A Cosmological View for the Time - Variation of the Fundamental Constants of Nature

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Abstract

Time variation of constants of nature is still a question of debate among astronomers, physicists, geologists, and palaeontologists. But are the fundamental physical constants really varying in space or time and how changing these parameters may occur?. Paul Dirac was interested in this question in the large number hypothesis (LNH). He arrived by coincidence at the revolutionary hypothesis that the gravitational constant G should be varied inversely with the cosmic time t. LNH sparked off many ideas and arguments about the possibility of time or space variations of the fundamental constants of nature. In this work, we review details and arguments regarding the time and space variation of dimensional and dimensionless constants based on a detailed comparison for the recorded literature over about one and a half-century.

Key Words: Fundamental Constants of Nature, Dirac Large Numbers Hypothesis (LNH), Cosmological Constant.

DOI Number: 10.14704/nq.2020.18.12.NQ20233 **NeuroQuantology 2020; 18(12):18-29**

Introduction

The fundamental constants of Nature plays an important role in the physical theories and divided into two kinds, the universal dimensioned physical constants refers to dimensioned constants, such as, gravitational constant G in $N\ Kg^{-2}\ m^2$, the speed of light c in m/s, Planck's constant h in *Joul.s*, Avogadro constant N_A in mol^{-1}, the elementary charge e in *Colum* or *Statcoulom*, and the cosmological constant Λ in cm^{-2}. The above-mentioned constants all have units in the *SI* system of units or in the *cgs* system of units.

Another kind of fundamental constants of nature is independent of the chosen system of units and given by pure numbers. For this reason, they are thought to be of importance such as, the ratio between the mass of the electron and the mass of the proton, $\mu = m_e/m_p$ and the fine structure constant α. These constants are the same in all units [1].

Classification of the fundamental constants depends on time, and therefore fundamental constants played an important role in the concept synthesizers. They created bridges between concept that were incompatible before that couples to matter [2].

$$\text{space\& time} \rightarrow \text{spacetime}$$

$$\text{particle\& waves} \rightarrow \text{wave function}$$

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Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 20 September 2020 **Accepted:** 22 November 2020

In other words, any constant deviation in time and space would reflect the existence of a massless field Lévy-Leblond (1979) proposed the classification into three types of fundamental constants:

Class A: a characteristic of a particular system (like a mass of the electron).

Class B: characteristic of a class of physical phenomena (like a charge of the electron).

Class C: the universal constants (like the speed of light, Planck constant, gravitation constant, cosmological constant, and the fine structure constant).

Many experiments have tried to find whether the traditional fundamental constants of physics are really constants or not. The notion of time-varying constants goes back to Dirac who expressed the opinion that very large (or small) dimensionless universal constants cannot be pure numeric values and must not occur in the basic laws of physics.

Dirac's large number hypothesis selected a set naturally constants like e, c, and m_e, m_p as constants and showed that:

$$\frac{F_{grav}}{F_{elec}} = \frac{G\, m_p m_e}{e^2/4\pi\epsilon_o} \sim \frac{H_o e^2/4\pi\epsilon_o}{m_e c^3} \sim 10^{-40}$$

Where H_o is Hubble constant and is approximately 70 $km/s/Mpc$ in the present days. But the Hubble constant is not a constant parameter in cosmology (it is inversely proportional to the age of the universe t).

Hence Dirac's large number hypothesis show that the strength of gravity is inversely proportional to the age of the universe ($G \propto 1/t$) and that the mass of the universe is proportional to the square of the universe's age ($M \propto t^2$).

As well as, one can choose the other constants such as; Planck units, in which G, c, and Planck constant are fixed, to show these constants are also varying over the age of the universe. [3].

From a theoretical point of view, there is deeply linked between the constancy of the fundamental constants and Einstein equivalence principle. This principle is the driving idea of theories of gravity from Newton to Einstein. According to Einstein general relativity, the constancy of fundamental constants takes all their importance in the field of the tests of the equivalence principle [540]. The constancy of constants as a test of the equivalence principle is related to the local position invariance, the universality of free fall, Local lorentz invariance, as well as it is at the basis of all metric theories of gravity and implies that all matter fields are universally coupled to a curved spacetime metric $g_{\mu\nu}$ which is call the physical metric, [4].

$$S_{matter}\ (\psi, g_{\mu\nu})$$

If the coupling constants are spatially dependent, then the acceleration of the free fall will be deduced from the action of a point particle (a test mass) embedded in a general relativistic gravitational field$g_{\mu\nu}(x)$, [5].

$$S_{mi} = -\int m_i[\alpha_{EM}, \dots] \sqrt{-g_{\mu\nu}(x) dx^\mu dx^\nu}$$

Where the mass mi of a body, in view of $E_{tot} = mc^2$ is define by $m_i = m_i[\alpha_{EM}, \dots]$, andthe fine-structure constant α_{EM} had become replaced by a space time field $\psi(t, x)$.

In the slow-velocity limit $v' = a_i = g - \nabla \ln m_i = m_i[\alpha_{EM}, \dots]$

The coefficients correlated with the various coupling constants are assumed to be not universal, therefore $a_i \neq a_j$ in case of the composition of body i differs from the composition of body$j$.

Th explicit prediction for the composition values are related to the violation parameters of the equivalence principle.

$$\eta_{ij} = \frac{a_i - a_j}{\langle a \rangle}$$

In general, the violation parameter of the equivalence principle has a complicated dependence on the nuclear composition of bodies i and j during the nuclear interactions.

