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THE LIGHT SPEED AND THE INTERPLAY OF THE QUANTUM VACUUM, THE GRAVITATION OF ALL THE UNIVERSE AND THE FOURTH HEISENBERG RELATION*

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A recently proposed model which accounts for the observed time dependence of the fine structure constant is summarized. The model is based on the combined effect of the fourth Heisenberg relation and the gravitation of all the expanding universe on the quantum vacuum. As is shown here, it predicts that the light must have now an acceleration close to $H_0c \simeq 6.9 \times 10^{-10}$ m/s^2. This suggests an explanation of the anomalous acceleration $a_P \simeq 8.5 \times 10^{-10}$ m/s^2 found in the Pioneer 10 spacecraft, because an acceleration of light has the same radio observational signature as an acceleration of the ship.

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1. Introduction

This essay considers two predictions of a phenomenological model recently proposed by the author[1] in which the interplay of the quantum vacuum, the gravitation of all the expanding universe and the fourth Heisenberg relation modifies the electromagnetic properties of empty space, changing its permittivity and permeability and causing a progressive decrease in time of its optical density. The model predicts the cosmological variation of two fundamental constants: the fine structure constant and the light velocity. These two variations are discussed here *in the frame of a weak field Newtonian approximation*, in a scheme similar to the Newtonian cosmology of McCrea and Milne[2] (including however the effect of the quantum vacuum and the rest mass of the particles).

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2. Summary of the Model: The Thinning Down of the Quantum Vacuum

The quantum vacuum fixes the observed value of the electron charge and of other quantities, but there is no operative theory to answer some fundamental questions, for instance why its energy density seems to be so small. Lacking such a theory, it is considered phenomenologically in this model as a transparent optical medium characterized by its permittivity and permeability. As shown below, these two quantities must depend on the gravitational potential Φ because of the fourth Heisenberg relation.[1] The consequence is that the renormalization of the electron charge and of other quantities varies in the spacetime, so that their observed values are not constant.

The simplest phenomenological description of the vacuum is that it consists in virtual particles that pop up with variable energy E (including rest-mass, kinetic and electromagnetic energy) and disappear after a certain average lifetime, which is equal to $\tau_0 = \hbar/E$ according to the fourth Heisenberg relation. If the virtual particles are in a gravitational potential Φ they acquire an extra potential energy $E\Phi/c^2$, so that their lifetime must be there

$$\tau_\Phi = \hbar/(E + E\Phi/c^2) = \tau_0/(1 + \Phi/c^2). \tag{1}$$

Note that Φ must be here the potential produced by all the visible universe and that only virtual electron-positron pairs will be considered. The clear and maybe surprising consequence is that the number density of pairs $\mathcal{N}$ must depend on the gravitational potential Φ as

$$\mathcal{N}_\Phi = \mathcal{N}_0/(1 + \Phi/c^2)\,. \tag{2}$$

Those pairs renormalize the electron charge, from its bare value to its dressed smaller one, and fix the electromagnetic properties of empty space such as the permittivity, the permeability and the velocity of light. Note that the potential Φ, as defined here, is produced by all the mass and energy in the universe, including the dark matter and the dark energy. Since the value of Φ increases in time (becomes less negative) because the galaxies are separating, Eq. (2) implies that the number density of pairs and the optical density of space decrease in time, the electron charge being progressively less renormalized (increasing therefore). In other words, the permittivity and permeability are decreasing while the electron charge and the light velocity are increasing, their variation being however very small (i.e. adiabatic). This explains why α was smaller in the past, as observed.[3] Note that this is not an *ad hoc* hypothesis but a reasonable consequence of quantum physics.

