence can be detected by searching for apparent deviations from the predictions of Newtonian gravity. We review the phenomenology behind searches for a "fifth force", and present a summary of the existing experimental constraints.

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This year marks the 10th anniversary of the "fifth force" hypothesis — the suggestion that there exists in nature a new intermediate range force similar to gravity, and co-existing with it [1-9]. Much of the work carried out during this period has been reported at Moriond, and so it is appropriate to use the occasion of this year's Moriond Workshop to review what we have learned during the past decade.

In the simplest models, a "fifth force" would arise from the exchange of a new ultra-light boson which couples to ordinary matter with a strength comparable to gravity. There are numerous theories of physics at the Planck scale which predict the existence of such ultra-light bosonic fields [3-6], whose effect is to modify the expression for the interaction energy $V(r)$ for two point masses m_1 and m_2:

$$V(r) = \frac{-G_\infty m_1 m_2}{r}(1 + \alpha e^{-r/\lambda}). \tag{1}$$

Here $r = |\vec{r}_1 - \vec{r}_2|$ is the separation of the masses, and G_∞ is the Newtonian gravitational constant for $r \to \infty$. The constants α and λ characterize the strength of the new interaction (relative to gravity), and the range of the new force. Differentiating $V(r)$ leads to the following expression for the force $\vec{F}(r)$, which is what is measured in most experiments:

$$\begin{aligned} \vec{F}(r) &= -\vec{\nabla}V(r) = -G(r)\frac{m_1 m_2 \hat{r}}{r^2}, \\ G(r) &= G_\infty[1 + \alpha(1 + r/\lambda)e^{-r/\lambda}]; G_o \equiv G_\infty(1+\alpha), \end{aligned} \tag{2}$$

We see from Eq.(2) that in the presence of a "fifth force" ($\alpha \neq 0$) the usual inverse-square law breaks down. It follows that a search for deviations from the inverse-square law can be interpreted as a probe for new forces, and hence of physics at the Planck scale. The results of any test of the inverse-square law can then be expressed in terms of an exclusion plot in the $\alpha - \lambda$ plane, as shown in Fig. 1. (In anticipation of the ensuing discussion, we note that tests of the inverse-square law are also referred to as "composition-independent" tests for new forces.)

The stimulation for the fifth force hypothesis in 1986 came in part from the recognition that in many specific theories the parameter α in Eq.(1) is not a fundamental constant of nature, but depends on the chemical compositions of the test masses. To understand how this comes about we consider the coupling of new bosonic field to the baryon number $B = N + Z$, where N and Z denote the numbers of neutrons and protons respectively. The additional potential energy $V_5(r)$ arising from the interaction of masses 1 and 2 is

$$V_5(r) = f^2 \frac{B_1 B_2}{r} e^{-r/\lambda}, \tag{3}$$

where f is a new fundamental constant. It is straightforward to show that the sum of Eq.(3) and the usual Newtonian potential leads to Eq.(1) with α replaced by α_{12},

$$\alpha_{12} = -\xi(B_1/\mu_1)(B_2/\mu_2), \tag{4}$$

where $\xi = f^2/G_\infty m_H^2$, $\mu_{1,2} = m_{1,2}/m_H$, and $m_H = m({}_1H^1)$. It follows from Eqs.(1)-(4) that the acceleration difference $\Delta\vec{a}_{12}$ of 1 and 2 towards the Earth is given by

$$\Delta\vec{a}_{12} = \xi(B/\mu)_\oplus[(B/\mu)_1 - (B/\mu)_2]\vec{\mathcal{F}}, \tag{5}$$

where $\vec{\mathcal{F}}$ is the field strength of the source (in units of acceleration), which in this case is the Earth (denoted by $\oplus$). For a coupling to another charge Q, e.g. isospin $Q = I_z = N - Z$, one merely substitutes $B \to Q$ in Eq.(5). Since $\vec{\mathcal{F}}$ depends explicitly on λ it follows that an experimental limit on $\Delta\vec{a}_{12}$ leads to a constraint among the parameters ξ, λ, and Q. In practice the constraints in the $\xi - \lambda$ plane are usually plotted for different choices of Q, as in Fig. 2 for $Q = B$ and $Q = I_z$.

