

## Short range gravitational fields: Rise and fall of the fifth force

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During the 80's, some experiments and the repetitions of old ones, lead to the hypothesis of a fifth force. Nevertheless, a more accurate research was not able to confirm this hypothesis. This article wants to go over again the most important steps of the event.

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### 1 Introduction

In the study of dynamics, the concept of mass is introduced relatively to the laws of motion; it is therefore called *inertial mass* ( $m_i$ ). It is a universal concept and it concerns with all kind of matter, whether it be a proton or an apple.

Studying gravitation, another kind of mass is introduced instead, which is called *gravitational* ( $m_g$ ), necessary to characterize the intensity of this interaction. It is then possible to divide the gravitational mass in active and passive: this depends on whether it undergoes or generates the gravitational field.

If gravitation is a universal property too, just like the laws of dynamics, then the ratio:

$$k = \frac{m_g}{m_i} \quad (1)$$

does not depend on the type of matter and, choosing the units of measure opportunely, one will obtain  $k = 1$ . This choice is implicitly made when the universal gravitational constant  $G$  is defined, therefore the constance of  $k$  is equal to that of  $G$ .

This is the so called *principle of weak equivalence*, to be distinguished from other forms of the principle of equivalence (medium and strong) which regards other aspects of the gravitational theory, more linked with the theory of general relativity (see [10]).

The most famous experiment to verify the principle of equivalence is, without doubt, that made by Galileo Galilei at the beginning of XVII century. Other experiments followed, by Newton, Huygens, Bessel just to quote some of them. An important step was realized by von Eötvös in 1889 and in 1922, obtaining an accuracy of  $5 \cdot 10^{-8}$  [34]. Later on, in

1964 Roll, Krotov and Dicke reached  $10^{-11}$ , using the gravitational field of the Sun [23]. Again, other experiments were made, especially on an interplanetary scale, which confirmed the validity of the principle of equivalence (see [10], [35]). On a geophysical scale instead, one had stopped at von Eötvös results of 1922.

### 2 The first skirmishes

In 1981, an article by Stacey, Tuck, Holding, Maher and Morris was published dealing with some anomalous measures of the universal gravitational constant  $G$ , made in a mine site in Queensland, Australia [26]. In this article and in others, Stacey's group underlines a value of  $G$ , obtained through the measures of the acceleration of gravity  $g$  in mines, also considering many corrective factors [17], [26]. Therefore they think that the explanation of this anomaly lies in the presence of a short-range potential, of the Yukawa type, that overlaps the newtonian potential:

$$U = -G_\infty \frac{m}{r} (1 + \alpha e^{-\frac{r}{\lambda}}) \quad (2)$$

where  $\alpha$  and  $\lambda$  are respectively the intensity and the action range of the Yukawa type potential and  $G_\infty$  is the value of  $G$  going to infinite, where Eq. (2) is to be reduced to the traditional Newton equation. The principle of equivalence has as consequence the constance of  $G$  in time and space, therefore a variation on geophysical scale would lead to the negation of the very principle. As far as Eq. (2), for  $r \ll \lambda$  one would have:

$$G(r) \approx G_\infty (1 + \alpha - \frac{\alpha r^2}{2\lambda^2} + \dots) \quad (3)$$

Therefore, a new type of interaction, which should be added to the other four known, that is the gravitational, the electromagnetic and the strong and weak nuclear interaction (actually they should be three, because the electromagnetic and the weak nuclear were unified at the end of the 70's by A. Salam, S. Glashow, S. Weinberg and the experimental test was achieved thanks to C. Rubbia at the beginning of the 80's).

To these achievements, an article by Fischbach *et al.* [13] was to be added soon. After a reanalysis of the experiments lead by von Eötvös on the principle of equivalence between the inertial and gravitational mass [34], Fischbach *et al.* find out a similar course and attributes it to a short-range interaction depending upon the material. From the authors' viewpoint this interaction had not been observed in the most precise experiment by Roll, Krotov and Dicke [23], for these are referred to the Sun and to a wide distance that makes the potential effects of this new interaction negligible. As a matter of facts, the two parameters  $\alpha$  and  $\lambda$  which appear in Eq. (2) and which would be respectively the intensity and action range of the fifth interaction, have these values:  $|\alpha| \approx 10^{-2} \div 10^{-3}$  and  $1 \leq \lambda \leq 10^4$  m.

### 3 A nest of hornets

At this point a nest of hornets was stirred up: a pair of comments, meant to stress some thoughtlesses, were directed towards Fischbach's group, in particular to notify a wrong sign for  $\alpha$  [19], [31]: Fischbach *et al.* [13] spoke about a repulsive force though their analysis showed an attractive one. To these objections the authors answered that the sign change did not invalidate the global reasoning [14]. However, one has to mark that the sign  $\alpha$  will change several times, as well as the limits of  $\lambda$ , insomuch that the evolution of these two parameters results more complicated than a hiccupping snake's route.

