A vacuum component of the Universe must evolve

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The evolution of the vacuum component of the Universe is investigated in the quantum as well as the classical regimes. Probably our Universe has arisen as a vacuum fluctuation and very probably it had a high symmetry for Planckian parameters. In the early epochs of its cooling, during the first second, the vacuum component of the Universe had been losing its high symmetry by phase transitions, since condensates of quantum fields carried negative contributions (78 orders) to its positive energy density. After the last phase transition (quark-hadron) the vacuum energy 'has hardened'. At this moment ($10^{-46}$ sec) its energy density can be calculated using Zeldovich’s formula, inserting an average value of the pseudo-Goldstone boson masses (pi-mesons) that characterizes this chromodynamical vacuum. The chiral symmetry was then lost. The dynamics of the equilibrium vacuum after its 'hardness' is considered by applying the holographic principle. During of next $4 \times 10^{17}$ sec the vacuum component of the Universe had been losing 45 orders by the creation of new quantum states. Utilizing the holographic principle, we solve the cosmological constant problem because 123 crisis orders disappear in usual physical processes. The density of vacuum energy from redshift $z = 0$ up to redshift $z = 10^{11}$ is also calculated in the classical regime of the Universe evolution using the "cosmological calculator".

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I. INTRODUCTION

In this article we propose that a Λ-term, vacuum energy, cosmological constant and dark energy have a common origin. The research of the vacuum energy evolution presented a large interest always. A. Einstein had introduced the Λ-term in his field equations as a property of space-time \[ G_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi G N T_{\mu\nu}. \] (1)

If one puts the Λ-term in the right side of the above equation (1) then it will be a form of energy called dark energy, due to the absence of a good explanation of its nature,

\[ G_{\mu\nu} = -8\pi G N T_{\mu\nu} - \Lambda g_{\mu\nu}. \] (2)

The present value of this form of dark energy is:

\[ \rho_{DE} = \rho_\Lambda \sim 10^{-47}(\text{GeV})^4 \sim 0.7 \times 10^{-29}\text{g/cm}^3, \] (3)

if $H = 70.5$ (km/sec$^{-1}$/Mpc). Furthermore, this form of dark energy provides the reason of the present accelerated expansion of our Universe (generally speaking our Universe is one of many universes in a multiverse). It is suggested that in the Planckian epoch of the Universe evolution, this form of dark energy had the density (UV cutoff):

\[ \rho_\Lambda \sim 2 \times 10^{76}(\text{GeV})^4 \sim 0.5 \times 10^{94}\text{g/cm}^3, \] (4)

for $M_{Pl} = 1.2 \times 10^{19}$ GeV. From equations (3) and (4), a question arises why this huge difference takes place in the present value of Λ-term to its value in the Planckian epoch (123 orders)? This inexplicable difference caused a crisis of theoretical astrophysics as mentioned in all reviews [2–9], although many interesting hypotheses were constructed to overcome this crisis [10–25].

Probably, the most adequate explanation of dynamical (relaxation) mechanism for Λ-term has been suggested by V. Rubakov [18]. Namely, the theory of primordial nucleosynthesis requires that a large part of the vacuum energy had already reduced to nucleosynthesis epoch. Therefore, the relaxation of the vacuum energy should have occurred at some earlier cosmological stage. Besides, the theory of formation of baryon structures in the Universe requires a

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long matter dominated epoch that points also in the same direction. The last observations showed that a parameter 
\( w = p/\rho \) characterizing dark energy is close to \(-1\) with \(-0.14 < 1 + w < 0.12\) \[26\]. But, in the early epochs during 
phase transitions the \( \Lambda \)-term was not the cosmological constant. It had become practically the cosmological constant 
only after the last (quark-hadron) phase transition when the temperature of the Universe dropped from \( 10^{19} \text{ GeV} \) to 
\( 150 \text{ MeV} \). Before this in a positive vacuum energy, condensates of quantum fields had carried negative contributions 
as has already been noted (for existence of the large scale baryon structure the small positive vacuum energy is only possible \[27\]). A. Dolgov was the first one who has discussed this compensation hypothesis for the vacuum energy of 
the Universe \[28\].

Probably, other time it is necessary to give the definition of vacuum. A vacuum is defined as the stable state of 
quantum fields without excitation of wave modes. In geometrical physics a vacuum is the state in which the geometry 
of space-time does not deform. In quantum cosmology a vacuum is condensates of quantum fields appearing as the 
result of relativistic phase transitions. In classical physics a vacuum is a world without particles and this world is flat. 
The equation of state for a vacuum is \( p = -\rho \). At the first we consider a quantum regime of the vacuum evolution 
and after we consider a classical one. A novel concept presented in this article is that the Universe is expanding by 
losing vacuum energy by the creation of new quantum states (45 orders during \( 1.37 \times 10^9 \text{ years} \)). 45 orders of the 
classical regime and 78 orders of the quantum regime decreased vacuum energy of the Universe on 123 orders and 
probably this is the solution of the cosmological constant problem, if the cosmological constant is the vacuum energy.