All this implies that the permittivity and the permeability must depend on Φ or, equivalently, they must be multiplied by relative values that are equal to unity now at Earth. In weak gravity, therefore, their values at a generic spacetime point P can be expressed at first order as

$$\begin{aligned} \epsilon_{\rm r}(P) &= 1 - \beta[\Phi(P) - \Phi_{\rm E}]/c^2\,, \\ \mu_{\rm r}(P) &= 1 - \gamma[\Phi(P) - \Phi_{\rm E}]/c^2\,, \end{aligned} \tag{3}$$

where Φ_E is the present value of the potential at a reference terrestrial laboratory and β and γ are certain coefficients, which must be positive since the quantum vacuum is dielectric and paramagnetic.[1] It follows that the observed α, e and c must vary in spacetime, therefore (since $e(P) = e/\epsilon_r$, $c(P) = c/\sqrt{\epsilon_r \mu_r}$, $\alpha = e^2/4\pi\epsilon_0 \hbar c$), their values at P being

$$\begin{aligned} e(P) &= e[1 + \beta\Delta\Phi/c^2]\,, \\ c(P) &= c[1 + (\beta + \gamma)\Delta\Phi/2c^2]\,, \\ \alpha(P) &= \alpha(1 + \xi\Delta\Phi/c^2)\,, \end{aligned} \tag{4}$$

where $\Delta\Phi = \Phi(P) - \Phi_E$, $\xi = (3\beta - \gamma)/2$ and e, c, α are the constants that appear in the tables (no variation of $\hbar$ is considered here). Note that this model has something in common with the Mach principle since it implies that some properties of the material objects are affected by the distant stars.

To understand these variations, note that the main contribution to Φ comes from the far-away objects and it is almost uniform, in other words it is large but with almost zero gradient while the effect of the inhomogeneities of the mass distribution, *i.e.* the nearby stars and galaxies is much smaller but has a non-zero gradient. Indeed the average potential of all the universe over c^2 is of the order of -10^{-1}, as shown below, while the contributions of the Sun, the Earth and the Milky Way at a terrestrial laboratory are about -10^{-8}, -10^{-9} and -10^{-6}, respectively (see Ref. 1). Due to the general expansion, the global contribution to Φ is increasing and ϵ_r, μ_r are decreasing which implies an increase of α and an acceleration of light. Note also that the change of Φ is the sum of a spatial and a temporal changes, the effect of the former being like in an inhomogeneous but static transparent medium: a change of the wavelength without variation of the frequency, describable with a refractive index $n(\mathbf{r})$. On the other hand, the time change produces an adiabatic monotonous increase in the light velocity and the frequency, which must have cosmological consequences but is however negligible in terrestrial laboratory experiments as is shown in the following.

Neglecting the inhomogeneities near massive objects, the space averaged value $\Phi_{av}(t)$ can be taken for the potential, the time evolution of the fine structure constant and the light velocity being then

$$\alpha(t) = \alpha\{1 + \xi[\Phi_{av}(t) - \Phi_{av}(t_0)]/c^2\}$$

and

$$c(t) = c\{1 + (\beta + \gamma)[\Phi_{av}(t) - \Phi_{av}(t_0)]/2c^2\}\,,$$

where t_0 is the age of the universe. Note however that the effects of the inhomogeneities of the Milky Way, the Sun and the Earth at a terrestrial laboratory are in fact included here in the numerical values of $\alpha = \alpha(t_0)$ and $c = c(t_0)$, which is possible since these objects are not expanding. However, when dealing with a ship moving through the solar system, the variation of the potential of the Sun must be taken into account separately.

Let us take the best universe model, with flat sections $t = \text{constant}$ (i.e. $k = 0$) and with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$. In that case, the average gravitational potential produced by all the visible universe is presently equal to $\Phi_{\text{av}} = \Phi_0(\Omega_M - 2\Omega_\Lambda)$, where Φ_0 is the potential created by a mass distribution with the critical density (i.e. $\Phi_0 =\simeq -\int_0^{R_U} G\rho_{\text{cr}}4\pi r dr \simeq -0.3c^2$ where $R_U \approx 3,000$ Mpc). Since the potentials created by the matter and by the quantum vacuum in all the universe vary as the inverse of the scale factor $a(t)$ and as its square $a^2(t)$, respectively, it turns out that

$$\Phi_{\text{av}}(t) - \Phi_{\text{av}}(t_0) = \Phi_0 F(t)\,,$$

with

$$F(t) = \Omega_M[1/a(t) - 1] - 2\Omega_\Lambda[a^2(t) - 1]\,.$$

(Note that $F(t_0) = 0$, $\dot{F}(t_0) = -(1 + 3\Omega_\Lambda)H_0$, where H_0 is the Hubble parameter.)