Figures 1 and 2 respectively give the current (as of March 1996) constraints on composition-independent and composition-dependent deviations from Newtonian gravity. In each figure the shading denotes the regions in the $\alpha - \lambda$ or $\xi - \lambda$ plane which are excluded by the data at the 2σ level. We note that in each graph, the lower boundary of the shaded region is determined by superimposing the results of a number of different experiments. As we discuss in Ref. [9], composition-independent experiments achieve their maximum sensitivity for values of λ comparable to the dimensions of the apparatus, and hence no single experiment can be sensitive to all values of λ. The situation is somewhat different for composition-dependent experiments but, for different reasons, it is again necessary to rely on a collection of experiments over different distance scales [9].

One can summarize the current experimental situation as follows: There is at present no compelling experimental evidence for any deviation from the predictions of Newtonian gravity in either composition-independent or composition-dependent experiments. Although there are some anomalous results which remain to be understood, most notably in the original Eötvös experiment [10], the preponderance of the existing experimental data is incompatible with the presence of any new intermediate-range or long-range forces.

We conclude this discussion by briefly summarizing the status of each of the experiments or analyses in which an anomaly was reported.

(1) *Eötvös, Pekár, and Fekete* (1922); Ref. [10] The EPF data were the first indication of a possible intermediate-range composition-dependent "fifth force". More recent experiments with much higher sensitivity have seen no evidence for such a force, and hence (by implication) suggest that the EPF results are wrong. However, attempts to find significant flaws in their experiment have failed, as have efforts to explain the EPF data in terms of conventional physics. There remains a slight possibility that by virtue of of its configuration and/or its location, the EPF experiment might have been sensitive to a new force to which other experiments were not.

In any case, the origin and interpretation of the EPF results remain a mystery at the present time.

(2) *Long* (1976); Ref. [11] This work was the motivation for the very careful laboratory experiments of Newman and collaborators, as well as other groups (see, for example, Ref. [12]). None of the more recent experiments confirm Long's results. Subsequent analysis by Long himself suggests that he may have been seeing the effects of a tilt of the floor in his laboratory as his test masses were moved.

(3) *Stacey and Tuck* (1981); Ref. [13] This revival of the Airy method for measuring G_0/G_∞ by geophysical means initially found a result higher than the conventional laboratory value for G_0. Following the analysis of terrain bias by Bartlett and Tew [14], Stacey *et al.* re-examined their data and concluded that the discrepancy between their value of G_∞ and G_0 was a consequence of having undersampled the local gravity field at higher elevations.

(4) *Aronson, et al.* (1982); Ref. [15] This analysis of earlier Fermilab data on kaon regeneration presented evidence for an anomalous energy-dependence of the kaon parameters, such as could arise from an external hypercharge field. Since the effects reported in Ref. [15] have not been seen in subsequent experiments, we are led to conclude that the original data were probably biased by some unknown (but conventional) systematic effect. There is, however, a possibility that these results are correct, notwithstanding the later experiments. This arises from the circumstance that the data came from experiments (E-82 and E-425) in which the kaon beam was not horizontal, but entered the ground at a laboratory angle $\theta_L = 8.25\times10^{-3}$rad (to a detector located below ground level). It is straightforward to show that θ_L is related to the angle θ_K seen by the kaons in their proper frame by

$$\tan\theta_K = \gamma\tan\theta_L, \tag{6}$$

where $\gamma = E_K/m_K$ is the usual relativistic factor. For a typical kaon momentum in those experiments, $p_K = 70GeV/c$, $\gamma \cong 140$ and hence $\theta_K \cong 49°$. It follows that the incident kaons in these experiments would have had a large component of momentum *perpendicular* to the Earth, which would not have been the case for the subsequent kaon experiments. It can be shown that motion of a kaon beam perpendicular to a source of a hypercharge field can induce an additional γ-dependence in the kaon parameters [16]. It is thus theoretically possible that the ABCF results are not in conflict with the subsequent experiments, and this could be checked in a number of obvious ways. Similar observations have been made independently by Chardin.