Results and Discussion

Variation of the Dimensional Constants

In this section, we will demonstrate time - variation for the dimensional constants, G, h, N_A, e, and Λ.In figures 1- 5, the green diamond along with the dashed green line represents the recommended official values of the CODATA-2006. The blue circles indicate the recorded values of mentioned constants in the past. The dashed red line represents the line of best fit. Figure 6, little difference. There is no recommended official value of the cosmological constant as long as the cosmological take a variety of values in different sub universes.

1) Variation of the Gravitational Constant G with Time

As we mentioned before, Dirac's large numbers hypothesis pointing out that the universal gravitational constant G is inversely related to the age of the universe t, $G \propto t^{-1}$, then as the age of the universe varies, some constants must also vary as well [6].

The limit of variation of the gravitational constant with time is due to changing of Earth's radius and other planets. The pressure Pat radius r inside the planet is defined as [7].

$$\frac{dP}{dr} = -\frac{G\,\rho(r)M(r)}{r^2}$$

The possible variation of G is usually characterized by the quantity $\frac{\left(\frac{dG}{dt}\right)}{G} = \frac{G'}{G}$

One way to evaluate the average rate of change in the gravitational constant G with time is by analysing the difference of planets' radii. The first limit of variation in G which is coming from the fact that the radius of Mercury have been varied at most 1 km during the last 4000 million years. The variation ratio is given by:

$$\left|\frac{G'}{G}\right| < 8\,x\,10^{-12}\;yr^{-1}$$

The second limit of variation in G have been occurred in the late stages of stellar evolution. Assuming that the balance between the gravitational force and Fermi degeneracy pressure of the cold electron gas such that the mass scale M_{ch} can be measured by;

$$M_{ch} \sim \left(\frac{\hbar c}{G\,m_N^{\frac{4}{3}}}\right)^{3/2}$$

Which gives the average mass of a neutron star is proportional with sets of the mass scale $\mu \sim M_{ch}$, implies,

$$\frac{G'}{G} = -\frac{2\left(\frac{d\mu}{at}\right)}{3\mu} = -\frac{2\mu'}{3\mu}$$

Using the previous formula and the calculated masses of the neutron stars gives,

$$\frac{\dot{G}}{G} = (-0.6 \pm 2.0).\,10^{-12}yr^{-1}$$

The upper and lower panel of Figure 1 shows respectively a set of 33 high-precision measurements for the values of G since 1798along with its deviation from present official value (the lower panel). The figure explains the measurements and recommended values for G since 1780. The green diamond shows the official value for G was $G = (6.67428 \pm 0.00067)x10^{-11}N\,Kg^{-2}m^2$ in 2007 based on the 2006 CODATA recommended value of the universal Gravitational constant. The gravitational constant has been measured over the last 227 years and we can clearly notice that the measured values of G are varying over the last years. We notice that the measured values of G seem to be periodicity oscillated over the time and around the official value. The current change in gravitational attraction is explained as a result of the Earth's rotational inertia and it's affecting by the curvature of space-time, and be accompanied by variations of the density, which directly affecting G.

The experimental measurements in lower panel of Figure 1 reporting a deviating between the measured values of G and the official value in 2007. Where the highest % deviation from CODATA-2006 value of G has been recorded in 1798 was + *1.19443* when $G = (6.754 \pm 0.04)\ x\ 10^{-11}\ N\ Kg^{-2}\ m^2$, with uncertainty ~ 410 ppm), which is 0.07972 higher than the official value. Whereas the lowest % deviation from CODATA-2006 value of G has been recorded in 1873 was -3.4053 when $G = (6.447 \pm 0.11)$ x $10^{-11}\,N\,Kg^{-2}\,m^2$, with uncertainty 1100 ppm) and it is lower than the official value by 0.022728.

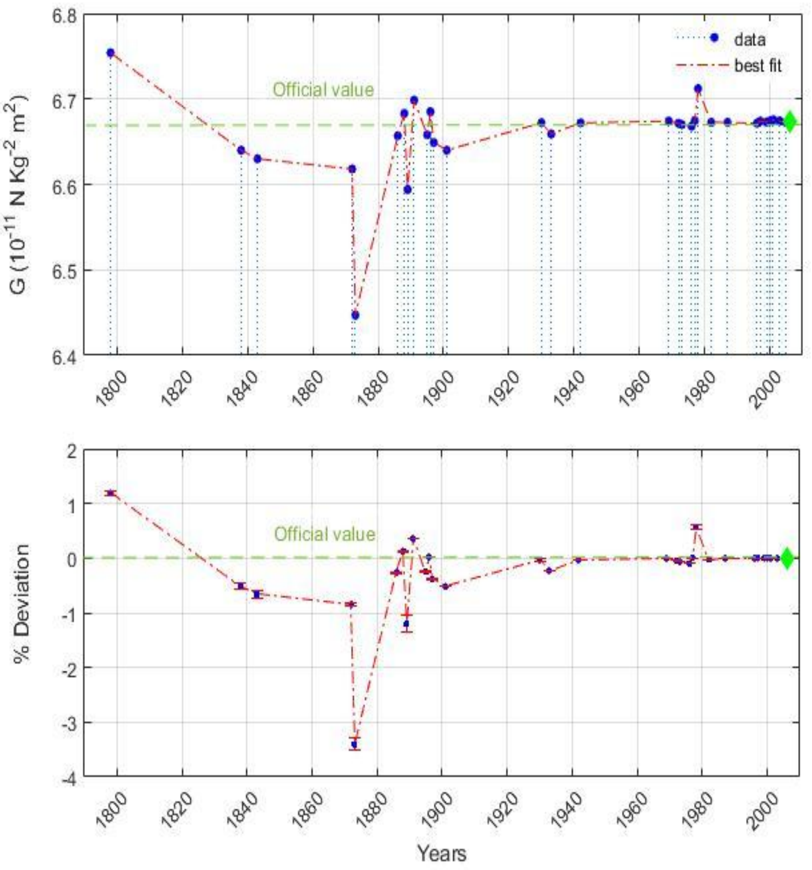

Figure 1. Upper panel, timeline of experimental measurements and official values for G since 1798. Lower panel, the percentage deviation from present official value of G.