II. PHASE TRANSITIONS

First of all we note that microscopic defects of a gravitational vacuum which were produced in the quantum regime 
of the Universe evolution contributed to the total energy of vacuum:

\[ \Lambda = \Lambda_{\text{QF}} + \Lambda_{\text{GVC}}, \]

here: QF are quantum fields, GVC is a gravitational vacuum condensate \[27\]. These microscopic topological defects 
(worm-holes, micromembranes, microstrings, monopoles) had different dimensions and might be a carrier of dark 
energy in very early epochs also. Besides, the gravitational vacuum condensate fixed the origin of time in our 
Universe \[29\]. Unfortunately, we do not know how exactly our Universe has been losing its high symmetry. The 
elementary chain of the phase transitions, from which only the two last ones can be calculated exactly, was described 
in our article \[30\]:

\[ P \Rightarrow D_4 \times [SU(5)]_{\text{SUSY}} \Rightarrow D_4 \times [U(1) \times SU(2) \times SU(3)]_{\text{SUSY}} \]

\[ 10^{14} \text{GeV} \quad 10^{16} \text{GeV} \]

\[ \Rightarrow D_4 \times U(1) \times SU(2) \times SU(3) \Rightarrow D_4 \times U(1) \times SU(3) \Rightarrow D_4 \times U(1) \]

\[ 10^5 - 10^{10} \text{GeV} \quad 100 \text{GeV} \quad 0.15 \text{GeV} \]

The two last condensates of quantum fields in the framework of Standard Model (\( \Lambda_{\text{SM}} \)) may be calculated. They 
have an asymptotic equation of state \( p = -\rho \) and they are named the Higgs condensate in the theory of electro-weak 
interaction (\( \rho_{\text{EW}} \)) and the quark-gluon condensate in quantum chromodynamics (\( \rho_{\text{QCD}} \)). Therefore:

\[ \Lambda_{\text{QF}} = \Lambda_{\text{EW}} + \Lambda_{\text{QCD}}, \quad \Lambda_{\text{QF}} = -\rho_{\text{EW}} - \rho_{\text{QCD}} \]

In our article \[27\] we have already given a value of \( \rho_{\text{EW}} \) as \( \Lambda_{\text{SM}} \):

\[ \rho_{\text{EW}} = - \frac{m_H^2 m_W^2}{2 g^2} - \frac{1}{128 \pi^2} (m_H^4 + 3 m_Z^4 + 6 m_W^4 - 12 m_t^4). \]

For mass of Higgs \( m_H \sim 160 \text{ GeV} \) we have:

\[ \rho_{\text{EW}} \sim -(120 \text{GeV})^4. \]

This estimate was obtained in the article \[9\]. But, the most interesting condensate for us is the quark-gluon one since 
at this moment of the Universe evolution the vacuum energy ‘has hardened’. In article \[9\], the estimate of energy 
density of the quark-gluon condensate is also presented:

\[ \rho_{\text{QCD}} \sim -(265 \text{GeV})^4. \]
Note that only the quark-hadron phase transition quenches more than 10 orders of the 78 orders.

\[
\left( \frac{120}{0.265} \right)^4 \sim 4 \times 10^{10}, \quad \left( \frac{M_{Pl}}{M_{QCD}} \right)^4 \sim 4.5 \times 10^{78}
\]

Unfortunately, the remaining contributions in the beginning and in the middle of the chain of relativistic phase transitions are not possible to calculate exactly. Besides, the initial stage might be more complicated. For example: \( P \Rightarrow E_0 \Rightarrow O(10) \Rightarrow SU(5) \ldots \) Whereas the last chromodynamical phase transition (QCD) was investigated in the review extensively. The chiral QCD symmetry \( SU(3)_L \times SU(3)_R \) is not an exact one and pseudo-Goldstone bosons are the physical realization of this symmetry breaking. The spontaneous breaking of the chiral symmetry leads to the appearance of an octet of pseudoscalar Goldstone states in the spectrum of particles. For the temperature of the chiral symmetry breaking (\( T_c \sim 150 \) MeV) the main contribution in the periodic collective motion of a nonperturbative vacuum condensate determined pi-mesons as the lightest particles of this octet. In this process pi-mesons are excitations of the ground state and they definitely characterize this ground state (that is they characterize the QCD vacuum). And density of this vacuum energy may then be calculated.