As a consequence, the time evolution of the fine structure constant, the light velocity at Earth and its present acceleration $a = \dot{c}(t_0)$ are given by

$$\begin{aligned} \alpha(t) &= \alpha\left[1 + \xi\frac{\Phi_0}{c^2}F(t)\right], \\ c(t) &= c\left[1 + \frac{\beta+\gamma}{2}\frac{\Phi_0}{c^2}F(t)\right], \\ a &= -\frac{\beta+\gamma}{2}\frac{\Phi_0}{c^2}[1 + 3\Omega_\Lambda]H_0 c\,. \end{aligned} \tag{5}$$

Note that, since $\dot{F}(t) < 0$, thus $\alpha(t)$ and $c(t)$ are increasing functions of time. It was shown in Ref. 1 that the prediction for $\alpha(t)$ agrees reasonably well with the observations by Webb *et al.*[3] if $\xi \simeq 1.3 \times 10^{-5}$ (see Fig. 1).

This essay examines the variation of the light velocity. As is seen, if $(\beta + \gamma)/2$ is of the order of unity, then a would be close to $H_0 c \approx 6.9 \times 10^{-10}$ m/s^2. In that case, β and γ must be not far from 0.5 and 1.5, respectively (with these values, the predictions of this model do not violate any experimental test of special relativity

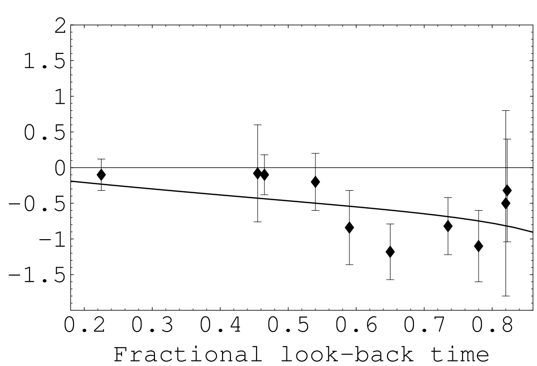

Fig. 1. $\Delta\alpha/\alpha$ (times 10^{-5}) versus fractional look-back time, predicted by this model), as compared with the data by Webb *et al.*[3] (explanation in the text).

or the equivalence principle, as shown below). The consequence: the light would accelerate adiabatically because of the thinning down of the quantum vacuum.

It may be noted that the potential Φ has been used to study quantum aspects of gravity or to explore eventual quantum violations of the equivalence principle, non-geometric elements in gravity or gravitationally induced neutrino-oscillation phases, even cases in which its gradient can be neglected (see Refs. 4 and 5 by Ahluwalia and coworkers and references therein)

3. The Adiabatic Acceleration of Light as a Blue Shift

It turns out that the frequency ω_0 of a monochromatic light wave with an adiabatic acceleration such as a increases in time so that ($\dot{\omega}$ being its time derivative)

$$\dot{\omega}/\omega_0 = a/c\,. \tag{6}$$

The time derivatives of $\epsilon_{\rm r}$, $\mu_{\rm r}$ are extremely small, of the order of $H_0 \approx 2.3 \times 10^{-18}\ {\rm s}^{-1}$ (indeed $\dot{\epsilon}_{\rm r}/\beta = \dot{\mu}_{\rm r}/\gamma = (\Phi_0/c^2)[1 + 3\Omega_\Lambda]H_0$). Taking the Maxwell equations with adiabatically time depending $\epsilon_{\rm r}(t)$, $\mu_{\rm r}(t)$ and neglecting the small quantities, the field equations of an electromagnetic wave are shown to be

$$\begin{aligned} \nabla^2\mathbf{E} - c^{-2}(t)\partial^2\mathbf{E}/\partial t^2 &= 0\,, \\ \nabla^2\mathbf{H} - c^{-2}(t)\partial^2\mathbf{H}/\partial t^2 &= 0\,. \end{aligned} \tag{7}$$

