International Journal of Theoretical Physics, Vol. 33, No. 7, 1994

Fundamental Physical Constants and Their Stability: A Review

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Received January 11, 1994

The choice, nature, classification, and precision of determination of fundamental physical constants are described. The problem of temporal variations is also discussed. The need for further determination of absolute measurements of G and time variations of the gravitational constant is pointed out.

1. In any physical theory we meet with constants which characterize the stability properties of different types of matter: of objects, processes, classes of processes, and so on. These constants are important because they arise independently in different situations and have the same value, at any rate within given accuracies. That is why they are called fundamental physical constants (FPC) (Staniukovich and Melnikov, 1983). To define strictly this notion is not possible, because the constants, mainly dimensional, are present in definite physical theories. In the process of scientific progress some theories are replaced by more general ones with their own constants, and relations between old and new constants arise. So, we may not talk about an absolute choice of FPC, but only about the choice corresponding to the present state of the physical sciences.

Quite recently (before the creation of the electroweak interaction theory and some grand unification models) it was considered that this *choice* is

$$c, \hbar, \alpha, G_F, g_s, m_p \text{ (or } m_e), G, H, \rho, \Lambda, k, I$$

where α, G_F, g_s and G are constants of electromagnetic, weak, strong, and gravitational interactions, H, ρ, and Λ are cosmological parameters (Hubble

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0020-7748/94/0700-1569$07.00/0

constant, mean density of the universe, and cosmological constant), and k and I are the Boltzmann constant and the mechanical equivalent of heat, which play the role of conversion factors between temperature on the one hand and mechanical units on the other. After adoption in 1983 of a new definition of the meter ($\lambda = ct$ or $l = ct$) this role is partially played also by the speed of light c. It is now also a conversion factor between units of time (frequency) and length, and is defined with absolute (null) accuracy.

Now, when the theory of electroweak interactions has a firm experimental basis and we have some good models of strong interactions, the more preferable choice is

$$\hbar, (c), e, m_e, \theta_W, G_F, \theta_C, \Lambda_{\mathrm{QCD}}, G, H, \rho, \Lambda, k, I$$

and, possibly, the three Kobayashi–Maskawa angles of θ_2, θ_3, and δ. Here θ_W is the Weinberg angle, θ_C is the Cabibbo angle, and Λ_{QCD} is a cutoff parameter of quantum chromodynamics. Of course, if a theory of the four known interactions is created, then we probably will have another choice. As we see, the macroconstants remain the same, though in some unified models, i.e., in multidimensional ones, they may be related in some manner (see below).

All these constants are known with different *accuracies*. The most precisely defined constant was and remains the speed of light c: its accuracy was 10^{-10} and now it is defined with null accuracy. Atomic constants e, $\hbar$, m, and others are defined with accuracies 10^{-6}–10^{-7}, G with the accuracy 10^{-4}, and θ_W with accuracy 10%; the accuracy of H is also 10%, though several groups give values differing by the factor of 2. An even worse situation now holds with other cosmological parameters (FPC): mean density estimations vary within an order of magnitude; for Λ we have limits above and below, and a zero value is also acceptable.

As to the *nature* of FPC, we may mention several approaches. One of the first hypotheses belongs to J. A. Wheeler: in each cycle of evolution of the universe FPC arise anew along with physical laws which govern its evolution. Thus, the nature of FPC and physical laws is connected with the origin and evolution of our universe.

A less global approach to the nature of dimensional constants suggests that they are needed to make physical relations dimensionless or they are measures of asymptotic states. The speed of light appears in relativistic theories in factors like v/c; at the same time velocities of usual bodies are less than c, so it also plays the role of an asymptotic limit. Other FPC have the same sense: $\hbar$ is the minimal quantum of action, e is the minimal observable charge (if we do not take into account quarks which are not observable in a free state), etc.

Finally, FPC or their combinations may be considered as natural scales defining basic units. If earlier basic units were chosen more or less arbitrarily, i.e., the second, meter, and kilogram, now the first two are based on stable (quantum) phenomena. Their stability is ensured by well-established physical laws which include FPC.

Exact knowledge of FPC and precision measurements are necessary for testing the main physical theories, extending our knowledge of nature, and, in the long run, for practical applications of fundamental theories. Some theoretical problems arise: (1) development of models for confrontation of a theory with experiment in critical situations (i.e., for verification of GR, QED, QCD, or GUT), (2) setting limits for spatial and temporal variations of FPC.

