A Cyclic Universe alternatively dominated by matter and antimatter

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Abstract. It was recently suggested that what we call dark matter and dark energy, can be explained as the local and global effects of the gravitational polarization of the quantum vacuum by the immersed Standard Model matter. This result appears as the consequence of the working hypothesis that by their nature *quantum vacuum fluctuations are virtual gravitational dipoles*. Here, we argue that, as a consequence of the same hypothesis, we may live in a cyclic universe with cycles alternatively dominated by matter and antimatter. Hence, we have related matter-antimatter asymmetry in the Universe with the cyclic nature of the Universe. At least mathematically there is no the initial singularity, there is no need for the cosmic inflation and there is an amusing explanation of the matter-antimatter asymmetry: our Universe is dominated by matter because the previous cycle was dominated by antimatter (and the next cycle would be dominated by antimatter again).

1. Introduction

According to our best knowledge (the Standard Model of Particles and Fields), particles and antiparticles are *always created in pairs*. However, as far as we know, *our Universe is dominated by matter*. How can a symmetric process of creation (matter and antimatter created in the same quantity) give rise to an asymmetric result (one of them dominates the universe)? It is one of the greatest mysteries in physics, astrophysics and cosmology. Apparently, in the primordial Universe, something has forced this matter-antimatter asymmetry. The mainstream hypothesis is that it is caused by CP violation, but please do not be misled by the known CP violation; in order to create such an enormous asymmetry it must be an unknown type of CP violation, many orders of magnitude stronger than the known one! It is an open question if such an extreme CP violation existed in the early Universe.

We propose a radically different scenario based on the *working hypothesis* that *by their nature quantum vacuum fluctuations are virtual gravitational dipoles*. The simplest and the most elegant realization of this hypothesis is, if particles and antiparticles have the gravitational charge of the opposite sign (which will be tested on ongoing experiments AEGIS [1], ALPHA [2] and GBAR [3] at CERN); of course nature may surprise us with a different realization of the gravitational dipoles-like behavior of the quantum vacuum.

Before we continue, let us mention major consequences [4, 5, 6, 7, 8, 9, 10] of our hypothesis. First, the hypothesis permits tconsidering the well-established Standard Model matter (i.e. matter made from quarks and leptons interacting through the exchange of gauge bosons) as *the only* matter–energy content of the Universe; of course a content immersed in quantum vacuum "enriched" with virtual gravitational dipoles. What we call dark matter and dark energy, can be explained as the local and global effects of the gravitational polarization of the quantum vacuum by the immersed Standard Model matter (the polarized quantum vacuum acts as an *effective gravitational charge*). In addition, the gravitational charge density of the quantum vacuum is zero, which is the simplest solution to the cosmological constant problem; a tiny, *effective* gravitational charge density might appear as the result of the immersed Standard Model matter.

In the present paper we enlarge this astonishing series of consequences. We may live in a cyclic Universe with cycles alternatively dominated by matter and antimatter; with each cycle beginning with a macroscopic size and the accelerated expansion. Consequently, there is no singularity, no need for an inflation field, and there is an elegant explanation of the matter-antimatter asymmetry in the universe: our universe is dominated by matter because the previous cycle of the Universe was dominated by antimatter (and the next cycle would be dominated by antimatter again). Of course, when a theory is in question, experiments and astronomical measurements always have the last word, but so far, there is no other competing theory which apparently has the potential to explain the whole spectrum of phenomena with a single hypothesis. Time will show if it is a way out of the greatest crisis in the history of physics.

In section 2 we address the question *What would be the outcome of an eventual Big Crunch*? The surprising answer is that a Big Crunch of our Universe would end at a macroscopic size with extremely fast conversion of matter to antimatter; it may look like a new Big Bang but it is not a Big Bang because it starts with a macroscopic initial size and hence without singularity and without need for an inflation field of unknown nature.

In section 3 we argue that during the expansion of the Universe quantum vacuum converts from a cosmological fluid with negative pressure to nearly pressureless fluid. According to the cosmological field equations it means that the accelerated expansion converts to the decelerated one.