2) Variation of Velocity of Light with Time

The varying speed of light plays an important role in the cosmological problems such as the flatness, horizon, and Lambda problems of Big-Bang cosmology, in the quantum gravity as in as a phenomenological project, and in the experiment/observation [9].

In point of view of Einstein's special theory of relativity, the constancy of the speed of light is directly connected to concepts of simultaneity, and according to this theory: the speed of light is constant only in vacuum when light propagation in an expanding universe, but it is varying in dielectric media [10].

The principle of varying speed of light was proposed by Magueijo as an alternative to the inflation theory [11].

Where c is model as: $c = c_o e^{-|\psi|^2}$

Where c_o is refer to the speed of light and it is constant when $t = 0$, and ψ is a scalar field.

Equation of$\psi$is given by,

$$\ddot{\psi} + 3\frac{\dot{a}(t)}{a(t)}\dot{\psi} = 0$$

$a(t)$ is the cosmic scale factor and depends only on time t, and $\dot{a}(t)$ is the expansion scale factor.

The speed of light during ψ dominated epoch.

$$c = c_o t^{\pm\sqrt{\frac{2}{k}}}$$

K is a parameter related to the geometry of space. $K = 0$ corresponds to Euclidean space (a flat universe), $K = +1$ corresponds to spherical and $K = -1$ corresponds to hyperbolic space [12].

According to Magueijo theory, there are two scenarios can be considered in the context of pres etc(t). Machian scenarios and phase transitions. Machian scenarios considered the speed of light varies like a power of the expansion factor $c \propto a^n$. Where n refers to time constraints.

In phase transitions, the speed of light varies suddenly at the critical temperature.

Such variations should be limited to the very early universe and so the c-function [13, 14].

$$c = c_o\left(1 + \left(\frac{a}{a_o}\right)^n\right)$$

Where a_o is a scale factor.The scale factor characterizes the relative size of the spatial sections as a function of time as,

$$(t) = R(t)/R0$$

$$\text{and } \psi = log\left(\frac{c}{c_o}\right)$$

Magueijo assumed c does not change in space (in suitable coordinates) and considered a variation in c in a massive scalar field ψ in flat space-time, such that,

$$c = \frac{c_o}{1 + \frac{c_o t}{R}}$$

Then he concluded that the speed of light goes to infinity at time $t = -\frac{R}{c_o}$, while it is decays to zero, as $t \longrightarrow \infty$. As time progresses the speed of light decays to zero.

Many scientists have been measured the speed of light using different methods. Figure 2 illustrate a graphical representation of the speed of light based on data from literature reviews in between 1780 to 1980. The present official value of the speed of light as is $c = 299{,}792.458 \pm 0.001\ Km/s$. We find that although the speed of light has not significantly changed over the last 200 years, the limits of changing of c have been distributed between the maximum value in 1883 where c = 300. 650 Km/s with a deviation from the present official value +0.2860, and the minimum value in 1979 where c = 299,792.4581±0.0019 with a deviation from the present official value +0.00000003. The percentage error in the two measurements is 0.001 and 0.0009 respectively. It is clear also that the speed of light c has been decreasing in the past which gives an indicates that c does decay with time.

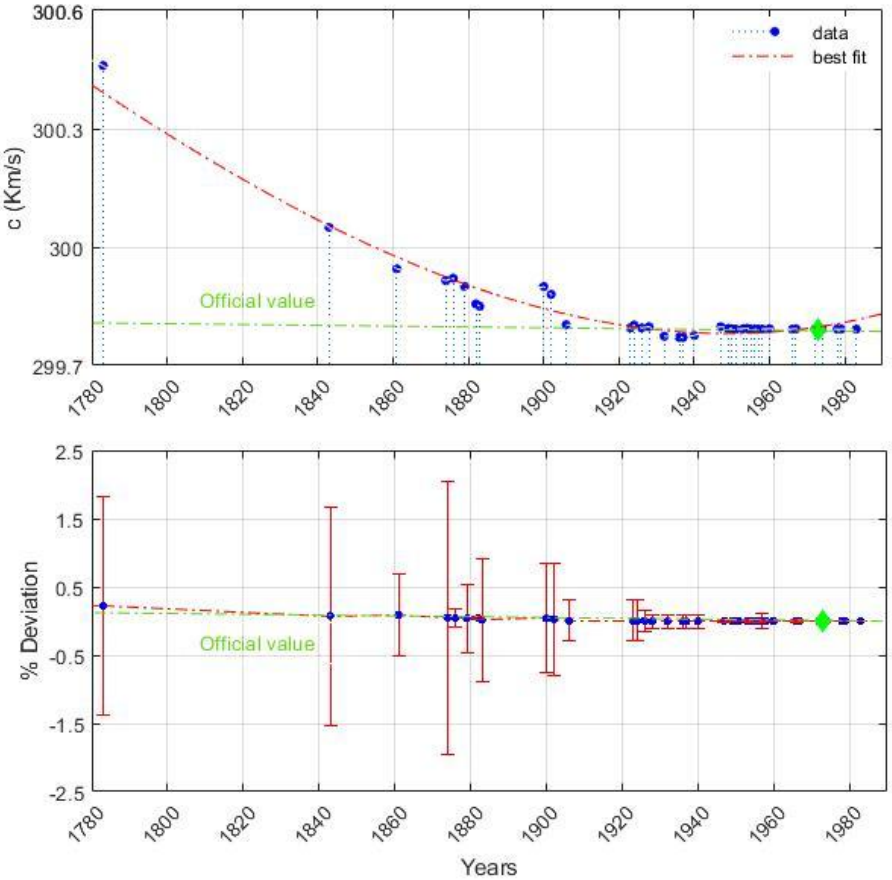

Figure 2. Upper panel, speed of light measurements over the past 200 years. Lower panel, the percentage deviation from present official value of c.

