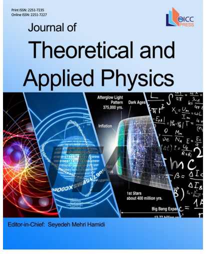

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Research Article

The Cosmological Constant as an Intrinsic Mass of Spacetime

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Abstract:

Supported by the dynamical role of spacetime in General Relativity, I suggest an argument of the materialization of spacetime at high scales$\sim M_P$. Such a materialization is given in terms of massive spacetime structures m_Λ, whose energy density corresponds to the observed small cosmological constant $\Lambda_{Obs}^{1/4} \sim 10^{-3}eV$, a candidate for Dark Energy in the universe. Under the known data, such an intrinsic spacetime mass is probed as $m_\Lambda \gtrsim 10^{-52}eV$.

Keywords: Spacetime; Cosmological constant; Gravity

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1. Introduction

The homogeneousity, isotropy and flatness of the universe at large scales have been established beyond reasonable doubt [1]. It obeys General Relativity (GR) and is made up of $\sim$ 5% visible matter, $\sim$ 25% Dark Matter, and of $\sim$ 70% Dark Energy (DE) exerting repuslive gravity which is behind the expansion of the universe [1–5]. That is to say, one of the biggest issues in modern physics is perhaps the nature of the DE dominating the actual energy content of the universe. In GR, DE is depicted in terms of the Cosmological Constant (CC) Λ, a small positive energy density $\rho_{\Lambda_{Obs}} \sim \left(10^{-3}eV\right)^4$, which is one of its most favoured candidate [6–8]. Originally, the CC was introduced in the GR field equations to make possible static solutions, corresponding to a static universe as widely believed at the time. Simple vacuum energy estimates of the CC value in Quantum Field Theory (QFT) yield results that are $\sim$ 120 orders of magnitude bigger than those derived from observations $\rho_{\Lambda_{QFT}}/\rho_{\Lambda_{Obs}} \sim 10^{120}$, known as the CC problem (CCP) [9]. Some values of the CC are set to zero by alternative considerations based on deep symmetries, especially supersymmetry where the contributions to the vacuum energy from the superpartners cancel each other perfectly. In some proposed modifications of Einstein's Special Relativity, especially Symmetrical Special Relativity (SSR) [10–14] where a universal minimum speed V (analogous the universal maximum speed c) is introduced creating a symmetric speed limit interval $V < v < c$. This modifies Lorentz transformations and aims to provide a new kinematic basis that, when it is applied to the Dark Energy problem, leads to a natural explanation for the CC as an effect of the corresponding vacuum state.

A non-zero value of CC has been widely adopted as a standard unit in the simplest and most successful cosmological models, the so-called ΛCDM, since the discovery of the acceleration of cosmic expansion in the real universe. It is noticeable that the ΛCDM cosmological model, with a small number of parameters and a few basic symmetries, treats precisely many detailed characters of cosmic structure and evolution [15]. However, the fact that why the CC is non-zero but so small (in natural units) or why it has the particular value it does, still doesn't have a sense with the absence of a generally accepted theory. Among the broadly held visions is the one stating that there is no way to calculate the CC value accurately, it is set at accident, and therefore its actual scale in our universe is adjusted by anthropic selection [16]. For this reason, close attention should be payed to observational data that indicate a possible non-zero CC and to the deep fabric of spacetime itself as well.

The objective of this paper is to contribute to the works dealing with the CCP. First, inspired by the dynamical behviour of the spacetime in GR, I construct a model for the CC as a pure spacetime property. That is, CC will be viewed as a pure energy of spacetime at high scales$\sim M_P$ in terms of uncharged massive structure$\sim m_\Lambda$. Next, I investigate the density of these structures according to the observed CC value, and then I approach such an intrinsic spacetime mass based on the knwon observational and theoretical data.