2. What would be outcome of a Big Crunch

If quantum vacuum fluctuations are virtual gravitational dipoles we can borrow a result from quantum electrodynamics, which is valid for virtual electric dipoles (for instance electron-positron pairs). The key point is that *quantum vacuum fluctuations can be converted into real particles*; something can be created from apparently nothing. A virtual electron-positron pair (and in principle any charged particle-antiparticle pair) can be converted to a real one by an external field which, during their short lifetime, can separate particle and antiparticle to a distance of about one reduced Compton wavelength. For a constant acceleration g (which corresponds to a constant electric field) the particle-antiparticle creation rate per unit volume and time, can be written as

$$\frac{dN_{m\bar{m}}}{dtdV} = \frac{c}{\lambda\!\!\!^{-}{}_m^4}\left(\frac{g}{g_{cr}}\right)^2 \sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n\frac{g_{cr}}{g}\right); \; \lambda\!\!\!^{-}{}_m \equiv \frac{\hbar}{mc}, \; g_{cr} \equiv \pi\frac{c^2}{\lambda\!\!\!^{-}{}_m} \qquad (1)$$

which is the famous Schwinger formula [12].

The Schwinger mechanism is valid only for an external field that has the tendency to separate particles and antiparticles. Consequently, Eq. (1) *can be used for the gravitational field, only if, particles and antiparticles have gravitational charge of the opposite sign*. Hence, if our hypothesis is correct, an extremely strong gravitational field (stronger than the critical acceleration g_{cr} in (1)) would create a huge number of particle-antiparticle pairs from the physical vacuum. It is important to underline that virtual pairs are spatially separated and converted into real pairs by the expenditure of the external field energy. Let us note that according to (1) the critical accelerations for creation of electron-positron and proton-antiproton pairs are respectively $7.4\times10^{29}\, m/s^2$ and $1.4\times10^{33}\, m/s^2$. These accelerations are much smaller than the gravitational accelerations which might exist in the primordial Universe.

Now, let us remember how cosmology works. The cosmological principle (i.e. the assumption of the large-scale homogeneity and isotropy of the Universe) determines the Friedman-Lemaitre-Robertson-Walker (FLRW) metric (see for instance [13]):

$$ds^2 = c^2 dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right)\right] \quad (2)$$

where k=+1, k=-1 and k=0 correspond respectively to closed, open and flat Universe.

The dynamics of the above space-time geometry is entirely characterised by the scale factor R(t) which is the solution of the Einstein equation $G_{\mu\nu} = -(8\pi G/c^4)T_{\mu\nu}$. The Einstein tensor $G_{\mu\nu}$ is determined by FLRW, but in order to solve the Einstein equation we must know the Energy-momentum tensor $T_{\mu\nu}$. Key point: The Energy-momentum tensor is approximated by the energy momentum tensor of a perfect fluid characterised at each point by its proper density ρ and pressure p.

If the cosmological fluid consists of several distinct components denoted by *n*, the final results are cosmological field equations [13]:

$$\ddot{R} = -\frac{4\pi G}{3} R \sum_n \left(\rho_n + \frac{3p_n}{c^2}\right) \; and \; \dot{R}^2 = \frac{8\pi G}{3} R^2 \sum_n \rho_n - kc \quad (3)$$

The cosmological field equations can be solved only if we know the content of the Universe. According to the Standard Model the content of the Universe are two well-established cosmological fluids: non-relativistic Standard Model matter (usually called pressureless matter or dust) and radiation, respectively described by (Note that index 0 denotes the present day value):

$$\rho_m = \rho_{m0}\left(\frac{R_0}{R}\right)^3, \; p_m = 0 \; and \; \rho_r = \rho_{r0}\left(\frac{R_o}{R}\right)^4, \; p_r = \frac{1}{3}\rho_r c^2 \quad (4)$$

The third fluid proposed by the Standard Model is quantum vacuum, but the use of this fluid is blocked by the cosmological constant problem; that is why other hypothetical fluids (dark matter, dark energy…) have been proposed. Following our hypothesis the full content of the universe can be modelled with only three fluids, two fluids described by (4), plus quantum vacuum "enriched" with virtual gravitational dipoles; we will come back to this in section 3.

