SPACE AND TIME DEPENDENCE OF FUNDAMENTAL CONSTANTS

This project is about the question whether the fundamental constants of physics were different in the cosmological past, i.e. at big bang times. I will present a model which allows to predict as well as to experimentally discriminate time variations of c, h, G and e. In the course of discussion there will also be comments on the Fermi scale and the fermion Yukawa couplings, but for the time being I will mostly consider c, h, G and e.

The quantities c, h and G are often and rightly used to define a system of 'natural' units for measurements of distance, time and mass: the Planck length LP, the Planck time TP and the Planck mass MP.

Consider, for example, the measurement of distances; and assume that all distances together with their standard for measuring (LP) change with time in the same way. It seems clear then, that such changes will not be visible, because everything including ourselves and the apparatus for measurement change in the same way.

Analogous statements hold true for measuring masses and time intervals, and actually also for charges, because if the elementary charge e changes with time, all other (compound) charges will change accordingly, and so the change will not be observable.

As a consequence, at this point of discussion one would conclude, that time variations of c, h, G and e, even if they occur, cannot be perceived by anybody inside our cosmos.

There are 2 ways out of this dilemma:

(i) one may consider dimensionless combinations of fundamental constants like the fine structure constant alpha which are independent from the choice of the standard rulers

(ii) one may be able to fish up remnant effects from the past which are due to the then valid values of fundamental constants

I will argue that possibility (ii) is to be considered more promising than (i). It turns out, that (i) time variations in dimensionless combinations have the tendency to cancel out in microscopic models where gravity and particle physics interactions have a common origin. On the other hand (ii) time variations of e.g. LP in the early universe can be traced back to well-known effects like the cosmological redshift. This will be explained in detail below.

About Time Variation of Dimensionless Combinations of Fundamental Constants

In this update I want to discuss the possibility (i) somewhat closer, starting with the fine structure constant:

Actually, the time variation of alpha has been quested in various astrophysical experiments (for example in the CMB or in the fine structure spectrum of distant quasars). If present at all, it has been found to be rather small. We shall see below that actually this is not so astonishing, the main reason being that time effects of electromagnetism and of gravitation in the numerator and denominator of alpha are likely to cancel out. I will explain in a moment, what I mean by that.

alpha is defined as the ratio e^2/4/pi/eps0/hbar/c. It has the numerical value of approximately 1/137 irrespective of the units chosen and is usually interpreted as the electromagnetic coupling strength. However, I prefer to consider alpha as the ratio of the Coulomb force FC=e^2/4/pi/eps0/r^2 between 2 elementary charges e and the gravitational force FN=G*MP^2/r^2 between 2 Planck masses MP. This is so, because G*MP^2=hbar*c.

In other words, if one has 2 pointlike objects both with Planck mass MP and electric charge e, then the ratio of the electric and the gravitational force between them is alpha, i.e. the gravitational force between these objects is 137 times bigger than the electric force.

Looking at alpha this way, i.e. as the ratio FC/FN, one realizes that it is dimensionless only because in describing electromagnetic effects one necessarily at some point has to refer to mechanics units. This is reflected by the fact that FC and FN - like all forces - have the same unit.

What I want to show is that under certain assumptions the time dependence of the electromagnetic numerator and the gravitational denominator cancels out in alpha. Before going into that argument, I want to answer 2 questions which readers may have:

1) h appears in the denominator of alpha. So is h more a 'mechanical' than an 'electric' quantity?

Answer: Yes, it is. This follows already from the fact that the purely 'mechanical' units LP, TP and MP are constructed from c, h and G. Furthermore, one may remember the Broglie relation p=h*k to realize that h defines the relation between a geometrical quantity (a length) and a physically active mechanical quantity (the momentum).

2) Are there other fundamental dimensionless ratios whose time dependence can be studied?

Answer: Unfortunaly, besides alpha there are not so many options. This has to do with the argument above about the interdependence of any electromagnetic measurement with gravitation. Furthermore, if there are only 4 quantities e, h, c and G and if these are used to define standard rulers for charge, distance, time and mass, there are not so many possibilities left to define 'dimensionless' combinations.