A simple and standard method to find the effect of the adiabatic variation of c is to insert the expression

$$\mathbf{E} = \mathbf{E}_0 \exp\{-i[\kappa z - (\omega_0 + \dot{\omega}t/2)t]\}$$

in Eq. (7) and work at first order in a and $\dot{\omega}$. It is straightforward to find Eq. (6) as the result. This means that the wavelength remains constant while the frequency increases with the same relative rate as the light velocity (*i.e.* all the increase in velocity is be due to the increase in frequency). An adiabatic acceleration of light has, therefore, the same radio signature as a blue shift of the source. A very special one, however: in a measurement of the frequency, an extra blue shift would be found (unrelated, however, to the velocity of the emitter), but observations of the wavelength would find no effect. In other words, the effect can be detected using radio waves or microwaves but the standard optical observations would see nothing. In any case, this effect adds to the cosmological redshift.

It must be stressed that, as said before, the spatial change of Φ produces no variation of ω. Indeed, in a static situation the quantum vacuum behaves as an transparent medium with constant optical density.

4. Comparison with the Experiments

It is easy to show that this model complies with the various experimental tests of special relativity or the equivalence principle,[6] the most important being the Eötvös, the Hughes-Drever and the gravitational redshift experiments, even if they put stringent bounds to any admissible theory. This is explained in Ref. 7, where more details are given. A variation of e could lead to a violation of the equivalence principle, since a small part of the mass of a body would change in a way that depends on its chemical composition.[8,9] In the case of an Eötvös experiment, it turns out however that, assuming that the distance between the positions of the balance is smaller that 1 m, the contribution of the effect of this model on the Eötvös ratio[6] η would satisfy $\eta \lesssim \beta \times 10^{-18}$, β being of the order of 1. Since the best bound in this type of experiments, obtained by Roll, Krotkov and Dicke and Braginski, is $\eta < 10^{-12}$, this model has no problem here.

The Hughes–Drever experiments[10,11] were devised as tests of the anisotropy of the space. By observing the Zeeman effect in nuclei, they establish the bound $\Delta m/m < 10^{-23}$, Δm being the anisotropic part of the mass of a nucleus. The anisotropy arises in this model because the electromagnetic mass of an nucleus changes differently along the diverse directions around a point. It is easy to show that the prediction of this model is $\Delta m/m < \beta \times 10^{-32}$. No problem again.

A consequence of the equivalence principle is that the frequency of a light beam changes in a gravitational field as $\Delta\omega/\omega = -(1+\delta)\Delta\Phi/c^2$ with $\delta = 0$. Several experimental tests set bounds for δ (a non-zero value would indicate a violation of the principle), the best being $|\delta| \lesssim 2\times 10^{-4}$.[6] It was obtained by Vessot and Levine[12,13] with the 1420 MHz line of the hyperfine spectrum of Hydrogen, between a terrestrial laboratory and a rocket travelling upwards until a height of 10,000 km. It turns out that the effect described in this model would produce a shift corresponding to $\delta = 6\xi \simeq 8 \times 10^5$, below the Vessot-Levine bound (near borderline at most). The conclusion is that the effect described here is not in conflict with the experiments at Earth (see Ref. 7 for the details). However, it has cosmological consequences.

5. Deflection of a Light Ray Grazing the Surface of the Sun

Let us consider now one further prediction of this model. As is known, General Relativity predicts successfully that a light ray grazing the Sun surface must be deflected by an angle $\Delta\varphi = 2GM_\odot/c^2R_\odot = 1.75''$, $M_\odot$, $R_\odot$ being the mass and radius of the Sun. Classical Newtonian physics can account also for this phenomenon, but giving just one half of the observed effect and only after the additional assumption that light consists of Newtonian particles with kinetic energy per unit mass equal to $c^2/2$. This model predicts also a deflection since the velocity of light depends on Φ, so that the gravitational field around any star behaves as an inhomogeneous optical medium. But note that this effect is predicted within the frame of wave theory, without the need of any assumption on the photons.