$R\,[m]$	10^{12}	10^{9}	10^{3}	1
$\ddot{R}\,[m/s^2]$	10^{33}	10^{42}	10^{60}	10^{69}
$\frac{dN_{m\bar{m}}}{dt\,dV}\left[\frac{pairs}{sm^3}\right]$	10^{72}	10^{90}	10^{126}	10^{144}
$\frac{dN_{m\bar{m}}}{dt\,dV}\left[\frac{M_{Sun}}{sm^3}\right]$	10^{15}	10^{33}	10^{69}	10^{87}

Table 1: Acceleration and particle-antiparticle creation rate for different scale factors *R*

In order to get an idea about the outcome of an eventual Big Crunch, we may use the gravitational version of the Schwinger mechanism (1) together with the first of cosmological equations (3); more precisely we use $g = \ddot{R}$ in order to calculate the particle-antiparticle creation rate (1). Today $\ddot{R}$ has a small value of the order of $10^{-9}\, m/s^2$. However (and it is crucial for our arguments), in the primordial Universe acceleration $\ddot{R}$ may be extremely big as can be seen from Table 1. It is useful to point out that in the first two numerical columns of Table 1, the sizes $R = 10^{12} m$ and $R = 10^{9} m$ correspond respectively to roughly the size of the Solar System and the size of the Sun.

With a conversion rate as in the first two numerical columns of Table 1, the matter of our Universe can be transformed into antimatter of the next cycle of the universe in a tiny fraction of second! With conversion rate as in third numerical column, the time needed for conversion is of the order of the Planck time. If the rate is as in the fourth column, conversion takes a tiny fraction of the Planck time. Apparently, if quantum vacuum fluctuations are gravitational dipoles, matter of our Universe cannot survive the trek to singularity; much before singularity it would be converted to antimatter of a new cycle of the Universe. Hence, there is a very simple and beautiful qualitative picture of the expected phenomena. An extremely strong gravitational field would create a huge number of particle-antiparticle pairs from the physical vacuum; with the additional feature that matter tends to reach toward singularity while antimatter is violently “ejected” farther and farther from singularity. The amount of created antimatter is equal to the decrease in the mass of the collapsing matter Universe. Hence, the quantity of matter decreases while the quantity of antimatter increases in the same amount; the final result might be conversion of nearly all matter into antimatter. If the process of conversion is very fast, it may look like a Big Bang starting with a macroscopic initial size many orders of magnitude greater than the Planck length.

3. The gravitationally polarized quantum vacuum as cosmological fluid

The results from the previous section have physical importance only if there is a future transition from expansion to contraction of our Universe. According to current mainstream cosmology expansion would be eternal; there is no mechanism to stop expansion. However, if our hypothesis is correct, the expansion may convert to contraction [10] (see also my articles in this proceedings devoted to dark matter and dark energy).

The key point is that our hypothesis permits replacing the galactic halo of dark matter by the halo of the gravitationally polarized quantum vacuum. Namely, in the limit of zero external gravitational field quantum vacuum may be considered as a fluid of randomly oriented gravitational dipoles (Figure 1); both the total gravitational charge and the gravitational polarization density $\mathbf{P_g}$ (i.e. the gravitational dipole moment per unit volume) are zero. However, the random orientation of virtual dipoles may be broken by

Figure 1. Randomly oriented gravitational dipoles (in absence of an external gravitational field)

Figure 2. *Halo* of non-random oriented gravitational dipoles around a body (or a galaxy) with baryonic mass M_b

the immersed Standard Model matter. Massive bodies (stars, black holes …) but also multi-body systems as galaxies are surrounded by an invisible halo of the gravitationally polarized quantum vacuum, i.e. a region of non-random orientation of virtual gravitational dipoles (Figure 2). This halo of the polarized quantum vacuum acts as an *effective gravitational charge*. Namely, the spatial variation of the gravitational polarization density generates a gravitational bound charge density [4, 5, 8, 9, 10] of the quantum vacuum $\rho_{qv} = -\nabla \cdot \mathbf{P}_g$ which may explain phenomena usually attributed to dark matter.