Of course, one may consider mass ratios like m(e)/m(mu) etc, but although these are fundamental parameters in the SM they are derived quantities in more fundamental microscopic theories.

Some Definite Predictions

Here I want to show that with some simple model assumptions it is possible to obtain information about the past time dependence of c0, h and G.

c0 is the speed of light as measured in a locally flat coordinate system, and is a constant in general relativity. Furthermore, instead of G I will use the Einstein constant K=G/c0^4, because it makes many of the formulas below simpler.

It is well known that in alternative to the 3 fundamental constants c0, hbar and K one may equivalently use the Planck length, time and energy

LP^2=hbar*K*c0 (1a)

TP^2=hbar*K/c0 (1b)

EP^2=hbar*c0/K (1c)

These 3 relations may be inverted to give

c0=LP/TP (2a)

hbar=EP*TP (2b)

K=LP/EP (2c)

The assumption to be made is that the universe is an elastic medium which expands according to the FLRW equations, and that this elastic medium is made up from tiny constituents invisible to us, all the ordinary particles and radiation we know being quasi-particles/wave-excitations of these constituents (for a more refined description see https://arxiv.org/abs/1505.03477).

The average distance L between 2 neighboring constituents will be called L and their binding energy E. For reasons that become clear later, L will be identified with the Planck length and E with the Planck energy.

I will start by considering a time variation of K only, i.e. K=K(t), and keep h and c0 time independent.

(i) The constancy of c0 can be justified within the above model by looking at the dispersion relation of photons.

(ii) A possible time dependence of h can be incorporated later.

(iii) From a physical point of view it seems clear that the dominant time dependence will be in Newton's constant, (i.e. in K), because it acts as a measure of the elasticity of the medium, and if a medium strongly expands like has happened from CMB times to the present, one certainly expects some variation of its elastic properties.

When the universe expands with FLRW scale factor a(t), the average distance L between 2 neighboring constituents increases proportional to a. Let 'now' mean the present time. Normalizing a(now) to 1 and assuming

L(now)=LP (3)

to be the Planck length, one has

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L(t)=LP*a(t) (4)

For the time variation of Newton's constant one therefore finds:

K(t)=L^2/hbar/c0=K(now)*a(t)^2 (5)

The time dependence of K in eq (5) obviously modifies the FLRW equations, and one might think that this has immediate phenomenological consequences. However, in relativity it is always possible to use a different coordinate system. In the case of FLRW, for example, one may use conformal time dtau=dt/a instead of proper time t. Using conformal time, it turns out that this can mimic and thus possibly hide the effect of (5) in the FLRW equations. This point will be discussed further in a future update.

According to eqs (2abc), in addition to the time dependence of the Planck length one also has to consider the time dependence of the Planck time TP and energy EP.

As for TP-->T(t), since we want to keep c0=L/T fixed, we must have

T(t)=LP*a(t)/c0 (6)

i.e. T must scale similar to L eq (4).

Finally, one has

EP=hbar*c0/LP --> E(t)=hbar*c0/L(t) (7)

This is a particularly interesting relation, because considering E to be the binding energy between 2 neighboring constituents, eq (7) gives a 1/L behavior for the binding energy as a function of distance.

I have drawn the supposed binding potential (=negative binding energy) as a function of L and have indicated the point EP(LP)=E(now)/L(now) on this curve, corresponding to the present state of the universe. For larger values of the expansion parameter a=L/L(now) I have added a slope in the curve and a minimum at some value L=LS corresponding to an equilibrium of the binding like is customary for elastic systems.

Comment 1: the binding energy E(t)=E(L(t)) eq (7) of the invisible constituents of the elastic medium has to be distinguished from the mass/energy of ordinary matter in the universe. The latter is given by 8pi/3*G*rho*a**2 and leads to an attraction towards L=L(now)*a-->0, while the binding energy

according to the figure leads to a repulsion towards L-->LS. In other words, the depicted curve represents the 'dark energy' of the universe, i.e. a repulsive force leading to an accelerated expansion - until finally it will slow down to reach its equilibrium at LS.

Comment 2: What ordinary matter does with this curve, is that by its normal gravitative attraction (L-->0) it brings us further to the left of the curve, as indicated by the small arrow in the figure.

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