As to *classification* of FPC, we may set them now into four groups according to their generality: (1) Universal constants such as $\hbar$, which divides all phenomena into quantum and nonquantum (micro and macroworlds), and to a certain extent c, which divides all motions into relativistic and nonrelativistic; (2) constants of interactions, like α, θ_W, Λ_{QCD}, and G; (3) constants of elementary constituents of matter, like m_e, m_w, m_x, etc., and (4) transformation multipliers such as k, I, and partially c. Of course, this division into classes is not absolute. Many constants have shifted from one class to another. For example, e was the charge of a particular object, the electron (class 3), then it became a characteristic of class 2 (electromagnetic interaction, $\alpha = e^2/\hbar c$, in combination with $\hbar$ and c), and the speed of light c was nearly in all classes: from class 3 it moved into class 1, then also into class 4. Some of the constants ceased to be fundamental (i.e., densities, magnetic moments, etc.) when they were calculated via other FPC.

As to the *number* of FPC, there are two opposite tendencies: the number of "old" FPC is usually diminished when a new, more general theory is created, but at the same time new fields of science arise, and new processes are discovered in which new constants appear. So, in the long run we may come to some minimal choice which is characterized by one or several FPC, perhaps connected with the so-called Planck parameters—combinations of c, $\hbar$, and G:

$$L = \left(\frac{\hbar G}{c^3}\right)^{1/2} \sim 10^{-33}\,\mathrm{cm}, \qquad m_L = (c\hbar/2G)^{1/2} \sim 10^{-5}\,\mathrm{g}$$

$$\tau_L = L/c \sim 10^{-43}\,\mathrm{sec}$$

The role of these parameters is important, as m_L characterizes the energy of unification of the four known fundamental interactions, strong, weak, electromagnetic, and gravitational, and L is a scale where classical notions of space-time lose their meaning.

2. The problem of the measurement and stability gravitational constant G is part of a very much developing field, called gravitational-relativistic metrology. It appeared due to the growth of precision in measuring technique, the spread of measurements over large scales, and the tendency to the unification of fundamental physical interaction (Melnikov, 1988).

Absolute value measurements of G. There are several laboratory determinations of G with precision of 10^{-3} and four at the level of 10^{-4}. They are (in $10^{-11}\,\mathrm{m^3\,kg^{-1}\,sec^{-2}}$)

1. Facy and Pontikis (France, 1972)	6.6714 ± 0.0006
2. Sagitov *et al.* (USSR, 1979)	6.6745 ± 0.0008
3. Luther and Towler (U.S.A., 1982)	6.6726 ± 0.0005
4. Karagioz (USSR, 1988)	6.6731 ± 0.0004

From this it is seen that the first three experiments contradict each other (they do not overlap within their accuracies), and only the fourth experiment is in accord with the third one.

The official CODATA value of 1986

$$G = (6.67259 \pm 0.00085) \cdot 10^{-11}\,\mathrm{m^3\,kg^{-1}\,sec^{-2}}$$

is based on the Luther and Towler determination. The problem is open and we need further experiments on the absolute value of G. Many groups are preparing and doing them using different techniques, e.g., the Karagioz group (Russia) which had an installation operating already for 2 years continuously (Karagioz *et al.*, 1993).

There exist also some satellite determinations of G (namely GM_{earth}) at the level of 10^{-8} and several geophysical determinations in mines. The last give usually much higher G values than the laboratory ones.

The precise knowledge of G is necessary for the evaluation of the mass of the earth and the planets, their mean density, and in the end for the construction of earth models; for the transition from mechanical to electromagnetic units and back; for the evaluation of other constants through relations between them given by unified theories; and for finding new possible types of interactions and geophysical effects.

The knowledge of the values of the constants has not only a fundamental meaning but also a metrological one. Modern systems of standards are based mainly on stable physical phenomena. So, the stability of constants plays a crucial role. As all physical laws were established and tested during the last two to three centuries in experiments on the earth and in near space, i.e., at rather short space and time intervals in comparison with the radius and age of the universe, the possibility of slow *variations* of constants (i.e., with the rate of evolution of the universe) cannot be excluded *a priori.*

So the supposition about the absolute stability of constants is an extrapolation and must be tested.

3. The problem of variations of FPC arose with attempts to explain the relations between micro and macroworld phenomena. Dirac was the first to introduce (Dirac, 1937) the so-called "large numbers hypothesis" which relates some known very big (or very small) numbers with the dimensionless age of the universe $T \sim 10^{40}$ (age of the universe in seconds, 10^{17}, divided by the characteristic elementary particle time, 10^{-23} sec). He suggested that the ratio of the gravitational to strong interaction strengths, $Gmp^2/\hbar c \sim 10^{-40}$, is inversely proportional to the age of the universe: $Gmp^2/\hbar c \sim T^{-1}$. Then, as the age varies, some constants or their combinations must vary also. Atomic constants seemed to Dirac more stable, so he chose the variation of G as T^{-1}.