Consequently, if quantum vacuum fluctuations are virtual gravitational dipoles, the quantum vacuum in the Universe is a cosmological fluid with *the sum of all gravitational charges equal to zero*; however, because of the existence of the halos of non-random oriented dipoles, it is a fluid with *a large effective gravitational charge*.

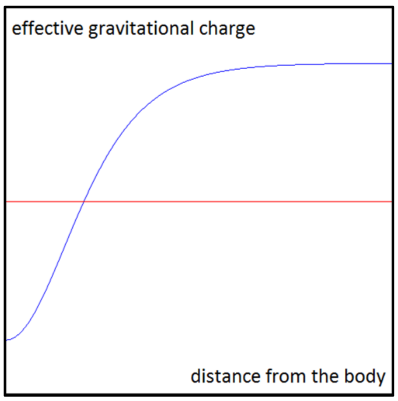

Figure 3. The effective gravitational charge of a body (blue line) increases from the “bare” charge measured at its surface to a constant maximum charge at a large distance from the body. Other bodies can prevent the effective gravitational charge from increasing above a limit presented by the red line

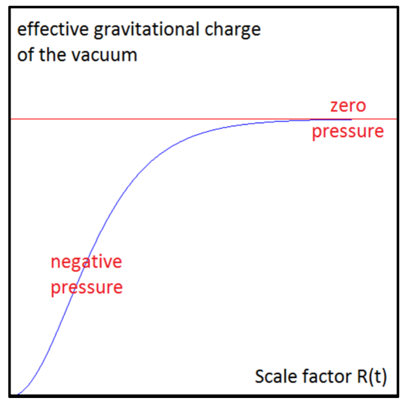

Figure 4. The effective gravitational charge of the quantum vacuum in the Universe depends on the scale factor R(t). Note that with the expansion of the Universe the polarized quantum vacuum converts from a cosmological fluid with negative pressure to a pressureless fluid!

Roughly speaking there is a maximum size of the halo for each massive body, galaxy or cluster of galaxies. Simply, after a characteristic size, the random orientation of dipoles dominates again. However, because of proximity of other bodies, many halos are smaller than the maximum size. A halo of the maximum size can be formed only if other bodies (competing in the polarization of the quantum vacuum) are sufficiently far away. This behaviour is schematically presented in Figure 3.

Hence, with the expansion of the universe, galactic halos must increase in size and *the content of the effective gravitational charge* caused by the polarization of the quantum vacuum. However, it is not an endless increase (see Figure 4); once the halos have reached their maximum size they remain unchanged with the further expansion. Now, the key point is that there is a period in which the size of the individual galactic halos and the total effective gravitational charge of the quantum vacuum *increase with the expansion*, which means that the polarized quantum vacuum behaves as a fluid with negative pressure, and, according to the first of cosmological equations (3) this is exactly what is necessary for the accelerated expansion of the Universe. Namely, this field equation tell us that the expansion of the Universe can be accelerated ($\ddot{R} > 0$) only if there is a cosmological fluid with sufficiently big negative pressure, so that the sum in the equation is negative.

However the accelerated expansion is only the first part of the story. The second part is that during the expansion of the Universe quantum vacuum converts from a cosmological fluid with negative pressure to nearly pressureless fluid (this is a consequence of the fact that increase of the effective gravitational charge is not endless). According to the cosmological field equations it means that the accelerated expansion converts to the decelerated one; apparently there is a mechanism to prevent an eternal expansion.

4. Conclusion

We have suggested physical mechanisms which can prevent both the collapse of the Universe to singularity and the eternal expansion. The phase of expansion of the Universe may be followed by contraction; a cyclic Universe may be the way in which nature works. The mystery of matter-antimatter asymmetry may be inherent part of the cyclic nature of the Universe.

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