Ya. Zel’dovich attempted to calculate a nonzero vacuum energy of our Universe in terms of quantum fluctuations of fields as a high order effect 40 years ago. He inserted the mass of proton or electron in his formula but the result was not satisfactory. The situation has changed since then if the average mass of pi-mesons (\( m_\pi = 138.04 \) MeV) is inserted and N. Kardashev’s modification of Ya. Zeldovich’s expression is used:

\[
\Lambda = 8\pi G_N^2 m_\pi^6 h^{-4} \text{ cm}^{-2},
\]

\[
\rho_\Lambda = G_N m_\pi^6 c^2 h^{-4} \text{ g cm}^{-3},
\]

then

\[
\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}} = \frac{\Lambda c^2}{3H_0^2}, \quad \rho_{cr} = \frac{3H_0^2}{8\pi G_N},
\]

can be calculated (here: \( G_N, h \) are the gravitation and Planck constants). If Hubble constant \( H_0 = 70.5 \text{ km sec}^{-1} / \text{ Mpc} \) then \( \Omega_\Lambda \sim 0.73 \). An experimental value for \( \Omega_\Lambda \sim 0.726 \pm 0.015 \) was recently obtained by the WMAP collaboration. We did similar calculations for different \( H_0 \) in the article 10 years ago. For energy \( \sim 150 \) MeV (the end of the last phase transition) the vacuum energy stopped to drop quickly and in further the vacuum energy dropped very slowly. However, even at this moment the large quantitative difference in densities of vacuum energy between ‘hardness’ and the modern value took place:

\[
(0.15/1.8 \times 10^{-12})^4 \sim 5 \times 10^{43}, \quad \rho_{DE} \sim (1.8 \times 10^{-12} \text{ GeV})^4.
\]

This difference is very large but it is essentially smaller than 123 orders. The question is: how and why vacuum energy relaxed to the modern value? Therefore, it is necessary to search another way for understanding of this and it may be the holographic one. Note that at the moment of quark-hadron phase transition (\( \sim 150 \) MeV) the relation of components of the Universe was also hardened.

III. HOLOGRAPHIC PRINCIPLE

The holographic theory of C. Balazs and I. Szapidi applied to cosmology gives the following formula for the vacuum energy density of the Universe in the holographic limit:

\[
\rho \leq 3M_{Pl}^4/8\pi R^2.
\]

The vacuum energy density of the Universe is bounded by the inverse area of its horizon. Here, important consequences of the holography take place: energy is decreased by the linear size of the Universe; energy density is decreased by its area. The authors of the article used the Fischler- Susskind cosmic holographic conjecture for which the entropy of the Universe \( (S) \) is limited by its “surface area” measured in the Planckian units:

\[
S \leq \pi R^2 M_{Pl}^2.
\]

In this case the connection between the vacuum energy density and a number of quantum states of the Universe is arisen and then the vacuum energy density following from equations \( 16 \) and \( 17 \) is:

\[
\rho \leq 3M_{Pl}^4/8S.
\]
Substituting the size of the observable Universe $R \sim 10^{28} \text{cm}$ in the formula (18), we can get the vacuum energy density of our Universe for $z = 0$ (that is now) in the holographic limit for $M_{Pl} = 1$:

$$\rho \sim 4 \times 10^{-57} (\text{GeV})^4.$$  \hspace{1cm} (19)

In other words, for expansion the vacuum energy is spent on producing new quantum states. This value is significantly different (10 orders) from the observable value of the vacuum energy density $\rho \sim 10^{-47} (\text{GeV})^4$ but it is another side of the question. Here it is necessary to give some explanation. General relativity is the prime example of a holographic theory [37]. But quantum field theories, in the present form, are not holographic ones [35]. Therefore, in the quantum regime of the Universe evolution the holographic concept does not work. The Universe came in the classical (Friedmann) regime, probably, when $t \sim 10^{-6}$ sec (corresponding to $E \sim 150 \text{MeV}$). $R_{QCD}$ was then the causal horizon. If

$$R_{QCD} \sim 3 \times 10^4 \text{cm}, \quad (R/R_{QCD})^2 \sim 10^{47}. \hspace{1cm} (20)$$