After the original Dirac *hypothesis* some new ones appeared and also some generalized *theories* of gravitation admitting the variation of an effective gravitational coupling. We may single out two stages in the development of this field:

1. Study of theories and hypotheses with variations of FPC, their predictions, and confrontation with experiments (1937–1977).
2. Creation of theories admitting variations of an effective gravitational constant in a particular system of units, and analyses of experimental and observational data within these theories (Melnikov and Staniukovich, 1978) (1977–present).

Within the development of the first stage, from the analysis of the whole set of astronomical, astrophysical, geophysical, and laboratory data the conclusion was made (Zaitsev and Melnikov, 1979) that variations of atomic constants are excluded, but variations of the effective gravitational constant in the atomic system of units do not contradict available experimental data at the level 10^{-11}–10^{-12} year^{-1}. Moreover, Canuto *et al.* (1977), Melnikov and Staniukovich (1978), and Zaitsev and Melnikov (1979) worked out that variations of constants are not absolute, but depend on the system of measurement (choice of standards, units, and devices using this or that fundamental interaction). Each fundamental interaction through dynamics, described by the corresponding theory, defines the system of units and the system of basic standards.

Now we review briefly some hypotheses on variations of FPC and experimental tests (Staniukovich and Melnikov, 1983).

Following Dyson (1972), we may introduce dimensionless combinations of micro and macroconstants:

$$a = e^2/\hbar c = 7.3 \times 10^{-3}, \qquad \gamma = Gm^2/\hbar c = 5 \times 10^{-39}$$

$$\beta = G_F m^2 c/\hbar^3 = 9 \times 10^6, \qquad \delta = H\hbar/mc^2 = 10^{-42}$$

$$\varepsilon = \rho G/H^2 = 2 \times 10^{-3}, \qquad t = T/(e^3/mc^3) \approx 10^{40}$$

We see that α, β, and ε are of order 1, and γ and δ are of order 10^{-40}. Nearly all existing hypotheses on variations of FPC may be represented as follows:

Hypothesis 1 (Standard): α, β, γ are constant, $\delta \sim t^{-1}$, $\varepsilon \sim t$. Here we have no variations of G, and δ and ε are defined via cosmological solutions.

Hypothesis 2 (Dirac): $\alpha, \beta, \varepsilon$ are constant, $\gamma \sim t^{-1}$, $\delta \sim t^{-1}$. Then $\dot{G}/G = 5 \times 10^{-11}\,\text{year}^{-1}$ if the age of the universe is taken as $T = 2 \times 10^{10}$ years.

Hypothesis 3 (Gamow): $\gamma/\alpha = Gm^2/e^2 \sim 10^{-37}$, so e^2 or α varies, but $G, \beta, \gamma, \varepsilon = \text{const}$, $\alpha \sim t^{-1}$, $\delta \sim t^{-1}$. Then $\dot{\alpha}/\alpha = 10^{-10}\,\text{year}^{-1}$.

Hypothesis 4 (Teller): Accounting also for deviations of α from 1, one assumes $\alpha^{-1} = \ln \gamma^{-1}$. Then β, ε are constants, $\gamma \sim t^{-1}, \alpha \sim (\ln t)^{-1}$, $\delta \sim t^{-1}$, and

$$\dot{\alpha}/\alpha = 5 \times 10^{-13}\,\text{year}^{-1}$$

The same relations for α and γ were used by Landau, DeWitt, Staniukovich, Terasawa, and others, but in different approaches in comparison with Teller.

Some other variants may be also possible, e.g., Brans–Dicke theory with $G \sim t^{-\tau}$, $\rho \sim t^{\tau-2}$, $r = [2 + (3w/2)]^{-1}$, a combination of Gamov's approach and Brans–Dicke's, etc. (Staniukovich and Melnikov, 1983).

4. There are different astronomical, geophysical, and laboratory *data* on possible variations of FPC.

Astrophysical data:

(a) From a comparison of fine structure ($\sim\alpha^2$) and relativistic fine structure ($\sim\alpha^4$) shifts in the spectra of radiogalaxies Bahcall and Schmidt (1967) obtained

$$[\dot{\alpha}/\alpha| \leq 2 \times 10^{-12}\,\text{year}^{-1}$$

(b) By comparing lines in optical ($\sim Ry = me^4/\hbar^2$) and radio bands of the same sources in galaxies, Baum and Florentin-Nielsen obtained the estimate

$$|\dot{\alpha}/\alpha| \leq 10^{-13}\,\text{year}^{-1}$$

and for extragalactic objects

$$|\dot{\alpha}/\alpha| \leq 10^{-14}\,\text{year}^{-1}$$

(c) From observations of superfine structure in H absorption lines of a distant radiosource Wolf *et al.* (1976) obtained

$$|\alpha^2(m_e/m_p)g_p| < 2 \times 10^{-14}$$

From these data it is seen that hypotheses 3 and 4 are excluded.