2. Cosmological constant in GR and QFT

2.1 Cosmological constant in GR

In GR, the CC originates from the Einstein field equations expressed in tensor notation and are given by[1]

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}, \tag{1}$$

where the tensor $G_{\mu\nu}$ written as the sum of the Ricci tensor $R_{\mu\nu}$ and the Ricci scalar R times the metric tensor $g_{\mu\nu}$ is the Einstein tensor describing the curvature of the $4D$ spacetime, and $T_{\mu\nu}$ is the stress-energy tensor representing the matter/energy content of spacetime such as radiation and galaxies [17]. These field equations (1) are often simply referred to as Einstein's equation. The meaning of these field equations (1) is that, at least gravitationally, the energy/mass guides the curvature of spacetime and the geometry/curvature of spacetime guides the movement of mass. After the application of GR to the cosmological scale by Einstein, he realized that his field equations (1) need to be adjusted in order to account for a static universe, one which neither expands nor contracts, as was believed at the time to be the state of our universe. For that, Einstein made this modification by adding an extra term, a constant as the Greek character Λ named the CC, to the left-hand side of his field equations (1) in the following way

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi GT_{\mu\nu}. \tag{2}$$

These new field equations form (2) suppose spacetime has an intrinsic curvature $\Lambda g_{\mu\nu}$. Such an intrinsic curvature was believed as necessary for a static universe until the observation of the expansion of the universe by Hubble. This fact caused the abandonment of the CC by Einstein [18]. Whilst, recent developments indicate that these modified equations (2) may be the meaningful after all, with the CC being interpreted as the vacuum energy density of empty space. Such a vacuum energy density enters into Einstein's field equations (1) as follows

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G\left(T_{\mu\nu} - \frac{\Lambda}{8\pi G}g_{\mu\nu}\right), \tag{3}$$

which is clearly the same form as the first field equations (1) with no CC but an energy-momentum tensor for the vacuum as

$$T^{vac}_{\mu\nu} = -\frac{\Lambda}{8\pi G}g_{\mu\nu}. \tag{4}$$

In arbitrary coordinates, the field equations (3) and (4) give the vacuum energy density in terms of the CC like

$$\rho^{vac}_{\Lambda} = \frac{\Lambda}{8\pi G}. \tag{5}$$

Thereby, the interpretations of the CC as either the energy density of the vacuum or as an intrinsic curvature of space are altogether equivalent. In contrast to ordinary matter and radiation, if there is really a constant non-zero vacuum energy (5), it will tend to dominate at long term as long as the universe expands, and thus the universe becomes vacuum-dominated. In recent times, the interpretation of the vacuum energy density has known much attention as a manner to elucidate the astonishing observation of the accelerated expansion of the universe. Generally, such an accelerating expansion is encapsulated in the idea of DE, and the CC fills famously the role of DE in the ΛCDM model of the universe [19]. For this reason, close attention should be payed to observational data which seems to provide empirical evidence for the profound origin of a possible non-zero CC.

2.2 Cosmological constant in QFT

It is known that naive estimates of the vacuum energy yield a value of the CC with a magnitude highly larger than observationsal ones [9]. Indeed, the energy density required to explain the accelerated expansion of the universe is of the same order as the critical density

$$\rho_{\Lambda_{Obs}} \sim \rho_{Crit} = \frac{3H_0^2}{8\pi G} \sim 10^{-12}eV^4, \tag{6}$$

where H_0 is the current value of the Hubble parameter characterizing the rate of expansion [15]. With the exception of neutrino mass scale, this energy density value (6) is tiny compared to energy scales in particle physics. From QFT, the total energy density of the vacuum is obtained by the regularized[2] sum of energies E_{ω_k} of the ground state oscillations of all the fields of

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[1] Natural units where $\hbar = c = 1$ are used.

[2] The result is of course infinite, and have to be appropriately regularized. This is achieved by introducing M_{Planck} as a cutoff at high frequencies.