Stacey's group shows up to help Fischbach's group with a new analysis of the anomalies took in the mines [17], [27], [28] and three other experiments. The first one was carried out by Thieberger [30], realizing an experiment based upon a hollow copper sphere bathed into water and free to move about: this should make it possible to measure the differences of acceleration between liquid and solid. Thieberger put the instrument on an precipice on the Hudson River, New Jersey: this is already something that puzzles us because it did not seem a good idea to place oneself near a river, therefore near to a flux of variable mass, to make an extremely accurate gravitational experiment. Anyway, Thieberger himself, in a footnote at the end of the article [30], reported that M. L. Good made him notice that the Coriolis' acceleration was not negligible in those circumstances and taking

this under consideration reduces the deviation of the measured  $G$ . A similar experiment made in Italy by Bizzeti *et al.* [7] did not point out notable variations.

The second one is a group led by Boynton, that repeats von Eötvös' experiment though in two different places; first on a precipice on the North Cascades, near to Index, Washington, then in a building of the department in Seattle [9]. Some deviations from the value of  $G$  are noticed, though the disturbances may be held responsible again.

A third experiment is made by Eckhardt *et al.* [11]: it consists in the measuring of the gravitational acceleration at ground level and at various distances from the ground, by climbing up a telecasting tower of 600 m. The experiment showed immediately its very limits: in a commentary, Bartlett and Tew proved that the effect of the surrounding ground had been underestimated [4]. Eckhardt group's questioned the feasibility of Bartlett and Tew's analytical method though not the possibility of a presence of ground effects [12] and, in a later and more accurate data analysis, the anomaly disappears [18].

In that period, a number of experiments were made, but they all gave negative results: on towers [25], [32]; the typical experiment of the free fall from a tower [21]; on a wider scale with submarine measures [36] or also near a channel's lock [5].

### 4 Is the Earth a perfect sphere?

There are other very important experiments: in 1990, Thomas and Vogel [33] wrote a very witty and interesting article disheartening many ideas of Stacey's group. The first, and perhaps the most important point, is that in the newtonian gravitational law, Earth is considered to be a homogeneous sphere, uniform and not-spinning. The famous formula:

$$U(r) = -G \frac{m}{r} \quad (4)$$

is referred to a perfect sphere. Nevertheless, reality is a little bit different and the Earth is lightly crushed at the poles, being therefore a spheroid. What is more, it is not even stationary, homogeneous and uniform. One can remember that the Earth is spinning, introducing a centrifugal potential:

$$U_c(r, \varphi) = \frac{1}{2} \omega^2 r^2 \cos^2 \varphi \quad (5)$$

where  $\omega$  represents the angular velocity and  $\varphi$  the latitude. The crushing of the poles instead produces a deformation of the gravitational field, expressible with a series of spherical harmonics:

$$U(r, \theta, \phi) = G \frac{m}{r} \sum_{n=0}^{\infty} \left(\frac{a}{r}\right)^2 \times \sum_{m=0}^n (A_n^m \cos m\phi + B_n^m \sin m\phi) P_n^m(\theta) \quad (6)$$

where  $a$  is the equatorial radius,  $\phi$  is the longitude,  $\theta$  is the colatitude and  $P_n^m(\theta)$  are Legendre's normalized functions in degree  $n$  and in order  $m$ . Eq. (6) describes the gravitational potential of the Earth as the sum of the potentials of endless ideal masses (monopoles, dipoles, ...), centred in the origin and with a statistic weight, due to the coefficients  $A_n^m$  and  $B_n^m$ . Eq. (6) can be considerably simplified taking under consideration various symmetries and geometries (see [6], [8]); therefore at the end of the process one can write:

$$U_s(r, \varphi) = -G \frac{m}{r} \left[ 1 - J_2 \left(\frac{a}{r}\right)^2 \frac{(3 \sin^2 \varphi - 1)}{2} \right] \quad (7)$$

where  $J_2 = 1.082626 \cdot 10^{-3}$  is the (dimensionless) coefficient of ellipticity of the Earth spheroid. Eq. (7) says that, in terms of spherical harmonics, the contribution of the quadrupoles is the most important one, after the newtonian potential, which is the first term of the series.

Then, the Earth gravitational potential can be expressed, with proper approximation, as:

$$U = U_s + U_c \quad (8)$$

Eq. (7) is very important, because it shows that the sole fact that the Earth is a spheroid, and not a sphere, involves an additional term of about  $10^{-3}$ , very near to that of  $\alpha$ , which shows the intensity of the Yukawa type potential.