(5) *Thieberger* (1987); Ref. [17] In this experiment a hollow copper sphere floating in a tank of water was observed to move in a direction roughly perpendicular to the face of a cliff on which the apparatus was situated. Although the reported results were compatible with the

original fifth force hypothesis, the results of more sensitive torsion balance experiments carried out subsequently were not. As in the case of the original Eötvös experiment, the implication is that Thieberger's observations can be explained in terms of conventional physics, e.g., as a convection effect.

(6) *Hsui*, (1987); Ref. [18]. This is another determination G_0/G_∞ using the Airy method, based on earlier data from a borehole in Michigan. Since the original measurements were not taken with the present objectives in mind, it is likely that this determination of G_0/G_∞ suffered from the same terrain bias that Stacey, *et al.* encountered. Moreover, a far more serious problem in Hsui's analysis was the imprecise and very limited knowledge of the mass distribution in the region surrounding the borehole, which the author himself noted.

(7) *Boynton, et al.* (1987); [Ref. 19] This torsion balance experiment detected a dependence of the oscillation frequency of a composition-dipole pendant on the orientation of the dipole relative to a cliff. A subsequent repetition of this experiment by the authors using an improved pendant and apparatus saw no effect. Despite efforts to shield the apparatus from stray magnetic fields, it is likely that the original effect was due to a small magnetic impurity in the pendant which coupled to a residual magnetic field.

(8) *Eckhardt, et al.* (1988); [Ref. 20] This was the original WTVD tower experiment in North Carolina which saw evidence for an attractive ("sixth") force. The analysis of terrain bias by Bartlett and Tew [14] suggested that Eckhardt, *et al.*, may have undersampled the local gravity field in low-lying regions surrounding their tower. When the tower results were corrected for this effect, the predicted and observed gravitational accelerations on the tower agreed to within errors. A subsequent experiment by these authors on the WABG tower in Mississippi [21] found agreement with Newtonian gravity, as did experiments on the Erie tower in Colorado [22] and the BREN tower in Nevada [23].

(9) *Ander, et al.* (1989); [24] This was another version of the Airy method, which used a borehole in the Greenland icecap, and observed an anomalous gravity gradient down the borehole. However, this effect could not be attributed unambiguously to a deviation from Newtonian gravity, since it could have also arisen from unexpected mass concentrations in the rock below the ice.