The same conclusion is reached on the basis of *geophysical data.*

(a) α-decay of $U_{238} \to Pb_{208}$. Knowing the abundances of U_{236} and P_{238} in rocks and independently the age of these rocks gives the limit

$$|\dot{\alpha}/\alpha| \leq 2 \times 10^{-13} \text{ year}^{-1}$$

(b) The spontaneous fission of U_{238} yields the estimate $|\dot{\alpha}/\alpha| \leq 2.3 \times 10^{-13}$ year^{-1}

(c) Finally, β-decay of Re_{187} to Os_{187} yields

$$|\dot{\alpha}/\alpha| \leq 5 \times 10^{-15} \text{ year}^{-1}$$

All astronomical and geophysical estimations are strongly model-dependent. So, of course, it is always desirable to have *laboratory tests* of variations of FPC.

(a) Such a test was first done by the Russian group at the Committee for Standards (Kolosnitsyn, 1975). Comparing rates of two different types of clocks, one based on the Cs standard and another on the beam molecular generator, they found that $|\dot{\alpha}/\alpha| \leq 10^{-10}$ year^{-1}.

(b) From a similar comparison of Cs standard and SCCG (super conducting cavity generator) clock rates, Turner (1976) obtained the limit

$$|\dot{\alpha}/\alpha| \leq 4.1 \times 10^{-12} \text{ year}^{-1}$$

All these limits were placed on the variation of the fine structure constant. From the analysis of decay rates of K_{40} and Re_{187} the limit on the possible variation of the weak interaction constant was obtained [for the approach for the variation of β, see, e.g., Novello and Rotelli (1972)].

$$|\dot{\beta}/\beta| \leq 10^{-19} \text{ year}^{-1}$$

But the strictest data were obtained by A. Schlyachter (USSR) from the analysis of the ancient natural nuclear reactor data in Gabon, Oklo, an event that took place 2×10^9 years ago:

$$|\dot{G}_s/G_s| < 5 \times 10^{-19} \text{ year}^{-1}, \qquad |\dot{\alpha}/\alpha| < 10^{-17} \text{ year}^{-1}$$

$$|\dot{G}_F/G_F| < 2 \times 10^{-12} \text{ year}^{-1}$$

So, all existing hypotheses on the variation of atomic constants are excluded.

5. We still have no unified theory of all four interactions. There is a good theory of electroweak interactions, models of GUT which include the strong interaction, and also some attempts to create a theory of everything (TOE). As we have no such theory, it is possible to construct systems of measurements based on any of these four interactions. But in practice this is done on the basis of the best worked out theory—electrodynamics (more precisely, QED). Of course, this may be done also on the basis of the gravitational interaction (as it was partially earlier). Then, different units of basic physical quantities arise based on the dynamics of the given interaction, i.e., the atomic (electromagnetic second, defined via the frequency of atomic transitions, or the gravitational second, defined by the mean motion of the earth around the sun (ephemeris time).

It does not follow from anything that these two seconds are always synchronized in time and space. So, in principle, they may evolve relative to each other, for example, with the rate of the evolution of the universe or some other rate.

That is why, in general, variations of the gravitational constant are possible in an atomic system of units ($c, \hbar, m$ are constant) and that of the masses of all particles in a gravitational system of units ($G, \hbar, c$ are constants by definition). In practice we can test only the first variant, as modern basic standards are defined in the atomic system of measurements. Possible variations of FPC could be tested experimentally, but for this it is necessary to develop corresponding theories admitting such variations and their definite effects.

Mathematically these systems of measurement may be realized as two conformally related metric forms. Arbitrary conformal transformations give us a transition to an arbitrary system of measurements.