3) Variation of Planck's Constant with Time

Planck's constant h is often considered a time dependent quantity and the Planck length, time and mass follow the Lorentz contraction. The speed of light is different in higher dimensions.

The reduced Planck constant $\hbar = \frac{h}{2\pi}$ enters into the denition of the Heisenberg uncertainty principle [15].

Deformations of the quantum phase space describe by the commutation relation in the case of a Darboux transformation is always possible to express locally the structure as a nontrivial commutator between position and momenta, and all other commuters being zero [16,17].

$$[x^i, p_j] = i\hbar\left(\delta_j^i + f_j^i(x,p)\right)$$

$[x^i, p_j]$ represents two sets of the position and momentum operators at any given instant, and f_j^i depends upon some small parameter.

Random fluctuations of the reduced Planck's constant are introduced via an adimensionalgaussian stochastic variable $\varepsilon(t)$, so that the effective Planck constant reads $\hbar(1+\varepsilon(t))$, with,

$$\overline{\varepsilon(t)} = 0$$

$$\overline{\varepsilon(t)\varepsilon(t')} = \tau\delta(t-t')$$

Where τ is a time parameter and given by $\tau = \sigma^2\Delta t$, where σ is the variance and Δt is a typical correlation time. The previous equation states that fluctuations are uncorrelated for time differences $(t-t') > \Delta t$.

If $\hbar$ fluctuates, then $[x,p] = i\hbar(1+\varepsilon(t))$,

Planck's constant h should be invariant in flat space like mass and light speed, although it might be changed slowly with time, but the possibility of changing is very small and we can't measure it.

In Figure 3, we show the historical values of Planck's constant records from 1950 to the end of 2010.

Figure 3 shows the available literature of Planck's constant in comparison with the official value of the Planck's constant in SI unit recommended by 2006 CODATA ($h = 6.62606896\,(33) \times 10^{-34}\, j.s$).

The figure given here indicates that Planck's constant has changed slowly in the last 30 years and that the difference was less than 5 parts in 10^3 per year. Figure 3 also shows that Planck's constant has significantly changed with time before 1980 and the maximum deviation value was 0.01 in 1973.

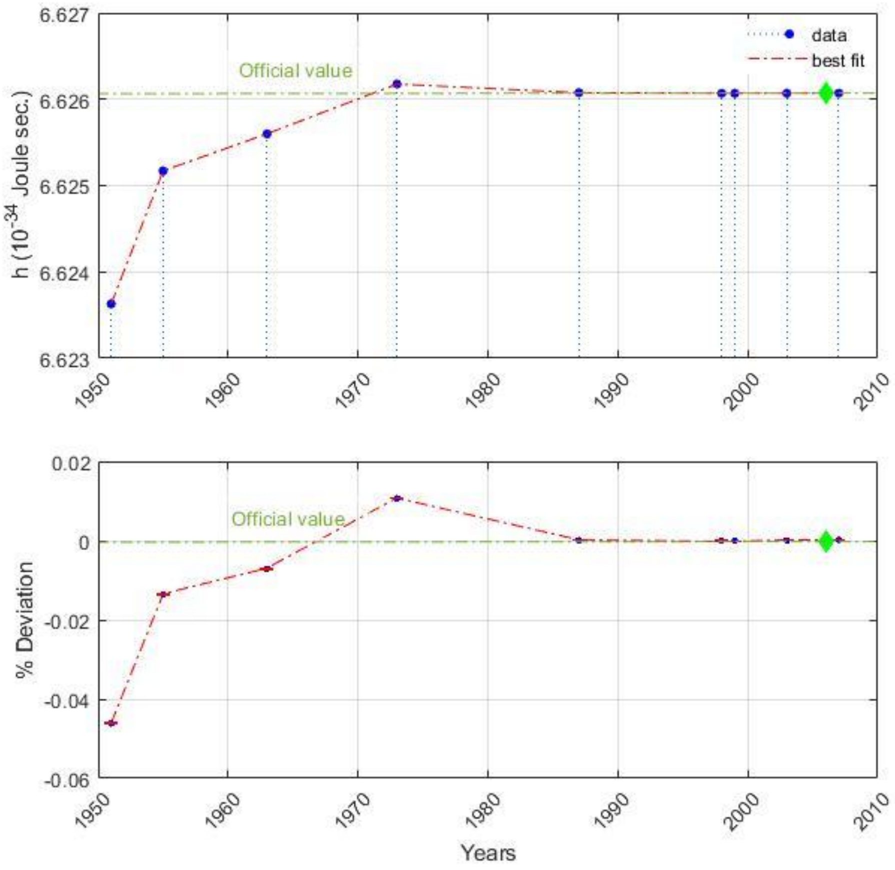

Figure 3. Upper panel, Planck's constant records from 1950 to the end of 2010. Lower panel, the percentage deviation from present official value of h.