Note that the holographic idea was first proposed in articles [37, 39] and Ya. Bekenstein was the first who discussed this idea applying them to black holes (BH) considering BH entropy (a number of microstates) as a measure of information hidden in BH [40]. But the existence of the Universe horizon gives a “strong argument” supporting this holographic approach to the solution of the cosmological constant problem. Here the increase of entropy of the Universe (new quantum states) is evident. Besides, both of these sizes (10 orders) are derived from the proportionality of entropy and the horizon area together with the fundamental Clausius relation $dS = dQ/T$ in which $dS$ is one quarter of the horizon area, $dQ$ and $T$ are the energy flux across the horizon and Unruh temperature seen by an accelerating observer inside the horizon [37]. It is non-equilibrium thermodynamics of space-time in some sense and here thermodynamic derivation of the Einstein’s equations appears. Even more interesting moment is the statement that gravitation on a macroscopic scale is a manifestation of thermodynamics of the vacuum. It was the nontrivial idea of T. Jacobson [37], although S. Hawking [39] many years ago underlined the thermodynamic property of the de Sitter Universe to be similar to a BH which written in the static coordinates.

The curious table can be made using cosmological parameters of the seven-year WMAP data [11] and the cosmological calculator of N. Wright [42] if $\Omega_{\Lambda} = 0.73$; $\Omega_{m} = 0.27$; $H = 70.5 \text{ (kmsec}^{-1}/\text{Mpc})$. Then, the density of the vacuum energy in the classical regime as a function of redshift is:

| $t$ = | 13.76 | 13.62 | 13.36 | 13.09 | 12.47 | 11.88 | 11.34 | 10.35 | 9.48 | 8.71 | 7.98 | 7.36 | 6.71 | 5.98 | 5.34 | 4.78 | 1.58 | 1.24 | 1.01 | 0.80 | 0.64 | 0.54 | 0.49 | 0.44 | 0.39 | 0.33 | 0.27 | 0.22 | 0.18 | 0.11 | 0.07 | 0.03 | 0.01 | 0.003 | 0.001 |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $z$ = | 0      | 0.01   | 0.03   | 0.05   | 0.1    | 0.15   | 0.2    | 0.3    | 0.4    | 0.5    | 1      | 2      | 3      | 4      | 5      | 10     | 20     | 30     | 50     | 75     | 100    | 500    | 1000   | 5000   | 10$^4$ | 2$\times$10$^4$ | 5$\times$10$^4$ | 10$^5$ | 166666 | 10$^{10}$ | 2.5 | 24.3 | 95.6 | 262 | 7212 | 97402 | 1431298 | 10$^{10}$ | 0.51 | 0.82 |
| $10^{47}\rho = $ | 0.24 | 0.25 | 0.26 | 0.27 | 0.3 | 0.33 | 0.36 | 0.43 | 0.51 | 0.61 | 1.29 | 4.12 | 9.02 | 19.13 | 31 | 197 | 1465 | 4687 | 21307 | 1 |

| $t$ = | 16.8 | 16.37 | 0.44 | 0.22 | 0.13 | 25.4 | 6.9 | 1.8 | 0.3 | 75 |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $z$ = | 100 | 500 | 1000 | 1500 | 2000 | 5000 | 10$^4$ | 2$\times$10$^4$ | 5$\times$10$^4$ | 10$^5$ |
| $10^{47}\rho = $ | 166666 | 10$^{10}$ | 2.5 | 24.3 | 95.6 | 262 | 7212 | 97402 | 1431298 | 10$^{10}$ |

| $t$ = | 0.76 | 239 | 10$^3$ | 2396 | 25 | 0.27 | 0.003 |
|-------|--------|--------|--------|--------|--------|--------|--------|
| $z$ = | 10$^6$ | 10$^7$ | 10$^8$ | 10$^9$ | 10$^{10}$ | 10$^{11}$ |
| $10^{32}\rho = $ | 80128 | 10$^{24}$ | 7.29 | 10$^{20}$ | 7.26 | 10$^{16}$ | 6.67 | 10$^{12}$ | 5.71 | 10$^9$ | 4.62 |

where the time is in billions of years from the creation of the Universe up to $z = 30$; from $z = 50$ up to $z = 2000$ the time is in million years; from $z = 5000$ up to $z = 50000$ the time is in thousands years; from $z = 10^5$ up to $z = 10^6$ the time is in years; from $z = 10^7$ up to $z = 10^{11}$ the time is in seconds. For calculation of density of the vacuum energy, the simple approximate formulæ have been used:

$$\rho(z) = \frac{(3/8)M_{pl}^4[R_{QCD}/R(z)]^2}{10^{47}/[10^9/10^{30}]r^2(z)} \sim 0.375 \times 10^{-47}/r^2(z) \text{ (GeV})^4.$$  \hspace{1cm} (21)