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the theory [20, 21], which has no good reason to be zero but in fact is expected to be so huge as

$$\rho_{\Lambda_{QFT}} \sim_{0}^{k_{Planck}} \left(k^2 + m^2\right)^{1/2} d^3k \sim M_P^4 \sim 10^{112} eV^4, \tag{7}$$

where k is the mode's wave number and m is the particle's mass. So from (6) and (7) we read the large hierarchy

$$\rho_{\Lambda_{QFT}} / \rho_{\Lambda_{Obs}} \sim 10^{120}, \tag{8}$$

known as the vacuum catastrophe. This worst theoretical prediction (8) is believed to comes from the fact that the usual analysis largely relies on standard notions of fields and spacetime which are regular to all scales; however, several arguments point toward the idea that at the fundamental scale the physics of the continuum may emerge from an underlying discrete reality. Although the exact nature of the underlying fundamental physics is still undefined, one could not remain agnostic about it, yet he could take seriously the focal idea that at the Planck's mass M_P the nature is discrete, in the hope that this assumption might open the door for a novel look into the CCP.

3. Cosmological constant and spacetime structure

3.1 Cosmological constant and scale hierarchy

After all, the CC as a manifestation of vacuum energy is necessarily related to quantum fields and the structure of spacetime. In fact, this relation could be perceived in the hierarchy

$$\rho_{\Lambda_{Obs}} \sim \left[\left(\frac{M_{SM}}{M_P}\right)^2\right]^4 M_P^4 = \left(\alpha_G^2\right)^4 M_P^4, \tag{9}$$

where we can see that the underlying mechanism that induces the CC have to be resulted from a high suppression by a hierarchy factor going down from the Planck's scale M_P to the Standard Model (SM) scale M_{SM}. This hierarchy factor could be viewed as a characterizing coupling constant $\alpha_G \sim 10^{-16}$ whose the extremely small value suggests that it would be nothing but a gravitational-like fine structure constant, then we can have

$$\rho_{\Lambda_{Obs}} \sim \alpha_G^8 M_P^4. \tag{10}$$

So, the CC scale associated with the vacuum energy density would then be associated with the Planck's mass via the eight power of the gravitational-like fine structure constant α_G. Based on this scale analysis (9) and (10), if the CC which never changes in space and time is indeed DE, then it must be a fundamental property of spacetime; and this would then push into a high-energy scale $\sim M_P$ where the underlying mechanism which induces the CC must be resulted from a deep fabric of spacetime.

3.2 Spacetime origin of cosmological constant

Theoretically, the discrete picture of spacetime near to the Planck's mass $\sim M_P$ is accepted because, though any QFT that describes gravity is non-renormalizable, the energy scale at which we expect quantum gravity effect to be mesurable is extremely huge. Thence, at low energies, a valid effective theory can be utilized to materialize spacetime. More significantly, at high scales where the continuum classical perception of spacetime have to be shifted into a discrete quantum one, we can envision spacetime as a non-empty medium characterized by massive structures and as a result it will act non-trivialy.

Guided by this philosophy, and in spite of the fact that we still don't have an exact theory of gravity at an arbitrary scale at hand, we can visualize spacetime as being formed of uncharged structures of mass m_Λ, spaced by a small characteristic length ℓ_Λ. According to this picture, the dynamic of spacetime can be viewed as a large number of massive structures spaced by

$$\ell_\Lambda \pm \delta\ell_\Lambda \gtrsim \ell_p, \tag{11}$$

where $\pm\delta\ell_\Lambda$ are now the small spacetime perturbations, i.e., contractions and dilations of the characteristic length ℓ_Λ induced by massive objects, and ℓ_p is the Planck's length. In this regard, it is worth noting that in certain regions of the universe, for instance near to intense gravitational fields of huge massive cosmic objects such as black holes or giant stars, spacetime deformations $\delta\ell_\Lambda$ becomes considerable