4) Variation of Elementary Charge with Time

The most common value of the elementary charge mainly relied on its relationship with the fine structure constant α.

$$e = \sqrt{\frac{2\alpha h}{\mu_o c}}$$

The fundamental elementary charge varies through a dimensionless universal field $\varepsilon(\chi^{\nu})$ defined by $e = e_o \varepsilon(\chi^{\nu})$ [18].

Where e_o is a constant, and $\varepsilon \rightarrow 1$ at infinity.

From the point of view of Dirac's numerical relation, the elementary charge e is changing with the present age of the universe t_{pres}. and e^2 increases proportionally with t_{pres}. According to Dirac's numerical relation,

$$\frac{e^2}{G\,M^2} = t_{pres}\,.$$

Where M the mass of a nucleon, and the present age of the universe t_{pres}. expressed in elementary time units $\frac{\lambda}{c}$.

Figure 4 shows the evolution of the experimental values for the elementary charge from the available literature over one century along with deviation from the official recommended value given by CODATA-2006.

Figure 4 indicates that the values of the elementary charge e are fluctuating in the first period, 1010 – 1960. We see also the increase in deviation accelerated during this period.

Then, in the next period after 1960, e became an adjustable constant. While the deviation seemed to decrease in this period.

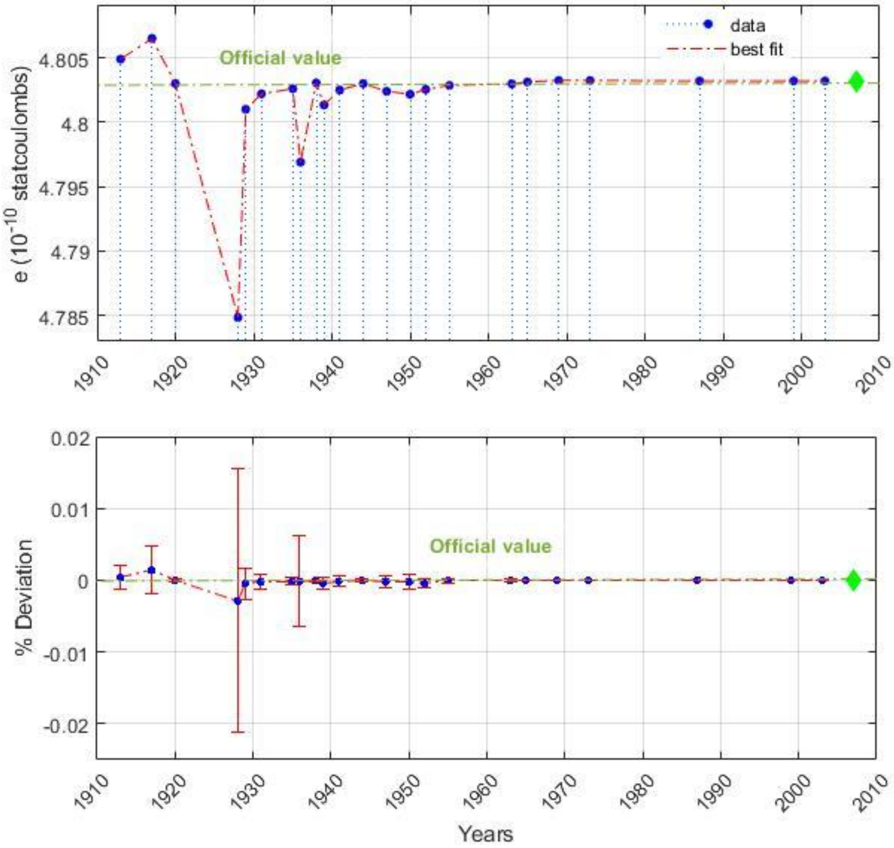

Figure 4. Upper panel: the value of the elementary charge over one century. Lower panel: the relative deviation from the official recommended value in CODATA - 2006.

5) Variation of Avogadro Constant with Time

In general, Avogadro constant NA is related to other dimensional physical constants and properties. It is very closely related to the elementary charge of the electron e, fine-structure constant α, and Planck constant h [19].

Figure 4 depicts in the recorded values of N_A along with its deviation from the official value of CODATA–2006 over the last 140 years. The official recommended value for the Avogadro constant as given by CODATA–2006 is $6.02214179(30) \times 10^{23}\ mol^{-1}$ [20].

As shown in Figure 4, the values of Avogadro constant changed rapidly between 1860 and 1920, while after 1930 the fluctuations in N_A are very closely related to the official recommended value.