One way to describe variable gravitational coupling is the introduction of a *scalar field* as an additional variable of the gravitational interaction. This may be done by different means (e.g., Jordan, Brans–Dicke, Canuto, and others). We prefer the variant of gravitational theory with conformal scalar field [Higgs-type field (Bronnikov *et al.*, 1968)] where Einstein's general relativity may be considered as a result of spontaneous symmetry breaking of the conformal symmetry (Domokos, 1976). In our variant spontaneous symmetry breaking of the global gauge invariance leads to nonsingular cosmology (Melnikov, 1979). In addition, we may get variations of the effective gravitational constant in the atomic system of units when $m, c, \hbar$ are constant and variations of all masses in the gravitational system of units ($G, c, \hbar$ are constant). This is done on the basis of approximate (Melnikov and Radynov, 1984) and exact cosmological solutions with local inhomogeneity (Melnikov and Radynov, 1985).

The effective gravitational constant is calculated using equations of motions. Post-Newtonian expansion is also used in order to confront the theory with existing experimental data. Among post-Newtonian parameters the parameter f describing variation of G is included. It is defined as

$$\frac{1}{GM}\frac{d(GM)}{dt}=fH \tag{1}$$

According to Hellings' (1983) data from the Viking mission,

$$\tilde{\gamma}-1=(-1.2\pm 1.6)\times 10^{3}, \qquad f=(4\pm 8)\times 10^{-2} \tag{2}$$

In the theory with conformal Higgs field (Melnikov and Radynov, 1984) we obtained the following relation between f and $\tilde{\gamma}$:

$$f=4(\tilde{\gamma}-1) \tag{3}$$

Using Hellings' data for $\tilde{\gamma}$, we may calculate in our variant f and compare it with f from Hellings (1983). Then we get $f=(-9.6\pm 12.8)\times 10^{-3}$, which agrees with (2) within its accuracy.

We used here only Hellings' data on the variation of G. But the situation with experiment and observations is not so simple. Along with Hellings (1983) there are some other data (Staniukovich and Melnikov, 1983):

1. From the growth of corals, pulsar spin slowdown, etc., one has $|\dot{G}/G|<10^{-10}\text{–}10^{-11}\ \text{year}^{-1}$. Lunar mean motion around the earth and ancient eclipse data give

$$|\dot{G}/G|=(6\pm 2)\times 10^{-11}\ \text{year}^{-1}$$

Reasenberg's (1987) estimates of the same Viking mission as in Hellings (1983) give

$$|\dot{G}/G|<(0\pm 2)\times 10^{-11}\ \text{year}^{-1}$$

2. Hellings' result in the same form is

$$|\dot{G}/G|<(2\pm 4)\times 10^{-12}\ \text{year}^{-1}$$

Acceta *et al.* (1992) find

$$|\dot{G}/G|<(\pm 0.9)\times 10^{-12}\ \text{year}^{-1}$$

As we see, there is a vivid contradiction in these results, so further experiments are necessary for solving the problem of the temporal G variation. The most promising are the planned future missions to Mars.

According to Hellings' estimations, after several years of observation of spacecraft on and around Mars one may have an improvement of an order of magnitude in the testing of $\dot{G}/G$.

As we saw, different theoretical schemes lead to temporal variations of the effective gravitational constant:

1. Empirical models and theories of Dirac's type, where G is replaced by $G(t)$.
2. Numerous scalar–tensor theories of Jordan–Brans–Dicke type, where G depends on the scalar field $\sigma(t)$.
3. Gravitational theories with the conformal scalar field arising in different approaches (Melnikov, 1986; Melnikov *et al.*, 1985).
4. Multidimensional unified theories in which there are dilaton fields and effective scalar fields appear in our four-dimensional space-time from additional dimensions (Melnikov, 1991). They may help also in solving the problem of a changing cosmological constant from Planckian to present values.

As it was shown in Marciano (1984) and Melnikov (1991), temporal variations of FPC are connected with each other in *multidimensional models* of the unification of interactions. So, experimental tests on $\dot{\alpha}/\alpha$ may at the same time be used for estimation of $\dot{G}/G$ and vice versa. Moreover, variations of G are related also to the cosmological parameters ρ, Ω, and q, which gives opportunities of raising the precision of their determination.

As variations of FPC are closely connected with the behavior of internal scale factors, they are a direct probe of properties of extra dimensions and corresponding theories (Ivashchuk and Melnikov, 1988; Bronnikov *et al.*, 1988*a,b*).

Other windows for testing hidden dimensions open when one studies multidimensional models in the spherically symmetric case. Then, as we may see, some deviations from the Newton and Coulomb laws are possible (Fadeev *et al.*, 1991*a–c*; Melnikov and Pronin, 1991; de Sabbata *et al.*, 1992; Bronnikov *et al.*, 1989; Bronnikov and Melnikov, 1992).

ACKNOWLEDGMENTS

The author is very grateful to Prof. M. Novello for the invitation to work at CBPF in June–August 1993.

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