There are further factors of correction to be notified. For example the correction for free air refers to anomalies introduced by observations above sea level and it can be given with the formula (see [8]):

$$g_a = -0.3086 \cdot 10^{-5} \cdot h \quad (9)$$

where  $h$  is the elevation above sea level. It is to be noticed that being  $g/h$  expressed in  $s^{-2}$ , Eq. (9) is valid both in SI ( $g_a$  in  $m/s^2$ ;  $h$  in m), and CGS ( $g_a$  in  $cm/s^2$ ;  $h$  in cm).

Bouguer's correction instead, takes under consideration the additional masses above sea level, considering them as flat, endless, homogeneous slabs, equal in thickness to the altitude of the point of observation. Supposing that the mean typical density of the Earth's crust is equal to  $2760 \text{ kg/m}^3$ , Bouguer's corrections turns out to be (see [8]):

$$g_B = 0.1119 \cdot 10^{-5} \cdot h \quad (10)$$

What has just been said about unity of measure is valid here as well. Using this anomaly, along with the study of seismic waves propagation, it was possible to identify the Chicxulub crater, where the catastrophic impact, leading to dinosaurs extinction 65 millions of years ago, probably took place [16]. In this case, the comparison with seismic data allows to consider this research as an indirect evidence for the classical theory validity.

Going back to Thomas and Vogel's article, they report a series of measure of gravity, taken near the sites for nuclear American tests in Nevada [33]. In this case the  $G$  value has undergone deviations up to a 4% rate, against the 1% in Stacey's measures. However, from the seismic analysis of the nuclear explosion, it has been possible to discover a reflection barrier at 10 km of depth that makes one suppose the existence of high density material, such to generate anomalous potential gradients. If, at this point, one analyses Stacey group's data, it will grow extremely probable that the anomaly hypothesis is due to the presence of some high density material, which is quite common in a mine. Other experiments, made in Greenland gave similar results [3]: the observed anomalies were due to intrusion in the ice of material at a high density.

There is still a kind of experiment on this scale left, those made by using the variation of the mass in pumped-storage reservoirs for hydroelectric power plants. In 1989, Müller *et al.* [20] traced no significant anomaly, after having taken some measure near Lake Hornberg in Germany. In 1997 instead, Achilli *et al.* [1] obtained a positive result near Lake Brasimone. Making a comparison of the two experiments, one notices some factors which may be crucial: differing from Lake Brasimone, Lake Hornberg has an asphalted ground, therefore water infiltrations are extremely reduced. What is more Müller's group used two gravimeters above and under the lake, while Achilli's group used one only, under the lake. The experimental error in Müller *et al.* is nearly totally due to the calibration of the two gravimeters ( $0.25 \pm 0.4\%$ ); in the case of Achilli *et al.* instead, to obtain a very reduced error (0.1%) a particular device was used, because with the usual method the error was too high (1%).

## 5 How to get rid of local anomalies

Taken into consideration what we said, one may well see that experiments on a geophysical scale are far too dependent on the anomalies of density present in the Earth crust. The possible alternatives are two: the first is to reproduce on laboratory scale the Roll,

Krotov, and Dicke's experiment [23]; the second is to make experiments in space, in situations where the gravitational perturbations would be reduced as much as possible.

The first was made in 1990 [2] and repeated, with some improvements in 1994 [29]: it was called the EötWash experiment. This is, perhaps, the most precise experiment up to now realized on laboratory scale in the terrestrial field. Various contrivances were used to compensate the possible anomalies and, at the end of measurement, the comparison between the inertial and the gravitational mass for two samples of copper and beryllium resulted as [2]:

$$\frac{m_i}{m_g}(\text{Cu}) - \frac{m_i}{m_g}(\text{Be}) = (0.2 \pm 1.0) \cdot 10^{-11} \quad (11)$$

the same order of precision obtained by Roll, Krotov and Dicke [23]. Moreover, Su *et al.* [29] reached about  $10^{-12}$  with several other samples. Therefore they did not find any fifth force, forcing its possible intensity to values still more negligible.

The second possibility, that of experiments in space has not been brought about yet. Many proposals have been made and one counts much on the future *International Space Station*, as research laboratory for experimental physics on gravitational fields [24]. Another experiment called *Galileo Galilei* was accurately elaborated: it is to be performed in space and it should reach a precision of  $10^{-17}$  [22].

## 6 Conclusions?

In March 1992, Fischbach and Talmadge wrote an article to see what the situation was [15]. Their conclusion was that, even though there lacked any evidence for the fifth force, the anomalies found by Thieberger [30] and the Boynton's group [9] were to be explained still. These conclusions are *definitively diplomatic* for they do not underline that it is possible to explain those anomalies by a wrong evaluation of perturbations. As Adelberger *et al.* [2] stress, it was never possible to reproduce these anomalies, not even by the researchers who showed them.

Nevertheless, one has to point out that this episode has spurred a quantity of experiments, which allowed to improve our knowledge of the gravitational field on a small scale.

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