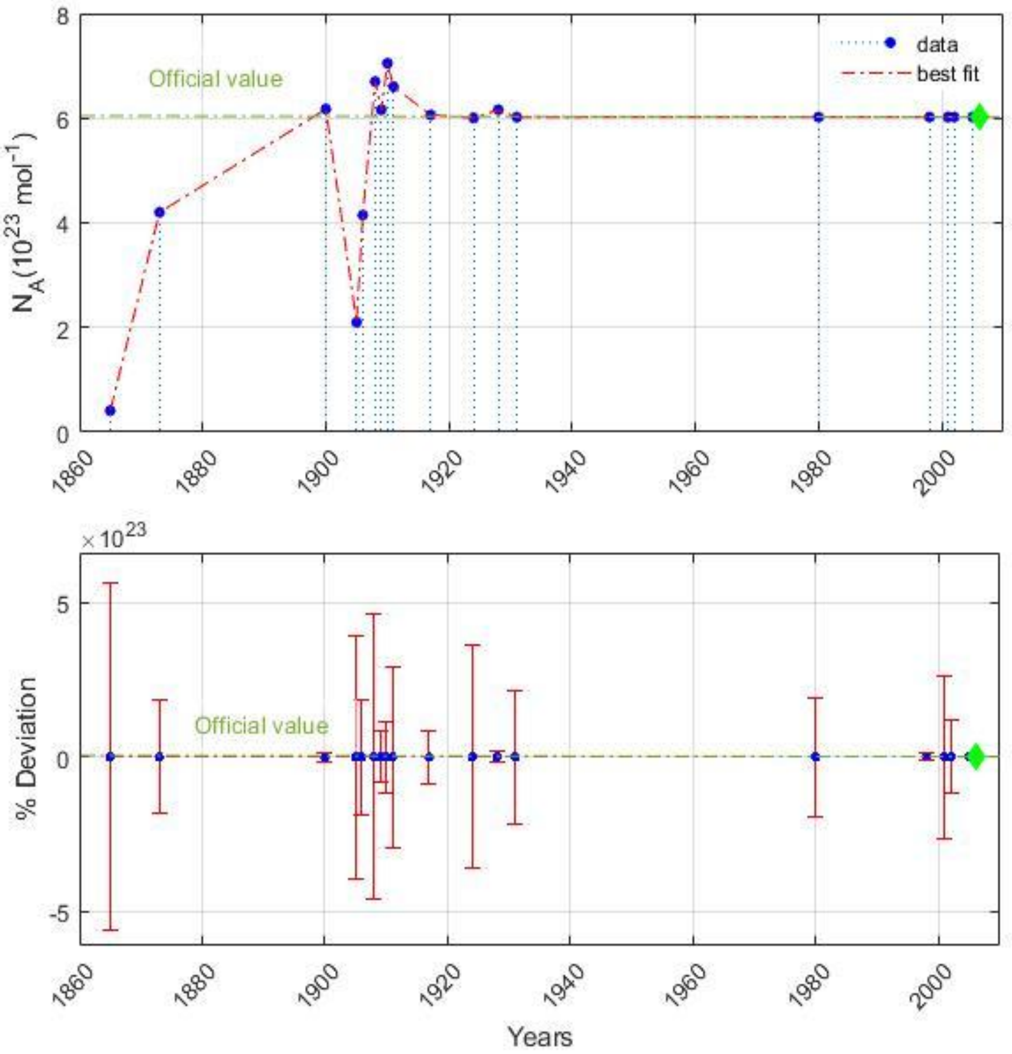

Figure 5. Variation of NA (upper panel) and its associated deviation (lower panel) as reported by various authors over the last one and a half centuries.

6) Variation of the Cosmological Constant

The cosmological constant is the simplest interpretation of the dark energy in the universe. It's explain the energy density of space or vacuum energy and it plays an important role in modern cosmology. Its original role is to allow static homogeneous solutions to a set of covariant Einstein's equations in general relativity that related to the geometry of a region of space-time to the distribution of matter and describe the static universe before Hubble discovered that the universe was expanding [21].

Einstein's original field equations in case of $c= \hbar =1$ are given by:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_{\mu\nu} T_{\mu\nu}$$

Where $R\mu\nu$ is the Ricci curvature tensor, which is a four-dimensional tensor representing the curvature of space-time, $T\mu\nu$ is a four-dimensional tensor representing energy and momentum, and R is the metric tensor.

Einstein modify his equations to be,

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_{\mu\nu} T_{\mu\nu}$$

Where Λ is the cosmological constant.

This solution of this equation is called the Einstein static universe.

The vacuum energy momentum tensor can be defined in form of the vacuum energy density ρ_{vac},

$$T_{\mu\nu}^{vac} = -\rho_{vac}\, g_{\mu\nu}$$

The cosmological constant has the same effect as an intrinsic energy density of the vacuum. Then effect of the energy momentum tensor is equivalent to,

$$\rho_{vac} = \rho_{\Lambda} \equiv \frac{\Lambda}{8\pi \dot{G}} \Leftrightarrow \Lambda = 8\pi \rho_{vac} \dot{G} \text{ or } \Lambda \text{ (in unit of length}^{-2}) \propto 1/R^2$$

Where R represents Einstein's radius of the universe.

But if ρ is the density of energy rather than density of mass then it requires dividing Λby c^2, and Λ (in unit of $time^{-2}$) $\propto 1/t^2$.

The effective cosmological constant Λ_{eff} given by [22].

$$\Lambda_{eff}=\Lambda_0+\Lambda_{zf}+\Lambda_{ew}+\Lambda_{qcd}$$

Where Λ_0 is a non-quantum term, $\Lambda_z f$is the zero point of the vacuum energy, Λ_{ew} represents a contribution from the electro-weak phase transition, and Λ_{qcd} represents a contribution from the quantum chromodynamic phase transition.

In Figure 6 we explain the varying of the cosmological constant as measured by various authors from 1972 - 2008.

We found that the last 40 years reveal a good interplay between the cosmological hypotheses and the observational measurements and the value of Λ in the past be larger and this is consistent with Newton's law of universal gravitation. It is clear that recently measured cosmological models in the upper panel of Figure 6 predict values of the order of $10^{-56} cm^{-2}$, where ($\Lambda \leq 10^{-56} cm^{-2}, = 10^{-58} cm^{-2}, < 2\,x\,10^{-56} cm^{-2}, < 10^{-56} cm^{-2}, = 10^{-57} cm^{-2}$) in 1972, 1983, 1994, 1996, 2000, and 2008 respectively. While the lower panel of Figure 6 show that the measured cosmological models have values of the order of $10^{-35} s^{-2}$, where ($\Lambda = 2.036\,x\,10^{-35} s^{-2}$) in 2001, and ($\Lambda = 1.934\,x\,10^{-35} s^{-2}$) in 2002.