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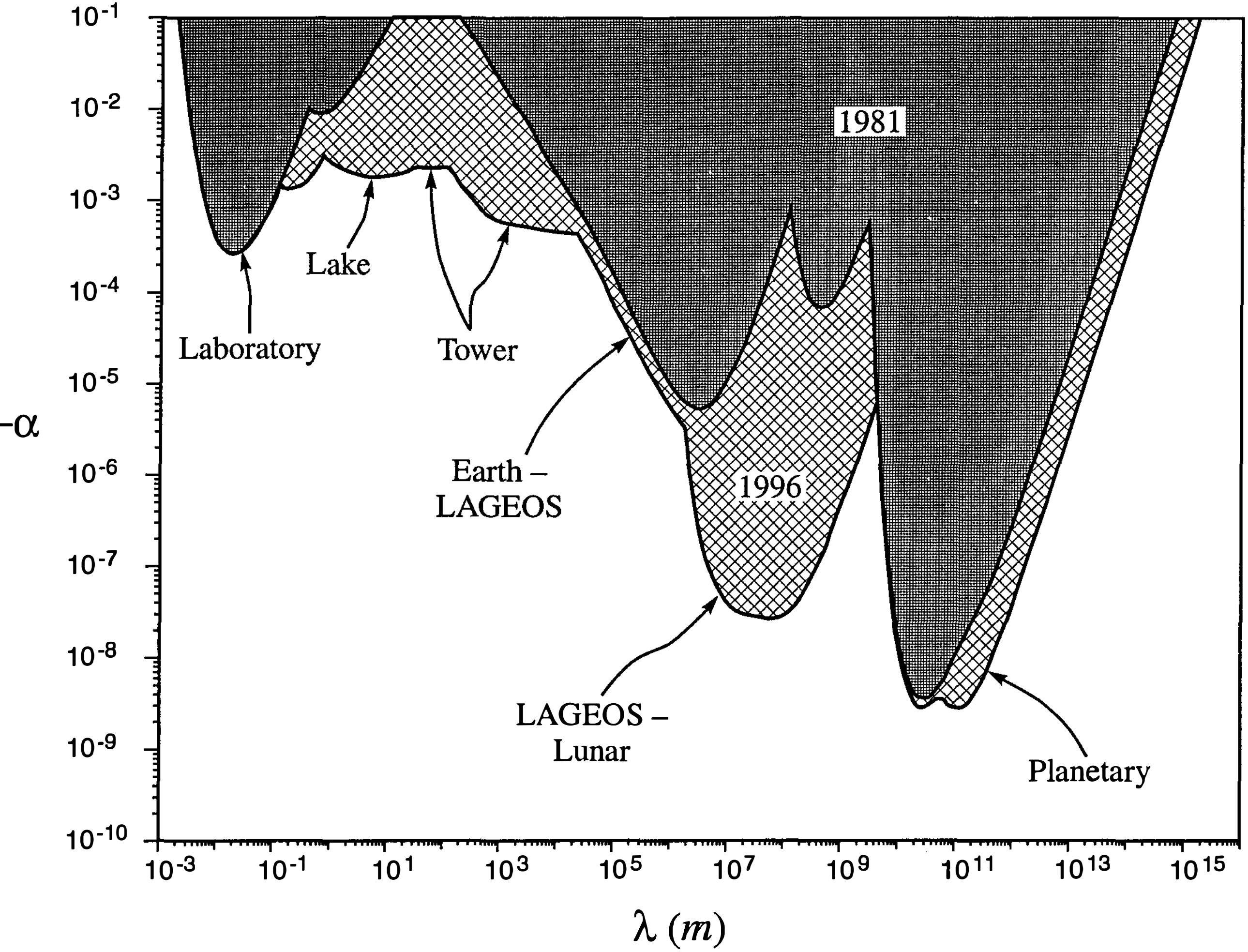

1981
1996
Laboratory
Lake
Tower
Earth – LAGEOS
LAGEOS – Lunar
Planetary
−α
λ (m)