According to Eq. (4), the light velocity depends on the distance to the Sun r as

$$c(r) = c\{1 - \eta R_\odot[r^{-1} - R_E^{-1} - (M_\oplus/M_\odot R_\oplus)]\}\,,$$

where $\eta = (\beta+\gamma)GM_\odot/2R_\odot c^2 = 2.12\times 10^{-6}(\beta+\gamma)/2$, $M_\oplus$, $R_\oplus$ are the mass and the radius of Earth and R_E is the radius of its orbit. (Note that, as the time needed for the bending is very short, we can neglect the time variation in $\Delta\Phi$, keeping only the space variation of c. Consequently, only the local mass inhomogeneity due to the Sun intervenes in this phenomenon, the effect of far away bodies being negligible.) Since the refractive index of the quantum vacuum increases as r decreases, the trajectories of the light rays are curves that bend towards the centre of the Sun. As each one is contained in a plane, let us take Cartesian coordinates (x, y) with the Sun centered at the origin. The ray trajectories are the solutions to the variational problem

$$\delta \int_1^2 (1 + y'^2)^{1/2} \mathrm{d}x / c(r) = 0 \,.$$

It is a simple matter to expand in series of η (which is small) the solutions of the corresponding Euler–Lagrange equation, $y(x) = y_0(x) + \eta y_1(x) + \cdots$. It turns out that, including the first order correction, the zero order grazing trajectory $y = R_\odot$ becomes $y(x) = R_\odot - \eta(R_\odot^2 + x^2)^{1/2}$. Clearly, the deflection angle is $\Delta\varphi = 2|y'(\infty)|$, i.e.

$$\Delta\varphi = 2\eta = (\beta + \gamma) G M_\odot / c^2 R_\odot = 2.12 \times 10^{-6} (\beta + \gamma) \,. \tag{8}$$

If $\beta + \gamma = 2$ (or 4), the predicted deflection angle is $\Delta\varphi = 0.875''$ (or $= 1.75''$) and the acceleration of light is $a = 5.9 \times 10^{-10}$ m/s^2 (or $= 11.7 \times 10^{-10}$ m/s^2).

The fact that the values of $\beta+\gamma$ that give $1.75''$ or half this value for the bending angle predict an acceleration of light which is close to the Pioneer acceleration is both intriguing and encouraging, given the approximations and the uncertainties of the model.

6. Has the Acceleration of Light been Observed?

Taking into account the previous arguments, this essay proposes the consideration of an intriguing possibility: that the acceleration of light (5) had been already observed but was attributed to unknown causes. In the nineties, Anderson *et al.*[14] detected an anomalous acceleration in the Pioneer 10 spacecraft, equal to $a_P = 8.5 \times 10^{-10}$ m/s^2, constant and directed towards to the Sun. The effect was seen again in the Pioneer 11, the Galileo and the Ulysses spaceships. What the team observed was a time increasing extra blue shift in the microwave signal from the ships, the frequency verifying (6) with $a = a_P$, which was interpreted as due to an extra acceleration towards the Sun. However no reason for this effect could be found until now, in spite of a thorough search.[15]

This work suggests an explanation. Could it be that the Pioneer did not suffer any extra acceleration? That it followed the standard Newton laws? That the observed and unmodelled acceleration is not due to the motion of the ship but is in fact an observational effect of the acceleration of light? Note that this model does predict that there must be a blue shift in the microwave signal coming from the Pioneer 10, which (i) increases linearly in time, (ii) verifies (6) and (iii) is not related to the velocity of the ship. Note also that, if $(\beta+\gamma)/2$ is of the order of 1, the predicted acceleration of light a would be close to $H_0 c \approx 0.8\, a_P$. With all that in mind and in spite of making use of a Newtonian approximation and of the simplifications which are made and the questions which arise, this essay proposes to consider and study as a respectable possibility that the answer to the previous questions could be affirmative. In that case, the combined effects of the fourth Heisenberg relation on the quantum vacuum and the expansion of the universe would imply (i) that the light velocity varies in space, being lower near massive objects, and (ii) that the light accelerates adiabatically, the apparent Pioneer acceleration being its observational signature, while the ship follows then and now the standard Newton laws.

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