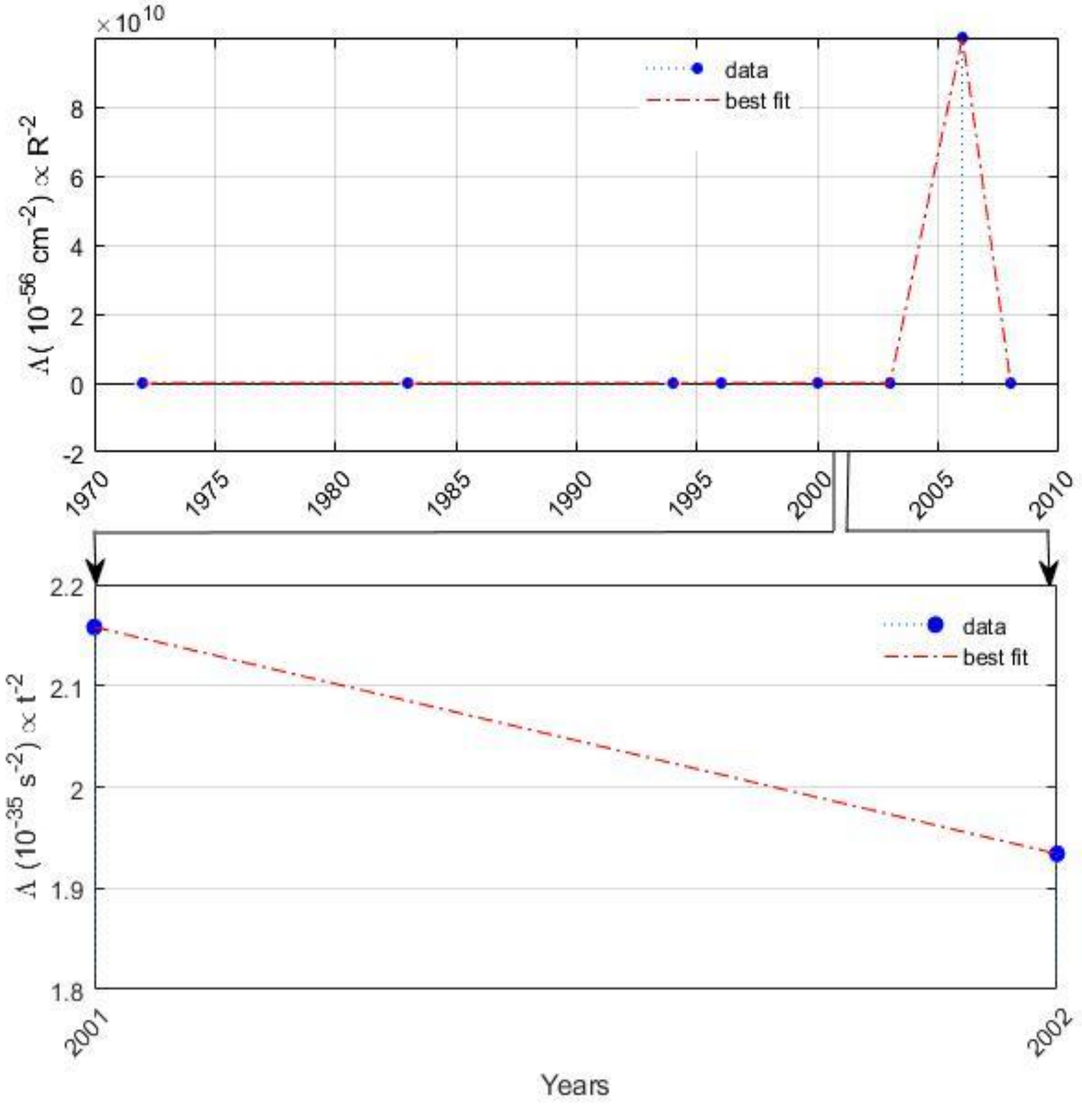

Figure 6. Varying of the cosmological constant. The upper panel represents $\Lambda \propto R^{-2}$and the lower panel represents $\Lambda \propto t^{-2}$.

Variation of the Dimensionless Constants

In this section, we will show how the universal dimensionless constant like the fine structure constant appears to have been smaller in the past.

1) Time - Variation of the Fine Structure Constant

The fine-structure constant $'\alpha'$ characterizes the strength of the electromagnetic interaction between elementary charged particles and is given in *cgs* units system as,

$$\alpha = \frac{e^2}{\hbar c}$$

Where c is the speed of light in a vacuum and it is related to the electric permittivity ϵ_0 and magnetic permeability μ_o of the free space as $c = \frac{1}{\sqrt{\epsilon_o \mu_o}}$, while $\hbar$ is the reduced Planck constant, $\hbar = \frac{h}{2\pi}$.

On the other hand, the fine-structure constant is a combination of three familiar time-varying constants: the speed of light, Planck's constant, and the elementary charge magnitude.

By consideration of the black hole thermodynamics, the variation of the fine structure constant is attributed to two contending theories; the first one is varying of the light theory and the other is with varying of the elementary charge [23].

According to uncertainty principle in quantum mechanics [24].

$$\Delta x \Delta p \gtrsim \hbar$$

Where Δx and Δp represents the position and momentum uncertainty for a quantum particle.