Figure 1

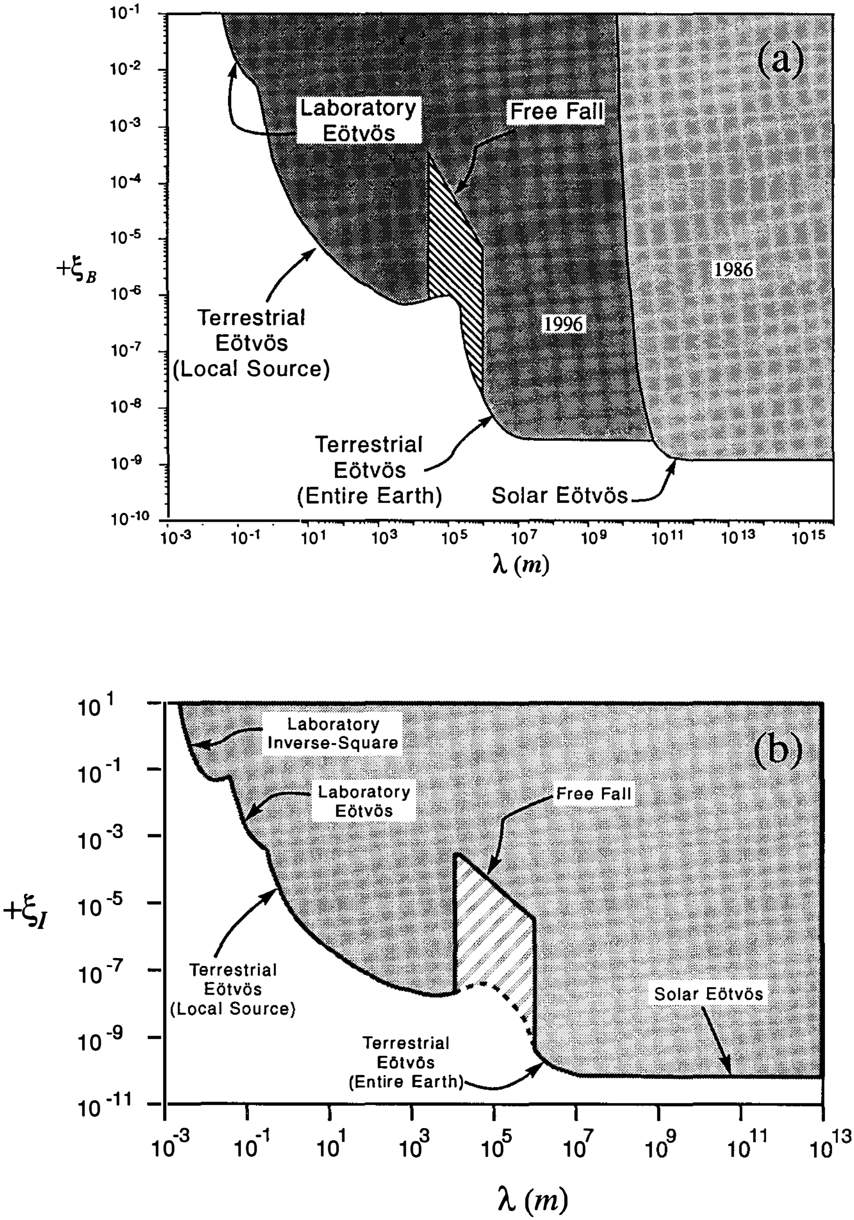
(a)
Laboratory Eötvös
Free Fall
1986
1996
Terrestrial Eötvös (Local Source)
Terrestrial Eötvös (Entire Earth)
Solar Eötvös
$+\xi_B$
$\lambda\ (m)$
(b)
Laboratory Inverse-Square
Laboratory Eötvös
Free Fall
Terrestrial Eötvös (Local Source)
Terrestrial Eötvös (Entire Earth)
Solar Eötvös
$+\xi_I$
$\lambda\ (m)$

Figure 2

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FIGURE CAPTIONS

Figure 1. Constraints on α and λ in Eq.(1) implied by composition-independent experiments. Results are shown as of 1981 and 1996, and in each case the shaded region is excluded at the 2σ level.

Figure 2. Constraints on $\xi_B(a)$ and $\xi_I(b)$ as a function of λ from composition-dependent experiments. ξ_B and ξ_I are the coupling strengths to $B = N + Z$ and $I_Z = N - Z$ respectively. The shaded regions are excluded at the 2σ level.

Résumé

En 1986 il y avait une suggestion qu'il existait une "cinquieme force" macroscopique dans la nature. Cette idée a stimulé un nouvel intérêt dans cette question. On prédit detelles forces dans beaucoup de theories qui unissent la gravité avec d'autres forces connues. On peut trouver cette présence en cherchant des déviations apparantes des prédictions de la théorie de gravité de Newton. Nous révisons donc la phénomenologie des recherches pour une "cinquieme force", et nous présentons une sommaire des résultats experimentaux courants.