$$|\delta\ell_\Lambda| \sim \ell_\Lambda. \tag{12}$$

This spacetime deformation (12) could be considered as being insignificant as stated by the cosmological principle in the distribution of galaxies where the universe appears to smooth out and become more homogeneous on the largest cosmic scales. Thus, the density ρ_{m_Λ} of such a spacetime structure depends on the geometry of spacetime which is determined by the matter/energy content of the universe. In particular, it depends on the density parameter being the ratio of the actual (observed) density to the critical density $\Omega = \rho_{Obs}/\rho_{Crit}$ which tells us which of the three Robertson-Walker geometries describes (open, flat or closed) our universe; and because these two densities are roughly of the same order (6), the universe appears to be flat. Therefore, at large cosmic scales we have

$$|\delta\ell_\Lambda| \ll \ell_\Lambda. \tag{13}$$

In this view and according to the proportionality relation (10), the mass density of spacetime could be roughly taken as

$$\rho_{m_\Lambda} \sim \alpha_G^8 m_\Lambda \ell_\Lambda^{-3} \sim Cst, \tag{14}$$

with the corresponding change in the spacetime mass density is

$$\pm\delta\rho_{m_\Lambda} \sim \pm\alpha_G^8 m_\Lambda \left(\delta\ell_\Lambda\right)^{-3} \ll \rho_{m_\Lambda}, \tag{15}$$

where now the factor α_G^8 encodes the distribution of spacetime structures m_Λ in the characteristic 3 dimensional spacial volum ℓ_Λ^3. With this and from (14) the typical spacetime mass is then

$$m_\Lambda \sim \alpha_G^{-8} \rho_{m_\Lambda} \ell_\Lambda^3. \tag{16}$$

At this stage, one could approach the spacetime mass by having a lower bound. Rightly, using the observed vacuum energy density in (6), the Planck's length limit in (11) and the value of the gravitational-like fine structure constant we obtain

$$m_\Lambda \gtrsim \alpha_G^{-8} \rho_{\Lambda_{Obs}} \ell_P^3 \sim 10^{-52} eV, \tag{17}$$

which appeared to be extremely light compared to the lightest elementary particles in the SM, namely neutrinos. Honestly, the existence of such ultralight spacetime structures at high scales $\sim M_P$ would hardly manifest itself gravitaionally in the dynamics of high-energy particles, except neutrinos due to their inert properties with respect to other conventional effects excluding gravity [22].

4. Conclusion

In this work, we have discussed the CC representing a energy density filling space uniformally and being the favoured candidate for the DE driving the accelerated expansion of the universe. Such an energy density has been addressed via different approaches in terms of vacuum energy idensity, a new dynamical scalar field (e.g. quintessence), and a pure geometrical origin in modified Einstein's equations at large scales. Here, we have addressed the CC through a possible connection with the fabric of spacetime at high energies $\sim M_P$. Properly, guided by the classical description of the energy/matter content of the universe and the dynamics of spacetime in GR along with the observational data, a discrete perception of spacetime has been suggested. With such a fundamental spacetime view, it was shown that this unknown energy could be thought of as a pure spacetime property. Indeed, within this materialized perception of spacetime, the origin and the smallness of this vacuum energy $\rho_{\Lambda_{Obs}} \sim \left(10^{-3} eV\right)^4$ could result from an intrinsic energy of the spacetime envisioned as massive structures m_Λ spaced by a characteristic length $\ell_\Lambda \lesssim \ell_P$. For a flat universe as currently accepted $\Omega = \rho_{Obs}/\rho_{Crit} \sim 1$ and according to this spacetime fabric CC has been described as the amount of these spacetime structures in the characteristic volume ℓ_Λ^3. Under the knwon obervational and theoretical data, a lower bound of spacetime mass has been derived as $m_\Lambda \gtrsim 0^{-52} eV$; which is an extremely light structure.

Despite the fact that these ultralight spacetime buildings appear to be far away from any kind of actual physical investigations, seen that our knowledge of gravity starts to be more comprehensible thanks to the recent theoretical and experimental efforts [23–25], such an intrinsic spacetime energy description of CC may shed light on possible connections with other related long-standing physical problems.

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Authors contributions
All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.
Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.
Conflict of interests
The author states that there is no conflict of interest.

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