The amount of energy E according to Planck–Einstein equation is directly proportional to the photon's electromagnetic frequency v as,

$$E = hv = \frac{hc}{\lambda}$$

The generalization uncertainty principle in the space time GUP consider the gravitational interactions and hence it is implying a fundamental distance scale of the order of the square Planck length l_p, and is given by,

$$\Delta x \, \Delta p \gtrsim \hbar + \beta l_p^2 \frac{\Delta p^2}{\hbar}$$

Where $l_p = \sqrt{\frac{G\hbar}{c^3}}\beta$ is a positive dimensionless coefficient. And this is suggested to define an effective type of Planck constant defined as,

$$\hbar_{eff} = \hbar \left(1 + \beta l_p^2 \left(\frac{\Delta p}{\hbar}\right)^2\right)$$

Hence,

$$\Delta x \, \Delta p \gtrsim \hbar_{eff}$$

and

$$\alpha_{eff} = \frac{e^2}{\hbar_{eff}\, c}$$

The possibility of variation in the fine structure constant in recent years has been observed with a high degree of accuracy by studying the variability of the speed of light c.

In high energy physics, $\epsilon_o = c = \hbar = 1$, and the fine structure in the natural units is,

$$\alpha = \frac{e^2}{4\pi}$$

Variations in the value of the fine structure can occur due to the changing of the elementary electric charge under specific conditions. [25].

Such that each electric charge quantum 'e' is considered as a form of quantization of imaginary energy E^e and expresses as [26].

$$e = \frac{E^e \sqrt{G}}{c^2}$$

Hence, the value of the fine structure constant also cannot be a constant in the Universe.

We plotted in Figure 7 measurements values of the fine structure constant from the available literature since 1910 - 2010 along with its deviation from the official recommended value of $\alpha^{-1} = 7.297352570\, x\, 10^{-3}$in 2006. The recent data in Figure 7 show that the behaviour of time-variation in the fine-structure constant is consistent with the theories and the values of the fine structure have been smaller in 1907 as shown in the upper panel of Figure 7. We see that the values of the fine structure falls rapidly in the past and it is less than the recommended official value by amount $0.157\, x\, 10^{-3}$ and deviation-0.02. After 1950 when quantum electrodynamics developed, the values of the fine structure constant will be growing and the average of changing is equal to 0.0875675011786.

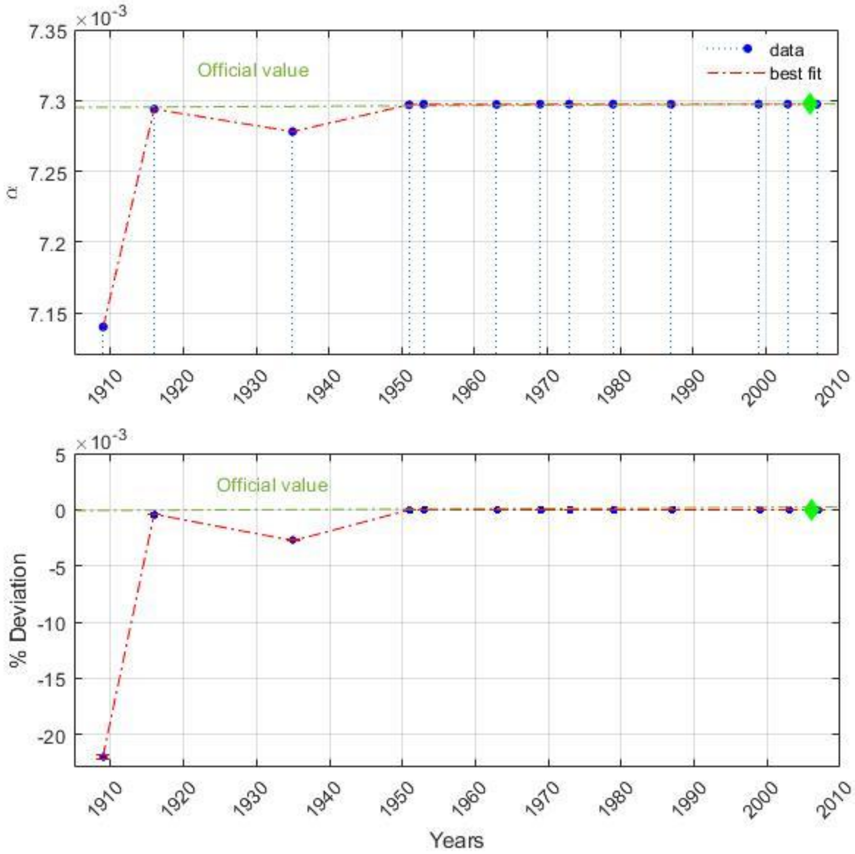

Figure 7. Time_ variation of the fine structure constant since 1910 – 2010. The upper panel illustrates data from literature reviews, and the lower panel shows the deviation from the recommended official value in 2006.

Conclusions

We have studied the time-variation of the fundamental constants of nature and found real changes in the values of the seven constants which confirm that the constants really are fluctuating with the age of the universe, or over astronomical distances.

The fundamental constants divide into dimensional and dimensionless physical constants. In general, measurements cannot measure a dimensionless quantity.

The value of a dimensionless constant will be dependent on the chosen units. Since it is possible to use the required units, the unique answer about the question of whether or not the fundamental constants of nature are time-depending will be depend on the choice of units.

We can for example select a unit so that the dimensionless constants are constant. In the international System of Units, the speed of light will be constant in the SI unit while the speed of light will be time-dependent if one depend the unit of length to be the distance between Earth and Mars.

However, the physical laws depend basically on the chosen system of units and therefore it cannot be argued that some laws of physics forbid a dimensionless constant to be varied. Hence, we can say that it is meaningless to speak about varyingof the dimensionless constants unless specifying the used system of units.

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