For example, how can one get the density of the vacuum energy at $z = 0.5$? For that one uses the cosmological calculator for $\Omega_{\Lambda} = 0.73$; $\Omega_{m} = 0.27$; $H_0 = 70.5$; $z = 0.5$ and the flat model [42]. Then, the age at red shift $z = 0.5$ was $8.71 \times 10^8$ years (or $2.61 \times 10^{17}$sec). The causal horizon was $R = 0.78 \times 10^{28} \text{cm}$ and $r^2(0.5) = 0.61$. Therefore, we have $\rho = 0.375 \times 10^{-47}/0.61 \sim 0.61 \times 10^{-47}$. Note that during the time span from $z = 3$ ($t_3 = 2.21 \times 10^9$years) till $z = 0$ ($t_0 = 13.76 \times 10^9$ years), the density of the vacuum energy decreased 40 times, while during the first $10^{-6}$ sec the Universe lost 78 orders owing to the phase transitions. An initial part of this table may be checked by the Ia supernova team in the following years [43].
IV. CONCLUSION

There are the following probable points.

1. The relative content of the Universe components $\Omega_{\Lambda}$, $\Omega_{DM}$ and $\Omega_b$ had hardened in the first instants of the Universe evolution. The subsequent evolution led to decreasing absolute values of the component only.

2. The cosmological constant relates the properties of microscopic physics of a vacuum with the large scale physics.

3. The vacuum energy density of our Universe was probably ($\sim M_{pl}^4$) at the moment of its creation (it might be a fluctuation in the high symmetrical quantum vacuum of a multiverse)

4. Supersymmetry is broken if and only if the cosmological constant is positive.

5. In the first parts of first second of our Universe evolution, there was a period of vacuum evolution when condensates of quantum fields carried negative contributions in the positive energy density of the vacuum. It was the period of the non-equilibrium vacuum in its quantum regime. The 78 orders of the vacuum energy density from the 123 orders were compensated before its ‘hardness’.

6. The vacuum energy of the Universe ‘has hardened’ for $T \sim 150$ MeV ( the quark - hadron phase transition started at temperature $T \sim 265$ MeV).

7. Assuming that during the first parts of first second, the vacuum energy had lost 78 orders then in the next $4 \times 10^{17}$ sec it has lost only 45 orders by the creation of new quantum states (that is the rate of loss of the vacuum energy has decreased $10^{55}$ times).

8. Of course, traces of relativistic phase transitions are not present nowadays although fractality in the distribution of the baryon component might be produced only phase transitions [44].

9. The problem of the cosmological constant is probably solved by the implementation of the holographic principle to the ‘equilibrium vacuum’ after its practical ‘hardness’.

10. A holographic idea extended to all past history of our Universe’s evolution from $z = \infty$ to $z = 0$ was already considered in the article [35]. But it is not probably that the holographic principle may be applied to very early stages of the Universe evolution since an inflation phase was in that moment. Of course, the quantum regime of evolution took place in any case.

11. AdS/CFT correspondence, which states that all information about a gravitational system in any space region is encoded in its boundary, provides the strongest support to the holographic principle. This was noted by J. Maldacena 12 years ago [45].

12. Probably, Bekenstein’s thermodynamics of BH may be a trace of the “thermal nature” of the Minkowski vacuum.

13. Introduced by E. Verlinde an entropic force [46] as the specific microscopic force of space-time is a very natural physical point of view. Here, classical gravity results from a thermodynamic approach.

14. We could not get exactly 45 orders (we have got 47 orders) but this moment is not critical to the cosmological constant problem. We are only showing in this publication that the crisis of astrophysics connected with the cosmological constant is absent.

Of course, some unsolved problems remain. We do not know well even the equation of state of the dark energy which gradually losses its dark status in favor of the vacuum energy (now $1 + w = 0.013^{+0.066}_{-0.068}$ (0.11 syst)) [47]. The evidence for cosmic acceleration exists now at the very high level (more than 50 $\sigma$ [48]) but no evidence for DE evolution from a global analysis of cosmological data [49]. Therefore, a scalar field must be probably included for the best coincidence with cosmological data although it will be a more complicate physical situation. If in this case DE is given by a dynamical scalar field then it may have a direct interaction with other material fields of the Universe, in particular with cold dark matter [50]. Practically everything about the dark energy including DE projects can be found in the last detailed review [51] and in the article [43].

Finally, note that other approaches to dark energy modeling, which predict $w \neq -1$ and f(R) gravity as well as proposals for control experiments are intensively investigated [52-60]. Lastly it is important to mention recent articles discussing the holographic principle in cosmology [61-64]. Also G. Vereshkov recently noted the important fact that the cosmological constant may be by Sakharov’s inducing gravitation [65].
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